World Sustainability Series

Monika Thakur *Editor*

Sustainable Food Systems (Volume I)

SFS: Framework, Sustainable Diets, Traditional Food Culture & Food Production

Springer

World Sustainability Series

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Due to its scope and nature, sustainable development is a matter which is very interdisciplinary, and draws from knowledge and inputs from the social sciences and environmental sciences on the one hand, but also from physical sciences and arts on the other. As such, there is a perceived need to foster integrative approaches, whereby the combination of inputs from various fields may contribute to a better understanding of what sustainability is, and means to people. But despite the need for and the relevance of integrative approaches towards sustainable development, there is a paucity of literature which address matters related to sustainability in an integrated way.

Notes on the quality assurance and peer review of this publication

Prior to publication, the works published in this book are initially assessed and reviewed by an in-house editor. If suitable for publication, manuscripts are sent for further review, which includes a combined effort by the editorial board and appointed subject experts, who provide independent peer-review. The feedback obtained in this way was communicated to authors, and with manuscripts checked upon return before finally accepted. The peer-reviewed nature of the books in the "World Sustainability Series" means that contributions to them have, over many years, been officially accepted for tenure and promotion purposes.

Monika Thakur
Editor

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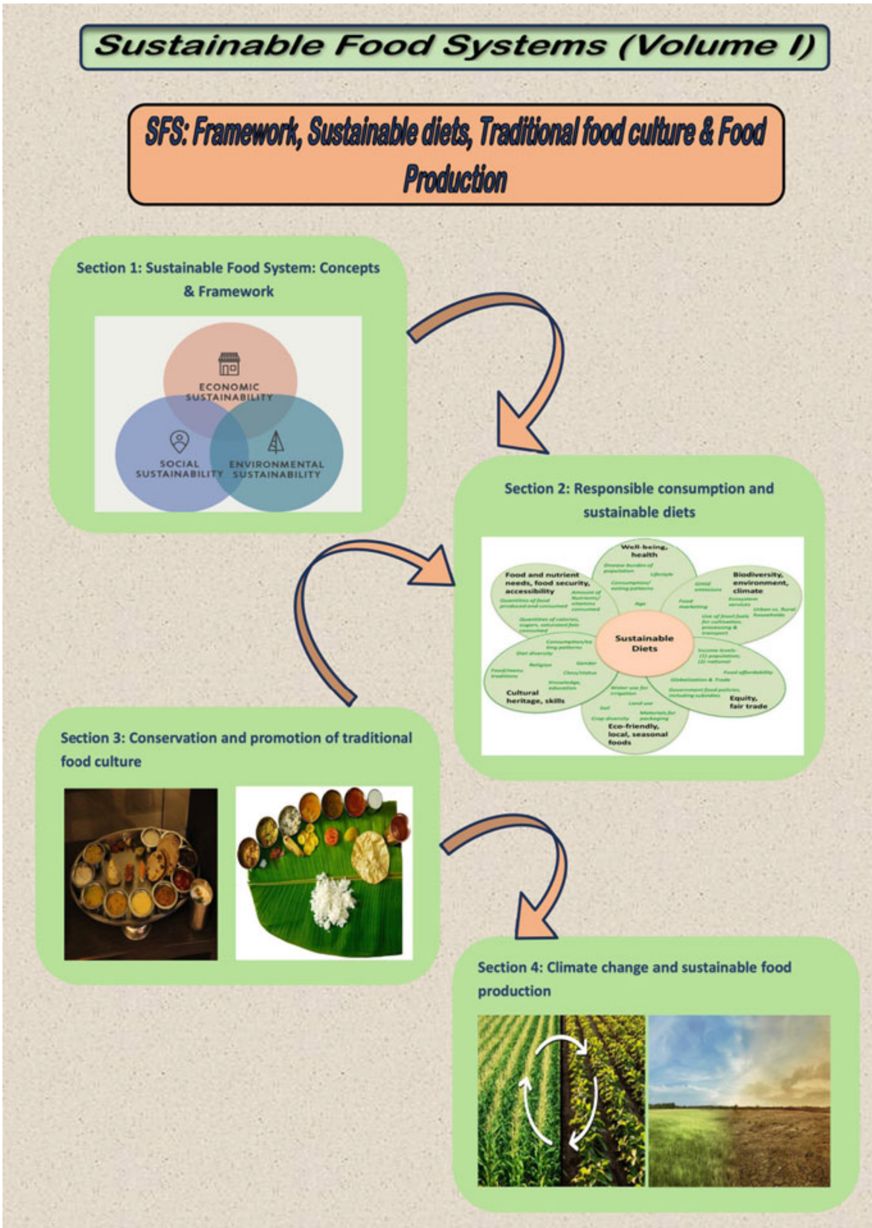

Sustainable Food Systems (Volume I)
SFS: Framework, Sustainable diets, Traditional food culture & Food Production
Section 1: Sustainable Food System: Concepts & Framework
ECONOMIC SUSTAINABILITY
SOCIAL SUSTAINABILITY
ENVIRONMENTAL SUSTAINABILITY
Section 2: Responsible consumption and sustainable diets
Sustainable Diets
Well-being, health
Food and nutrient needs, food security, accessibility
Biodiversity, environment, climate
Cultural heritage, skills
Equity, fair trade
Eco-friendly, local, seasonal foods
Section 3: Conservation and promotion of traditional food culture
Section 4: Climate change and sustainable food production

Preface

The **Sustainable Development Goals (SDGs)** of the United Nations are centred on a sustainable food system. The SDGs were adopted in 2015, and by 2030, they aim to eradicate hunger, achieve food security, and improve nutrition. To do this, significant changes in agriculture and food systems must be made. To achieve the SDGs, the global food system must be transformed to increase productivity, include poor and disadvantaged communities, be resilient and environmentally sustainable, and be able to provide everyone with a healthy diet. These are intricate and systemic problems that need coordinated solutions at the local, regional, national, and international levels.

Innovative frameworks, sustainable diets, traditional cultures, green and circular technologies and strategies, food safety, and diversity initiatives are part of the Sustainable Food System, which attempts to deliver high-quality, safe meals in a sustainable manner. It has been impossible to emphasise every aspect of the Sustainable Food System concept under the SDG Goals in a single book because it is such a huge concept. As a result, the Editor has divided this extensive, thorough, and compendious approach into two series, **Sustainable Food System I and II**, which are both balanced and well-organised.

The **"Sustainable Food System (Part I): Framework, Sustainable Diets, Traditional Food Culture & Food Production"** has a very comprehensive outline divided into four major sections and further 24 different chapters.

The **Part I: Sustainable Food System: Concepts and Framework** consists of five different chapters primarily focusing on the Sustainable food systems, its conceptual introduction, framework, and different concepts nationally and internationally. The **Part II: Responsible Consumption and Sustainable Diets** elaborated in nine different chapters. This section deals with different aspects of nutrients sustaining health and sustainable diets. The **Part III: Conservation and Promotion of Traditional Food Culture** compiled in four chapters will cover the conservation and promotion of traditional food cultures and their practices. The last and **Part IV: Climate Change and Sustainable Food Production** consists of six different chapters. This section will provide the current knowledge and innovative developments related to climate change, nutritional security and agronomic bio-fortification.

Readers will learn about a wide range of subjects in every chapter of this book, such as the idea and framework of sustainable food systems, difficulties and their solutions, sustainable diets, traditional food cultures, and climate change and its impact on food production. Each chapter provides insights into how sustainable technologies are changing the food systems, from the concept and framework of sustainable food systems to cutting-edge sustainable diets that they consume.

The authors of this book are renowned scholars, scientists, academicians, and authorities who have devoted their professional lives to the fields of agriculture, food science, nutritional, and life sciences. Each chapter provides readers with a thorough overview of the present situation and potential future developments in sustainable food systems by distilling their combined knowledge and ground-breaking research discoveries. We invite readers to learn more about the difficulties and cutting-edge solutions developed to address them as we travel through the **"Sustainable Food System: Framework, Sustainable Diets, Traditional Food Culture & Food Production"**. We hope that this book will act as a catalyst for innovation, collaboration, and fresh thinking that will advance the crucial field of Life Sciences and Food Science and Technology.

Noida, India Monika Thakur

Acknowledgements

Sustainable Food System (I): Framework, Sustainable Diets, Traditional Food Culture & Food Production is a comprehensive review of framework of sustainable food systems, difficulties and their solutions, sustainable diets, traditional food cultures, the climate change and its impact on food production. I am extremely indebted to Respected Founder President, **Dr. Ashok K Chauhan**, for his blessings and constant encouragement. It has been a great pleasure to acknowledge the wholehearted support received from **Dr. Atul Chauhan**, Chancellor, Amity University Uttar Pradesh and President RBEF, without their encouraging words, this endeavour is impossible. Special thanks to **Prof. Balvinder Shukla**, Vice Chancellor, Amity University Uttar Pradesh, India for her constant motivation and support at all the stages of the progress.

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Dr. Monika Thakur

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Abbreviations

%	Percent
&	And
/	Per
μCT	Microfocus X-ray computed tomography
μg	Micro gram
μl	Micro litre
μm	Micrometre
ATP	Adenosine Tri Phosphate
Bt	Bacillus thuringiensis
CFU/ml	Colony Forming Unit per ml
CH_4	Methane
CHO	Carbohydrates
cm	Centimetre
CO_2	Carbon dioxide
CO_2e	Carbon dioxide Equivalent
conc.	Concentrated
CSA	Community-supported agriculture
dil.	Dilute
DNA	Deoxy ribonucleic acid
e.g.	For example
Ed.	Edition
ed.	Editor
eds.	Editors
EN	Enteral Nutrition
et al.	Et. alia; and others
etc.	Et. cetera
FAO	Food and Agriculture Organisation
FSC	Food supply chain
FSMS	Food Safety Management System
FSSAI	Food Safety Standards Authority of India
FUSIONS	Food Use for Social Innovation by Optimising Waste

g	Gram
GHG	Greenhouse Gas
GHGs	Greenhouse gases
GRAS	Generally Recognised as Safe
GWPs	Global warming potentials
HACCP	Critical Control Points Hazard Analysis
HBV	Hepatitis B Virus
HIV	Human Immunodeficiency Virus
HPP	High Pressure Processing
HPV	Human papilloma virus
hrs.	Hours
i.e.	That is
in vitro	With in glass
in vivo	With in living
Kg	Kilogram
l	Litre
LCA	Life Cycle Assessment
m	Metre
mg	Milligram
MH	Million Hectares
min	Minutes
ml	Millilitre
mln tons	Million tonnes
mm	Millimetre
MoFPI	Ministry of Food Processing Industry
MS	Mass spectrometry
MT	Metric Ton
MT/ha	Metric Ton per Hectare
N_2O	Nitrous oxide
Nm	Nano metre
NTP	Non-Thermal Processing
°C	Degree Celsius
PKVY	Paramparagat Krishi Vikas Yojana Prevention Strategies
RTS	Ready to Serve
RVF	Rift Valley Fever
SFS	Sustainable food system
SI	Sustainable Intensification
SMEs	Small and medium-sized enterprises
sp.	Species (Singular)
spp.	Species (Plural)
sq Km	Square Kilometre
UV	Ultraviolet
var.	Variety
viz.	Vidalicet; namely
vol.(s)	Volume(s)

w.r.t.	With respect to
WEPs	Wild edible plants
WHO	World Health Organisation
WLPs	Wetland plants

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Sustainable Food System: Concepts and Framework

Nourishing the Future: Introduction to Sustainable Food Systems with Concepts and Framework

Ashmita Singh, Vatsala Sharma, Marion Grenier, Vinita Singh, and Monika Thakur

1 Introduction

Over the past half-century, remarkable strides have been made in enhancing food production, resulting in a noteworthy decrease in global hunger even as the world's population has doubled (World Bank 2008). However, it remains imperative to acknowledge that a significant proportion of the global populace, more than one in seven individuals, continue to grapple with insufficient protein and energy intake, alongside a prevalence of micronutrient deficiencies (FAO 2023). At present, we are confronted with a fresh array of intricate challenges (Evans 2009). Projections indicate that the global population will approach 9 billion by the mid-twenty-first century, closely linked to escalating affluence. With rising prosperity, there is a corresponding upsurge in purchasing power, leading to amplified consumption of processed foods, meat, dairy, and fish. This surge in demand places considerable strain on the food supply system. Concurrently, food producers are contending with escalating competition for finite resources like land, water, and energy. Simultaneously, they face mounting pressures to mitigate the adverse environmental impacts of food production (Tilman et al. 2001; Reid Walter 2005). Amidst these concerns, a prevailing threat emerges—the profound impacts of substantial climate change. The uncertainty surrounding the unfolding of climate change and the potential influence of mitigation and adaptation measures on the food system further compound the complexity of the situation (Solomon et al. 2007; Schmidhuber and Tubiello 2007). Therefore, while substantial headway has been made in diminishing global hunger in recent

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decades, significant challenges persist. The convergence of population expansion, escalating consumption patterns, environmental predicaments, and climate change underscores the pressing necessity for pioneering and sustainable solutions to ensure food security for an expanding global population.

2 The Global Food Challenge: Feeding a Growing Population Sustainably

Sustainability discussions are prominently focused on agriculture and food systems. The origins of environmental, economic, and social unsustainability are linked, to a certain extent, with the worldwide food system. Substantial trade-offs have emerged alongside the growth of food provision. Actions within the food cycle, spanning from agricultural cultivation to consumption, generate outcomes beyond consumable edibles, including waste and pollution, which are reintegrated into the natural ecosystem. Notably, food wastage alone contributes to approximately 3–5% of the overall impacts on global warming, surpassing 20% of the pressure on biodiversity, and accounting for 30% of the total agricultural land across the globe (European Commission 2014).

In the meantime, a staggering 842 million individuals continue to experience under-nourishment (FAO et al. 2013) and, in a parallel development, obesity has emerged as a significant public health concern, affecting 500 million obese adults (Finucane et al. 2011). The establishment of sustainable food systems has gained momentum as a prevailing slogan and a substantial endeavour to redirect our food systems and policies towards more well-aligned objectives, ultimately leading to enhanced societal well-being.

3 Sustainable Food Systems

A sustainable food system can be defined as one that ensures the provision of nourishing sustenance to fulfil present dietary requirements while concurrently safeguarding robust ecosystems capable of sustaining forthcoming generations, all with minimal adverse ecological consequences (Thakur and Modi 2020). This system fosters local production and distribution infrastructures, endeavours to make nutrient-rich nourishment universally attainable, accessible, and economically feasible, and operates in an equitable and ethical manner, safeguarding the well-being of farmers, workers, consumers, and communities (Story et al. 2009). The intricate fabric of the food system is substantially intricate, driven by a multitude of economic, socio-cultural, and environmental factors that extend both within and beyond its confines. The interwoven nature of these interactions accentuates the necessity for systematic approaches and comprehensive evaluation tools to steer transformative change.

3.1 Importance and Relevance of Sustainable Food Systems

In our swiftly evolving world, the significance and pertinence of sustainable food systems hold immense weight. With the global population poised to reach 9.7 billion by 2050 and grappling with the formidable challenges posed by climate change, food security, and ecological degradation, the adoption of sustainable food practices has become an absolute necessity. The fundamental objective of sustainable food systems is to delicately balance the fulfilment of prevailing dietary requirements for an expanding populace while concurrently safeguarding the Earth's natural resources and ecosystems for future generations. This pursuit entails the implementation of regenerative agricultural methodologies, curtailing food wastage, fostering biodiversity, and augmenting the accessibility and distribution of sustenance. Various studies have underscored the latent benefits of sustainable food systems, encompassing enhanced soil vitality, diminished greenhouse gas emissions, augmented resilience against climatic upheavals, and amplified socio-economic advantages for local communities (Willett et al. 2019). The embracement of sustainability within our food systems not only safeguards our environment but also assumes a pivotal role in ensuring a healthier and more equitable future for all.

4 The Triple Bottom Line of Sustainable Food Systems

The concept of the Triple Bottom Line (TBL) within Sustainable Food Systems pertains to the exhaustive evaluation of the sustainability encompassing food production, distribution, and consumption, grounded in three interrelated dimensions: social, environmental, and economic. This framework entails an evaluation of how the food system influences individuals, the environment, and financial considerations, with the goal of engendering a more well-rounded and sustainable approach to both producing and consuming food. By adopting this comprehensive approach, the sustainability of the food system is upheld, offering guidance for formulating decisions and policies that strive to establish a resilient, just, and ecologically conscientious food system, both for the current and forthcoming generations (Elkington 2004). The Triple Bottom Line framework within sustainable food systems encapsulates three intertwined pillars, each symbolizing a pivotal facet of sustainability (Hsu et al. 2019).

5 Environmental Sustainability

Environmental sustainability is centred around preserving natural resources and ecosystems while minimizing the negative impact of food production and consumption on the environment (Chaudhary et al. 2018). This pillar involves several key components, including:

- **Sustainable Agriculture**: This entails adopting practices that promote soil health, conserve water, reduce chemical inputs, and preserve biodiversity. For example: organic farming, agroforestry, and regenerative agriculture.
- **Climate Change Mitigation**: Efforts to reduce greenhouse gas emissions from agricultural activities, transportation, and food processing to mitigate the effects of climate change on the environment.
- **Water Conservation**: Implementation of water-efficient irrigation techniques and sustainable water management practices to preserve water resources and maintain the health of ecosystems.
- **Waste Reduction**: Minimizing food waste at all stages of the food supply chain to reduce the environmental burden and improve overall resource efficiency.
- **Responsible Sourcing**: Encouraging the use of sustainably sourced ingredients and materials to reduce environmental degradation associated with food production (Berry et al. 2015).

6 Social Equity

The social equity of sustainable food systems focuses on ensuring equitable access to nutritious and culturally appropriate food for all individuals and communities (Eizenberg and Jabareen 2017).

Some key elements include:

- **Food Security and Access**: Ensuring that everyone has reliable access to affordable, safe, and nutritious food to meet their dietary needs and preferences.
- **Food Justice**: Addressing social inequalities related to food access, distribution, and affordability, especially in marginalized communities.
- **Fair Labour Practices**: Supporting fair wages, safe working conditions, and workers' rights for those involved in food production and distribution, including farmers, farmworkers, and food workers.
- **Community Engagement**: Encouraging participatory decision-making processes that involve local communities in shaping sustainable food systems that meet their needs and preferences.
- **Food Sovereignty**: Respecting the rights of communities to control their own food systems and make decisions about food production and consumption that align with their cultural values and traditions (El Bilali et al. 2019).

7 Economic Viability

Economic viability is focused on balancing profitability and long-term resilience within the food system. This pillar encompasses various important aspects, some are included as follow:

- **Sustainable Business Practices**: Supporting businesses that prioritize environmental and social sustainability while maintaining financial viability.
- **Local and Regional Economies**: Fostering local food systems that support small-scale farmers, promote regional economic development, and reduce dependence on distant supply chains.
- **Fair Trade and Ethical Sourcing**: Encouraging fair trade practices and ethical sourcing to ensure fair compensation for producers and workers and promote transparency in supply chains.
- **Investment in Research and Innovation**: Supporting research and innovation to develop sustainable agricultural practices, food processing technologies, and distribution methods that enhance efficiency and productivity.
- **Cost-Internalization**: Accounting for the true environmental and social costs of food production and distribution to avoid negative externalities and create a more transparent and equitable pricing system (Moldan et al. 2012).

8 The Interconnectedness of Food Systems

The intricate interconnection of food systems stands as a foundational element that cannot be disregarded in the pursuit of global food security that is both sustainable and resilient. In our progressively globalized world, the production, distribution, and consumption of food are intricately woven together across regions and nations. A disruption within any segment of the food system can send reverberations throughout the entire network, affecting the availability, affordability, and quality of food in distant locales. This intricate linkage is palpable within the intricate fabric of agricultural trade, international supply chains, and the cross-border exchange of knowledge and technology. Consequently, addressing the multifaceted challenges confronting food systems, including climate change, population growth, and limited resources, necessitates united endeavors on a global scale. By comprehending and acknowledging the interdependencies inherent in food systems, we can effectively formulate and implement strategies that foster sustainability, fairness, and adaptability in the face of an uncertain future (High Level Panel of Experts on Food Security 2017).

9 Understanding the Complexity of Food Systems

Understanding the complexity of food systems is essential to develop sustainable food systems. The complexity of food systems comes from their interconnections, involving lot of different actors, from farmers to consumers. The activities are also multiple, such as production, aggregation, processing, distribution, consumption, and disposal of food product (World Bank 2008). One change in the chain can numerous repercussions on the rest of the contributors. Agricultural activities can lead to increase pollution, soil degradation, water use, and biodiversity loss (Tilman et al. 2001). Nowadays, it is crucial to take measures against. Careful management of resources is essential, as food systems rely on limited resources such as land, water, and energy. That's why it's important to develop Sustainable Food Systems in order to avoid food loss and waste as much as possible, throughout the chain. Climate change also affect a lot the production of food, and extreme weather can affect food security.

Moreover, new innovations such as mechanization, irrigation, genetic modification, and the globalization of supply chains are notably contributing to the complexity of global food systems. Given the expected negative effects of climate change on agriculture, the ability of our current food systems to continue feeding current and future populations is uncertain (FAO 2023). As global hunger and malnutrition continue to increase; it is becoming urgent for food systems to undergo a radical transition towards sustainable food systems.

10 Interactions Between Agriculture, Environment, Society, and Economy

Different disciplines, such as the natural, social, economic, and political sciences, are involved in contemporary food systems. A holistic approach to the 4 P (Planet, Population, Profit, Policy) is desirable for the development of food systems (Evans 2009). It is important to consider the environmental impact of food production and consumption.

However, the social and economic dimensions of food systems cannot be overlooked. Food access is not the same for everyone. Income disparities influence food consumption, lead to disparities in food access and in the nutritional status among different populations. Affordability and availability are two factors to take into consideration. It is very important for sustainable food systems to promote social equity and economic viability.

Furthermore, food choices depend on many factors, and habits vary according to culture and personal taste, and social habits. Food systems must adapt to everyone. Sustainable food systems focus on methods that minimize environmental impacts, and involve friendly farming practices, equitable access to food, healthy diet, and economic support.

11 Impacts of Food Systems on Human Health and Well-Being

Food systems have a direct impact on human health and well-being. Everyone's diet impact on the nutritional status and health. A nutrient-rich and diversified food can promote optimal growth and development, as well as overall good health.

On the other hand, a poor and deficient food system may lead to malnutrition, and diet-related non-communicable diseases such as obesity, diabetes, and cardiovascular diseases (Reid Walter 2005). A sustainable food system must promote a balanced and nutritious diet to improve public health and reduce diet-related diseases. Food safety is an essential part of sustainable food systems. Food and Agriculture Organization of the United Nations (FAO) encourages consumption of wholefoods and a minimized ultra-processed food (Solomon et al. 2007). A sustainable healthy diet should have a positive impact on human health and wellbeing (Schmidhuber and Tubiello 2007).

12 Drivers of Unsustainability in Food Systems

The factors driving unsustainability within food systems are multifaceted and hold significant implications for global well-being. A multitude of key elements contribute to the challenges faced by food systems worldwide. Foremost among these is the surge in population and urbanization, exerting immense pressure on agricultural production and resources. As the global populace continues its expansion, the demand for sustenance grows exponentially, culminating in the excessive depletion of land, water, and biodiversity. Furthermore, the intensification of agriculture, pursued for heightened yields and profits, frequently leads to the excessive use of chemical inputs, consequently degrading the environment and depleting soil fertility. The transportation and wide-scale distribution of food across extensive distances add to the carbon footprint of the food industry, further exacerbating the impact of climate change. Additionally, the widespread prevalence of food wastage across various supply chain stages, spanning production to consumption, not only squanders valuable resources but also compounds issues of food insecurity. These driving forces behind unsustainability underscore the urgency for comprehensive and immediate efforts to reshape food systems towards more sustainable and equitable practices (Foley et al. 2011; Tilman et al. 2011).

13 Industrial Agriculture and Its Environmental Impacts

Agroecology, as a suite of agricultural methodologies, endeavors to enhance agricultural systems by capitalizing on natural processes. It seeks to establish advantageous biological interactions and harmonies within the components of agroecosystems (Gliessman 1990). This approach aims to curtail the reliance on synthetic and harmful external inputs, instead tapping into ecological mechanisms and the services provided by ecosystems to design and implement agricultural practices that are environmentally sound (Wezel et al. 2014). The discourse on sustainability within agriculture stems from the observation that numerous agricultural systems, through diverse combinations of issues, yield adverse consequences for the environment, jeopardize the livelihoods of farmers, or disrupt the social fabric of rural regions. Unsustainability can originate from the management of soil, water, nutrients, and biota within farms (Hairiah and Weise 2001). However, it can also be articulated and articulated by social agents integral to farming (van Noordwijk and Cadisch 2002). These actors encompass individuals affected by lateral flows emanating from farms, including neighbors and environmental advocates. Additionally, they comprise those who supply indispensable resources (including investment) and the consumers of agricultural outputs, both directly and indirectly via value chains, with intermediary stakeholders. Beyond inputs and outputs, a farm's functioning is profoundly influenced by the regulatory milieu within which it operates. This regulatory environment is itself molded by the perspectives of investors, neighbors/activists, and value chain operators, though it may not comprehensively address all their concerns (Bernard et al. 2014).

14 Food Waste and Loss Along the Supply Chain

The issue of food loss and waste (FLW) holds significant importance due to its substantial socioeconomic toll and its intertwining with challenges related to waste management and climate change. FLW results in considerable squandering of precious resources while concurrently contributing to environmental deterioration (Beretta et al. 2013). Furthermore, FLW also bears ethical implications, given that nearly 12% of the global population experiences hunger (Lohnes and Wilson 2017). Despite growing awareness and concerted efforts to mitigate FLW, its incidence remains disproportionately high. As cited in Gustavsson et al. (2011), approximately half of all root crops, vegetables, and fruits globally go to waste. In light of the gravity of the situation, researchers have undertaken numerous investigations pertaining to FLW within the food supply chain (FSC). These studies delve into the origins of waste and proffer potential remedies.

Conventional comprehension of FLW predominantly centers on discarded or unused food items. Nevertheless, comprehending the constituents of FLW is intricate, given its multi-dimensional nature. Moreover, each dimension bears manifold

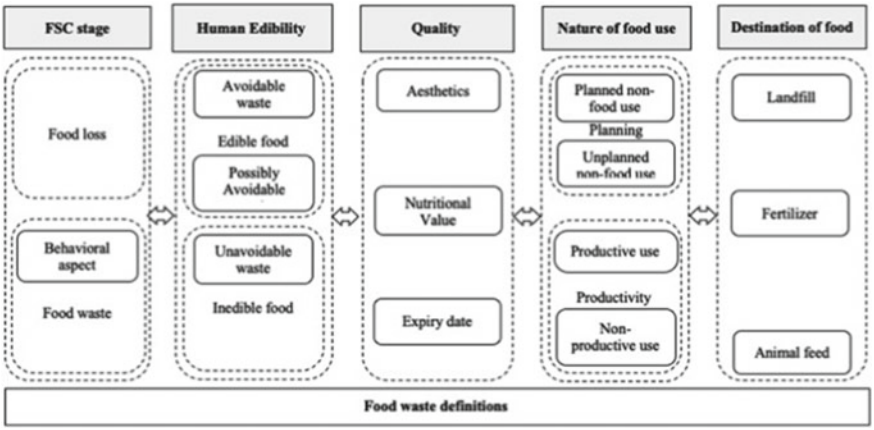

Fig. 1 Five dimensions of food waste

economic, social, and environmental implications (Irani et al. 2018). The delineations of FLW definitions are grounded in five comprehensive dimensions, encompassing the FSC stage, human edibility, food quality, purpose of use, and final destination of food, as illustrated in Fig. 1.

15 Unsustainable Consumption Patterns and Dietary Choices

Food consumption has been pinpointed as among the most resource-intensive and environmentally impactful household activities (Reinders et al. 2003). Given the essential nature of food, the dietary preferences of individuals and households are, and will continue to be, closely examined in the quest for sustainable consumption patterns. Unlike other products, food cannot be easily dematerialized or replaced by services, posing challenges to mitigating environmental effects. Consequently, dietary changes emerge as a key proposition for achieving sustainable lifestyles in developed nations.

The current trend toward adopting sustainable diets is a tangible reality (Antonides 2017). The motivations behind this shift encompass ethical, cultural, environmental, and health considerations (Bollani et al. 2019). Scrutinizing consumption behaviours aids in comprehending the rationale behind selecting specific behaviours over others. These insights can subsequently inform production adaptations, including the development of new products and policy measures aimed at promoting such consumption (Antonides 2017).

Yet, despite heightened awareness and efforts to reduce FLW, its prevalence remains high. According to the study by Lim et al. (2021) while many consumers possess knowledge and positive attitudes towards sustainability, concrete action to change consumption habits is not always evident, indicating a gap between intent and actual behaviour. This phenomenon of avoiding sustainable product purchases, often attributed to reasons like cost and taste preferences, highlights the prevalence of short-term gratification over long-term benefits (Aschemann-Witzel 2015). A similar behavioural pattern is noticeable among college students, as observed by Abraham et al. (2018), who found that although students have awareness of healthy nutritional requirements, their food choices prioritize convenience and taste over health considerations. Carrigan and Attalla (2001) further underscores that factors such as price, quality, convenience, and brand familiarity significantly impact consumer decisions, while ethical concerns hold less sway. Examining socio-economic status reveals disparities in food consumption behavior, with higher socio-economic status individuals displaying healthier dietary habits and greater concern for the environment (Konttinen et al. 2013). On the contrary, those with lower incomes tend to prioritize price when making food choices (Hupkens 2000; Bowman 2007). Despite these variances, the path toward sustainable consumption remains complex and multi-dimensional, encompassing economic, social, and environmental considerations.

16 The Principles of Sustainable Food Systems

The Principles of Sustainable Food Systems encompass a set of guiding principles that promote environmentally, socially, and economically responsible practices in food production, distribution, and consumption. These principles aim to address various challenges associated with the global food system, such as climate change, biodiversity loss, food insecurity, and social inequality.

16.1 Regenerative Agriculture and Soil Health

Regenerative Agriculture is an approach to farming that focuses on building and improving soil health, biodiversity, and ecosystem resilience while sequestering carbon and reducing the overall environmental impact of agriculture. It goes beyond sustainable practices by aiming to restore and regenerate the natural resources that are essential for agricultural productivity (Newton et al. 2020).

This process involves the following aspects:

- **Soil Health:** Regenerative agriculture prioritizes soil health as the foundation of sustainable farming. Practices such as minimal soil disturbance, cover cropping, crop rotation, and compost application help improve soil structure, increase organic matter, and enhance soil fertility.
- **Biodiversity:** Encouraging biodiversity in agricultural systems contributes to pest and disease management, pollination, and overall ecosystem resilience. Planting

diverse crop species and creating habitat for beneficial insects and wildlife are integral to regenerative farming practices.

- **Carbon Sequestration**: Regenerative agriculture seeks to capture and store carbon dioxide from the atmosphere in the soil, helping to mitigate climate change. Healthy soils with increased organic matter can sequester carbon, acting as a carbon sink.
- **Water Management**: Practices like contour farming, mulching, and water-efficient irrigation methods are employed to conserve water, improve water infiltration, and reduce soil erosion.
- **Agroforestry**: Integrating trees and woody plants with crops or livestock can provide additional ecosystem benefits, including shade, wind protection, and carbon sequestration.
- **Integration of Livestock**: Integrating livestock into cropping systems can help cycle nutrients, enhance soil health, and optimize land use.
- **Participatory Approach**: Regenerative agriculture often involves active collaboration between farmers, researchers, and communities to adapt and implement practices suitable for specific agroecological conditions (Rhodes 2017).

17 Biodiversity Conservation and Ecosystem Services

Biodiversity Conservation and Ecosystem Services are vital components of sustainable food systems that focus on maintaining the diversity of plant and animal species and the crucial benefits they provide to humans and the environment. Biodiversity refers to the variety of life on Earth, including the genetic, species, and ecosystem diversity, while ecosystem services encompass the valuable services and resources that ecosystems provide to support life. In the context of sustainable food systems, biodiversity conservation and ecosystem services play significant roles in enhancing agricultural productivity, promoting resilience, and fostering environmental sustainability (FAO et al. 2013).

Biodiversity is essential for agricultural systems as it provides several key benefits including:

- **Crop Genetic Diversity**: Biodiversity in crops and their wild relatives offers a diverse gene pool, providing valuable genetic traits for breeding programs. This genetic diversity enhances crop resilience to pests, diseases, and environmental stresses, contributing to more sustainable and adaptable food production.
- **Pollination**: Many crops depend on pollinators like bees, butterflies, and birds for reproduction. Biodiversity conservation ensures a healthy population of pollinators, which in turn leads to improved crop yields and quality.
- **Natural Pest Control**: Biodiverse ecosystems support the presence of natural enemies of pests, such as predators and parasitoids. By maintaining natural pest control mechanisms, farmers can reduce their reliance on chemical pesticides, benefitting both the environment and human health.

- **Soil Fertility**: Biodiversity contributes to healthy soil ecosystems by fostering nutrient cycling, organic matter decomposition, and beneficial soil microorganisms. This promotes sustainable soil fertility and nutrient availability for plant growth.
- **Ecosystem Services**: Ecosystem services are the invaluable contributions that ecosystems offer to support life and human well-being.
- **Nutrient Cycling**: Ecosystems efficiently cycle nutrients, such as nitrogen and phosphorus, which are vital for plant growth. Sustainable food systems harness these natural processes to optimize nutrient availability for crops.
- **Water Regulation**: Natural ecosystems help regulate water flow and maintain water quality, which is crucial for sustainable irrigation, flood control, and maintaining freshwater resources for agriculture.
- **Climate Regulation**: Forests and other ecosystems play a significant role in sequestering carbon dioxide, mitigating climate change. Conserving and restoring ecosystems contribute to climate resilience and carbon storage.
- **Biodiversity Support**: Ecosystems provide habitat and resources for a wide array of species, supporting biodiversity conservation and fostering ecosystem resilience.
- **Cultural and Recreational Values**: Ecosystems offer cultural and recreational benefits, providing aesthetic, spiritual, and recreational value to communities.

18 Local and Seasonal Food Production

Local and seasonal food production is a fundamental aspect of sustainable food systems that emphasizes the sourcing and consumption of food from nearby regions and during its natural growing season. This practice seeks to reduce the environmental impact of food transportation, support local economies, promote fresher and more nutritious foods, and connect consumers with the agricultural cycles of their region (Barbara et al. 2012).

Some key aspects are:

- **Reduced Carbon Footprint**: Local food production reduces the carbon emissions associated with long-distance transportation of food. This results in lower greenhouse gas emissions, contributing to climate change mitigation.
- **Conservation of Resources**: By minimizing transportation distances, less energy and fuel are consumed, leading to conservation of natural resources and a more efficient food system.
- **Preserving Biodiversity**: Supporting local farmers and traditional crops can contribute to preserving regional biodiversity and protect indigenous plant varieties.
- **Supporting Local Economies**: Purchasing food from local farmers and producers supports the local economy, creating jobs and contributing to community development.

- **Strengthening Food Security**: Local food systems enhance food security by reducing dependency on distant supply chains, making communities more resilient to disruptions in global food trade (Måren 2019).
- **Fresher and More Nutritious**: Seasonal foods are typically harvested at their peak ripeness, ensuring higher nutritional content and better taste compared to out-of-season produce that may be harvested prematurely and transported long distances.
- **Dietary Diversity**: Seasonal eating encourages a varied and diverse diet, as different crops thrive during different times of the year.
- **Reduced Need for Preservatives**: With shorter transportation distances, local and seasonal foods often require fewer preservatives, leading to healthier and more natural food choices.
- **Less Dependency on Artificial Inputs**: Supporting local farmers may promote sustainable farming practices, such as organic and regenerative agriculture, reducing the need for synthetic fertilizers and pesticides (Marchetti et al. 2020).

19 Social Justice and Fair Trade

Social justice and fair trade are essential components of sustainable food systems that aim to ensure equitable and ethical practices throughout the food supply chain. These principles prioritize the well-being and rights of farmers, workers, and communities involved in food production and distribution. Fair trade seeks to create a more just and inclusive food system by providing fair wages, safe working conditions, and respecting the rights of those involved in producing the food we consume (Pérez-Valls et al. 2019).

Fair trade practices ensure that farmers and food producers receive fair prices for their products. By offering fair compensation, these practices empower farmers to invest in their businesses, improve agricultural practices, and support their families and communities (Nier et al. 2019). It also promotes safe and healthy working conditions for agricultural workers and food producers. It discourages the use of child labour, exploitative practices, and unfair treatment of workers, advocating for dignity and respect for all individuals in the food supply chain. Fair trade initiatives often prioritize supporting small-scale farmers, who may face challenges in accessing global markets and competing with larger agribusinesses (Renard 2003). Fair trade helps empower these farmers, providing them with opportunities to participate in international trade and improve their livelihoods. Through fair trade, a portion of the proceeds from sales may be invested back into local communities. This can fund projects such as schools, healthcare facilities, clean water initiatives, and infrastructure improvements, contributing to broader community development (Low and Davenport 2005).

20 Circular Economy and Waste Reduction

The Circular Economy and Waste Reduction are key principles of sustainable food systems that aim to minimize waste generation, promote resource efficiency, and create a closed-loop system where materials are continuously reused, repurposed, or recycled. The circular economy approach strives to break away from the traditional linear model of “take, make, dispose” and instead focuses on designing out waste and maximizing the value of resources throughout their lifecycle (MacArthur 2013; Marchetti et al. 2020).

Reduce, Reuse, Recycle

The circular economy encourages waste reduction through the 3Rs: Reduce, Reuse, and Recycle. Reducing waste involves preventing waste generation at the source, for example, by optimizing production processes, improving storage and distribution practices, and encouraging responsible consumption patterns. Reusing items or materials involves extending their lifespan by repairing, refurbishing, or repurposing them, reducing the need for new resources. Recycling allows materials to be collected, processed, and transformed into new products, diverting them from landfills and reducing the demand for virgin resources.

- **Food Waste Prevention**: Reducing food waste is a crucial aspect of waste reduction. Food waste occurs at various stages of the supply chain, from production and post-harvest handling to distribution and consumption. Adopting measures such as better harvesting practices, improved storage and transportation, and consumer education can significantly reduce food waste and its environmental impact.
- **Closed-loop Systems**: Circular economy principles promote the development of closed-loop systems, where materials and resources are continually circulated within the economy. This involves designing products and packaging with recyclability and reusability in mind, as well as developing processes that facilitate the return and reuse of materials within the supply chain.
- **Resource Efficiency**: Circular economy practices prioritize resource efficiency by extracting maximum value from resources, minimizing waste, and optimizing resource use. This includes using renewable energy sources, adopting efficient production processes, and promoting the use of recycled materials (EU 2014; WRAP 2020)

1. **Benefits of Sustainable Food Systems**

Embracing sustainable food systems presents a myriad of advantages that effectively tackle urgent global challenges while concurrently fostering enduring resilience and overall well-being. By adopting practices rooted in regenerative agriculture, curbing wastage, and ensuring just distribution, these systems play a pivotal role in safeguarding the environment, promoting social fairness, and nurturing economic prosperity. The positive outcomes linked with sustainable food systems encompass enhanced soil health, amplified biodiversity, and decreased emissions of greenhouse gases, all of which culminate in a more robust and climate-resilient agricultural sector (FAO 2019). Furthermore, these sustainable approaches bolster localized food production, cultivating stronger community bonds while concurrently diminishing the carbon footprint associated with long-haul food transportation (High Level Panel of Experts on Food Security 2017). By prioritizing nutritional aspects, sustainable food systems also make strides towards advancing public health and curtailing diet-related ailments (Garnett 2014). Moreover, these systems empower farmers through equitable trade and income avenues, fortifying rural progress and the reduction of poverty (Gillespie 2012). The acknowledgment of these advantages underscores the pressing necessity for collective action in transitioning to sustainable food systems, thereby securing a more equitable and healthier future for all.

21 Environmental Benefits: Conservation of Resources and Mitigating Climate Change

One of the key benefits of sustainable food systems is the preservation of valuable resources. Sustainable food prioritizes practices like organic farming, low-input-, biodynamic-, regenerative agriculture, permaculture, and agroecology (Allen and Prosperi 2016). It allows the respect of biodiversity and ecosystems. Sustainable food systems play a crucial role in mitigating the impact of climate change. In particular, a healthy plant-based diet with fewer animal sources could reduce greenhouse gas emissions and be beneficial for the health (Tuomisto et al. 2017).

21.1 Social Benefits: Improving Livelihoods and Fostering Community Resilience

From a social perceptive, a sustainable food system takes into consideration all categories of the population, including vulnerable groups. It allows the distribution of added value, upholds cultural traditions, ensures the safety and rights of employees, and promotes animal welfare (FAO 2018).

21.2 Economic Benefits: Enhancing Local Economies and Creating Jobs

Sustainable food systems support local economies, involving local production. A food system is seen as sustainable if each' actor's actions are financially viable. All activities should provide a profit, or economic added value for the following groups: wages for workers, taxes for the government, profit for businesses and increase in the accessibility of food for consumers (FAO 2018).

21.3 Health Benefits: Promoting Nutritious Diets and Reducing Food-Related Diseases

Sustainable food systems improved nutrition by providing more nutritious food. Moreover, safety is a priority, and the use of pesticides and harmful chemicals is limited. These systems can reduce food-related diseases.

These food systems can reduce the prevalence of malnutrition, including undernutrition, overweight, obesity and diet-related non-communicable diseases (NCDs) like cardiovascular disease, diabetes, hypertension (Fanzo et al. 2022).

22 Solution and Innovations for Sustainable Food Systems

Solutions and innovations for sustainable food systems encompass a wide range of strategies and technologies aimed at addressing the environmental, social, and economic challenges associated with food production, distribution, and consumption. These solutions focus on enhancing resource efficiency, reducing waste, promoting biodiversity, and ensuring equitable access to nutritious food. Let's explore some of these solutions:

- **Agroecology and Regenerative Agriculture**: Agroecology and regenerative agriculture are sustainable farming practices that prioritize soil health, biodiversity, and ecosystem resilience. These approaches promote crop diversity, minimize chemical inputs, and use ecological principles to enhance agricultural productivity while preserving natural resources (Reganold and Wachter 2016).
- **Precision Agriculture and Smart Farming**: Precision agriculture employs advanced technologies such as sensors, GPS, and data analytics to optimize resource use and improve crop yields. Smart farming integrates IoT devices and AI to monitor and manage agricultural operations more efficiently (Davydov 2022).
- **Sustainable Aquaculture**: Sustainable aquaculture practices focus on responsible fish farming to minimize environmental impacts and support fish populations. These practices include integrated multi-trophic aquaculture, closed-loop systems, and efficient feed management (Tlusty and Thorsen 2017).
- **Food Waste Reduction and Food Rescue**: Efforts to reduce food waste involve implementing measures to prevent food loss at various stages of the supply chain and promoting food rescue initiatives to redirect surplus food to those in need (Kitinoja 2016).
- **Sustainable Packaging and Circular Economy**: Innovations in sustainable packaging aim to reduce single-use plastics and promote recyclable, compostable, or reusable packaging materials. Embracing circular economy principles encourages closed-loop systems for packaging materials (Geyer et al. 2017).

- **Vertical Farming and Indoor Agriculture**: Vertical farming and indoor agriculture utilize controlled environments, hydroponics, and vertical stacking to grow crops in urban areas, reducing land use, water consumption, and transportation needs (Despommier 2013).

23 The Role of Stakeholders in Building Sustainable Food Systems

Many stakeholders play a role in the implementation of sustainable food systems and can influence decision-making and outcomes.

23.1 Government and Policy-Makers

Regional and local governments play a role increasingly important about new food policies. Government sets up laws, legislation, and regulations and can directly influence the direction of food systems. Through financial support, government can encourage farmers to use ecologically beneficial practice like organic farming.

Policy-actors involved state agency traditionally involved in food-policies (departments of agriculture, rural-, economic development) but also public health, climate change, education, sustainable development (Renting and Wiskerke 2010).

23.2 Farmers and Producers

Farmers have a significant influence on the development of sustainable food systems. They are responsible of the production of food. In that way, they can choose sustainable and environmentally friendly practices instead of conventional farming methods. They have a important impact on economic growth and employment creation. Methods such as organic farming, permaculture, and agroecology should be prioritized to preserve the planet for this and the future generation.

23.3 Consumers and Food Choices

Along with farmers, consumers play a vital role since their dietary decisions have an impact on the entire food value chain (WFO 2020). Consumers are not just bystanders in the global food system. Through their food choices, customers are influencing the future of food production. By choosing sustainable agriculture practices and local food, consumers are at the vanguard of creating sustainable food systems, that benefit the earth and its inhabitants. Therefore, science communication needs to be improved to truly influence the behaviour or consumers (Mehrabi et al. 2022).

23.4 Business and Food Industry

The food industry may influence the food choices of consumers. Food companies should be more supportive of local producers. The food industry has been associated with mass production and intensive farming methods, associated with negative impacts on the environment. Nowadays, more and more businesses admit the need for sustainable food. They are collaborating with farmers which promote sustainable agriculture. New business models should place farmers and industry on the same level, to enable a stronger relationship between the two (WFO 2020).

24 Conclusion

In conclusion, the journey through the exploration of sustainable food systems has unveiled a comprehensive understanding of the intricate web that sustains our global nourishment. As the demand for food rises alongside an expanding population, the imperative of embracing sustainable practices becomes even more pronounced. The convergence of environmental stewardship, social equity, and economic viability, encapsulated within the triple bottom line, exemplifies the holistic approach needed to address the multifaceted challenges of today's world.

It was also observed that food systems are not isolated entities but rather intricate networks that intertwine agriculture, environment, society, and economy. These interconnectedness highlights the significant influence that food systems hold over human health and well-being, amplifying the need for conscientious decisions that ripple positively through all dimensions of life.

However, it is equally important to acknowledge the barriers and drivers that shape the trajectory of food systems. Unsustainable practices like industrial agriculture, waste generation, and inequalities in food access have illuminated the path towards unsustainability. Yet, within these challenges lie seeds of transformation. By adhering to the principles of regenerative agriculture, biodiversity conservation, and circular economy, we can nurture flourishing ecosystems while safeguarding the health of communities and economies alike.

The potential benefits of adopting sustainable food systems are far-reaching. From ecological preservation and enhanced social welfare to economic prosperity and improved health outcomes, the rewards of our collective efforts promise a better future for generations to come. To tread this path successfully, we must collectively embrace solutions such as agroecology, alternative food networks, and technological innovations. These initiatives, coupled with policy reforms and proactive stakeholder involvement, offer promising avenues towards realizing sustainable food systems on a global scale.

As we conclude, the urgency to transition towards sustainable food systems cannot be overstated. This transformation stands not merely as an aspiration but as a pressing necessity for the well-being of our planet and its inhabitants. By fostering collaboration, raising awareness, and empowering individuals and communities, we have the potential to create a paradigm shift that reshapes our relationship with food and the environment. With policy reforms and cutting-edge research as our guiding lights, we embark on a journey that promises a brighter, more nourished future—a future where sustenance is harmonized with environmental harmony, societal equity, and economic resilience. The prospect of such a future ignites our efforts today and propels us towards a truly sustainable tomorrow.

References

Abraham SP, Noriega BR, Shin JY (2018) College students eating habits and knowledge of nutritional requirements. J Nutr Human Heal 2. https://doi.org/10.35841/nutrition-human-health.2.1.13-17

Allen T, Prosperi P (2016) Modeling sustainable food systems. Environ Manage 57:956–975. https://doi.org/10.1007/s00267-016-0664-8

Antonides G (2017) Sustainable consumer behaviour: a collection of empirical studies. Sustain 9:1686. https://doi.org/10.3390/su9101686

Aschemann-Witzel J (2015) Consumer perception and trends about health and sustainability: trade-offs and synergies of two pivotal issues. Curr Opin Food Sci 3:6–10. https://doi.org/10.1016/j.cofs.2014.08.002

Barbara B, Sandro D, Organización de las Naciones Unidas para la Agricultura y la Alimentación (2012) Sustainable diets and biodiversity: directions and solutions for policy, research and action. Food and Agriculture Organization of the United Nations (FAO)

Beretta C, Stoessel F, Baier U, Hellweg S (2013) Quantifying food losses and the potential for reduction in Switzerland. Waste Managt 33:764–773. https://doi.org/10.1016/j.wasman.2012.11.007

Bernard F, van Noordwijk M, Luedeling E, Villamor GB, Sileshi GW, Namirembe S (2014) Social actors and unsustainability of agriculture. Curr Opin Environ Sustain 6:155–161. https://doi.org/10.1016/j.cosust.2014.01.002

Berry EM, Dernini S, Burlingame B, Meybeck A, Conforti P (2015) Food security and sustainability: can one exist without the other? Public Health Nutr 18:2293–2302. https://doi.org/10.1017/S136898001500021X

Bollani L, Bonadonna A, Peira G (2019) The Millennials' concept of sustainability in the food sector. Sustain 11:2984. https://doi.org/10.3390/su11102984

Bowman S (2007) Low economic status is associated with suboptimal intakes of nutritious foods by adults in the National Health and Nutrition Examination Survey 1999–2002. Nutr Res 27:515–523. https://doi.org/10.1016/j.nutres.2007.06.010

Carrigan M, Attalla A (2001) The myth of the ethical consumer—do ethics matter in purchase behaviour? J Consum Mark 18:560–578. https://doi.org/10.1108/07363760110410263

Chaudhary A, Gustafson D, Mathys A (2018) Multi-indicator sustainability assessment of global food systems. Nat Commun 9:848. https://doi.org/10.1038/s41467-018-03308-7

Davydov DA (2022) Postcapitalism: from consumer individualism to expressive individualism? Her Russ Acad Sci 92:S467–S474. https://doi.org/10.1134/S1019331622120036

Despommier D (2013) Farming up the city: the rise of urban vertical farms. Trends Biotechnol 31:388–389. https://doi.org/10.1016/j.tibtech.2013.03.008
Eizenberg E, Jabareen Y (2017) Social sustainability: a new conceptual framework. Sustainability 9:68. https://doi.org/10.3390/su9010068
El Bilali H, Callenius C, Strassner C, Probst L (2019) Food and nutrition security and sustainability transitions in food systems. Food Energy Secur 8:e00154. https://doi.org/10.1002/fes3.154
Elkington J (2004) Enter the triple bottom line
European Commission (2014) Commission Staff Working Document Impact Assessment on Measures Addressing Food Waste to Complete SWD (2014) 207 Regarding the Review of EU Waste Management Targets
Evans A (2009) The feeding of the nine billion: global food security for the 21st century. Royal Institute of International Affairs
Fanzo J, Rudie C, Sigman I, Grinspoon S, Benton TG, Brown ME, Covic N, Fitch K, Golden CD, Grace D, Hivert M-F, Huybers P, Jaacks LM, Masters WA, Nisbett N, Richardson RA, Singleton CR, Webb P, Willett WC (2022) Sustainable food systems and nutrition in the 21st century: a report from the 22nd annual Harvard Nutrition Obesity Symposium. Am J Clin Nutr 115:18–33. https://doi.org/10.1093/ajcn/nqab315
FAO (2018) Sustainable food systems: concept and framework. What is a sustainable food system? Why take a food systems approach? Changing food systems
FAO (2023) FAOSTAT. Food and Agriculture Organisation. https://www.fao.org/faostat/en/#home. Accessed 27 Aug 2023
FAO, IFAD, WFP (2013) The state of food insecurity in the world. FAO, Rome
Finucane MM, Stevens GA, Cowan MJ, Danaei G, Lin JK, Paciorek CJ, Singh GM, Gutierrez HR, Lu Y, Bahalim AN, Farzadfar F, Riley LM, Ezzati M (2011) National, regional, and global trends in body-mass index since 1980: systematic analysis of health examination surveys and epidemiological studies with 960 country-years and 9·1 million participants. The Lancet 377:557–567. https://doi.org/10.1016/S0140-6736(10)62037-5
Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O'Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM (2011) Solutions for a cultivated planet. Nature 478:337–342. https://doi.org/10.1038/nature10452
Food and Agricultural Organization of the United Nations (2019) The state of the World's Biodiversity for Food and Agriculture
Garnett T (2014) Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? J Clean Prod 73:10–18. https://doi.org/10.1016/j.jclepro.2013.07.045
Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3. https://doi.org/10.1126/sciadv.1700782
Gillespie G (2012) Thoughts on John Ikerd's the essentials of economic sustainability. J Agric Food Syst Community Dev 269–274. https://doi.org/10.5304/jafscd.2012.031.019
Gliessman SR (1990) Agroecology: researching the ecological basis for sustainable agriculture, pp 3–10
Gustavsson J, Cederberg C, Sonesson U, Otterdijk R, Mcybeck A (2011) Global food losses and food waste: extent, causes and prevention. Food and Agriculture Organization of the United Nations, Rome
Hairiah K, Weise S (2001) 6 Sustainability of tropical land use systems after forest conversion
High Level Panel of Experts on Food Security (2017) HLPE The High Level Panel of Experts on Food Security and Nutrition and Food Systems
Hsu C-Y, Chen M-Y, Yang S-C (2019) Residents' attitudes toward support for island sustainable tourism. Sustainability 11:5051. https://doi.org/10.3390/su11185051
Hupkens C (2000) Social class differences in food consumption. The explanatory value of permissiveness and health and cost considerations. Eur J Pub Heal 10:108–113. https://doi.org/10.1093/eurpub/10.2.108

Irani Z, Sharif AM, Lee H, Aktas E, Topaloğlu Z, van't Wout T, Huda S (2018) Managing food security through food waste and loss: small data to big data. Comput Oper Res 98:367–383. https://doi.org/10.1016/j.cor.2017.10.007

Kitinoja L (2016) Innovative approaches to food loss and waste issues. Frontier issues brief for the Brookings Institution's Ending Rural Hunger project

Konttinen H, Sarlio-Lähteenkorva S, Silventoinen K, Männistö S, Haukkala A (2013) Socio-economic disparities in the consumption of vegetables, fruit and energy-dense foods: the role of motive priorities. Public Health Nutr 16:873–882. https://doi.org/10.1017/S1368980012003540

Lim V, Bartram L, Funk M, Rauterberg M (2021) Eco-feedback for food waste reduction in a student residence. Front Sustain Food Syst 5. https://doi.org/10.3389/fsufs.2021.658898

Lohnes J, Wilson B (2017) Bailing out the food banks? Hunger relief, food waste, and crisis in Central Appalachia. Environ Plan A 50

Low W, Davenport E (2005) Postcards from the edge: maintaining the 'alternative' character of fair trade. Sustain Dev 13:143–153. https://doi.org/10.1002/sd.275

MacArthur E (2013) Towards the circular economy. Ellen MacArthur Foundation

Marchetti L, Cattivelli V, Cocozza C, Salbitano F, Marchetti M (2020) Beyond sustainability in food systems: perspectives from agroecology and social innovation. Sustainability 12:7524. https://doi.org/10.3390/su12187524

Måren IE (2019) Food systems for sustainable terrestrial ecosystems (SDG 15). Food Ethics 2:155–159. https://doi.org/10.1007/s41055-018-00032-2

Mehrabi S, Perez-Mesa JC, Giagnocavo C (2022) The role of consumer-citizens and connectedness to nature in the sustainable transition to agroecological food systems: the mediation of innovative business models and a multi-level perspective. Agriculture 12:203. https://doi.org/10.3390/agriculture12020203

Moldan B, Janoušková S, Hák T (2012) How to understand and measure environmental sustainability: indicators and targets. Ecol Indic 17:4–13. https://doi.org/10.1016/j.ecolind.2011.04.033

Newton P, Civita N, Frankel-Goldwater L, Bartel K, Johns C (2020) What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Front Sustain Food Syst 4. https://doi.org/10.3389/fsufs.2020.577723

Nier S, Klein O, Tamásy C (2019) Global crop value chains: shifts and challenges in south–north relations. Soc Sci 8:85. https://doi.org/10.3390/socsci8030085

Pérez-Valls M, Céspedes-Lorente J, Martínez-del-Río J, Antolín-López R (2019) How organizational structure affects ecological responsiveness. Bus Soc 58:1634–1670. https://doi.org/10.1177/0007650317696313

Reganold JP, Wachter JM (2016) Organic agriculture in the twenty-first century. Nat Plants 2:15221. https://doi.org/10.1038/nplants.2015.221

Reid Walter V (2005) Millennium ecosystem assessment. Island Press, Washington, DC

Reinders AHME, Vringer K, Blok K (2003) The direct and indirect energy requirement of households in the European Union. Energy Policy 31:139–153. https://doi.org/10.1016/S0301-4215(02)00019-8

Renard M-C (2003) Fair trade: quality, market and conventions. J Rural Stud 19:87–96. https://doi.org/10.1016/S0743-0167(02)00051-7

Renting H, Wiskerke H (2010) New emerging roles for public institutions and civil society in the promotion of sustainable local Agro-food systems

Rhodes CJ (2017) The imperative for regenerative agriculture. Sci Prog 100:80–129. https://doi.org/10.3184/003685017X14876775256165

Schmidhuber J, Tubiello FN (2007) Global food security under climate change. Proc Natl Acad Sci 104:19703–19708. https://doi.org/10.1073/pnas.0701976104

Solomon S (Atmospheric chemist), Intergovernmental Panel on Climate Change., Intergovernmental Panel on Climate Change. Working Group I (2007) Climate change 2007: the physical science basis : contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Story M, Hamm MW, Wallinga D (2009) Food systems and public health: linkages to achieve healthier diets and healthier communities. J Hunger Environ Nutr 4:219–224. https://doi.org/10.1080/19320240903351463

Thakur M, Modi VK (2020) Emerging technologies in food science—focus on the developing world. Springer Nature

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108:20260–20264. https://doi.org/10.1073/pnas.1116437108

Tilman D, Fargione J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger WH, Simberloff D, Swackhamer D (2001) Forecasting agriculturally driven global environmental change. Science 292:281–284. https://doi.org/10.1126/science.1057544

Tlusty MF, Thorsen Ø (2017) Claiming seafood is 'sustainable' risks limiting improvements. Fish Fish 18:340–346. https://doi.org/10.1111/faf.12170

Tuomisto HL, Scheelbeek PFD, Chalabi Z, Green R, Smith RD, Haines A, Dangour AD (2017) Effects of environmental change on agriculture, nutrition and health: a framework with a focus on fruits and vegetables [version 2; peer review: 2 approved]. Wellcome Open Res 2. https://doi.org/10.12688/wellcomeopenres.11190.2

van Noordwijk M, Cadisch G (2002) Access and excess problems in plant nutrition. Plant Soil 247:25–39. https://doi.org/10.1023/A:1021194628358

Wezel A, Casagrande M, Celette F, Vian J-F, Ferrer A, Peigné J (2014) Agroecological practices for sustainable agriculture. A review. Agron Sustain Dev 34:1–20. https://doi.org/10.1007/s13593-013-0180-7

WFO (2020) World Farmers' Organisation policy paper on Sustainable Food Systems "The Farmers" route to Sustainable Food Systems

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Srinath Reddy K, Narain S, Nishtar S, Murray CJL (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

World Bank (2008) World Bank, World Development Report 2008: Agriculture for Development. World Bank, Washington, DC

WRAP (2020) Food surplus and waste in the UK-key facts

Sustainable Food System—Plant-Based Alternatives and Health Impacts

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1 Introduction

A sustainable food system prioritizes local production, reduces inputs, and utilizes resources efficiently on-site. It values biodiversity and ecology, avoids the use of chemicals, conserves water and energy, and operates within the limits of our natural resources. This suggests that sustainable agriculture must be resource-conserving, waste-reduction-focused, have a good influence on the environment, and be socially supported. Enough food must be produced to feed everyone while also protecting the environment and natural resources, enhancing the quality of life, and efficiently using resources. Food system (FS) refers to the interconnection of activities occurring during the processing, production, distribution, consumption, and disposal of food products derived from the fishery, forestry, or other aspects of the natural, economic or societal environments in which they are situated. But what makes up the food system? The input supply system, waste management, and farming are examples of subsystems that make up the food system and interact with other essential systems (e.g., energy system, trade system, health system, etc.). In consequence, a change in one system may lead to a change in another. For instance, the use of more biofuel in the energy system will have a big impact on the food system. The Farm's Bill, which was passed in 1977 and 1990, defines sustainable agriculture as an integrated system of animal and plant production techniques with specific applications that will, over time, meet human needs for food and fibre, improve the environment, and expand the base of natural resources upon which the agricultural economy depends, maintain the financial viability of agricultural operations; raise the level of living for the general public and farmers. Producers need to utilise non-renewable resources and on-farm resources as efficiently as possible. By growing fruits and vegetables,

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breeding animals, or fishing closer to the points of sale, a sustainable food system, whether local or regional, brings farmers and customers closer together. In terms of food security, the availability of more wholesome and reasonably priced food increases with the proximity of producers to households and neighbourhoods. Here's a high consumption and high demand for natural resources in a crop production process. 40% of the 10–20% of fossil fuel energy consumed by agricultural operations is indirect energy required to create chemical fertilizers and insecticides. To conserve all the resources, it's essential to work with natural processes for waste reduction and limit the impact on the environment. Theoretically, this entails using feed additives, artificial fertilizers, growth regulators, and insecticides for cattle in moderation. Instead, it relies more on techniques to preserve soil fertility, such as legumes, mineral-bearing rocks, crop rotations, animal manures, mechanical cultivation, and cultural, biological and natural controls to manage weeds, pests, and insects.

2 History

In 1980, Sustainable farming was first mentioned by author Wes Jackson in his book New Roots for Agriculture. Sustainable agriculture is a result of several early movements. The use of humus in the soil to sustain productivity and soil quality was stressed by the humus farming movement. Following World War Two, Mochichi Okada introduced natural agricultural methods utilising humus farming in Japan.

Three views have influenced the development of sustainable agriculture: as a method of food self-sufficiency; and as a means of preserving rural communities. In farming practice, agricultural research, or even agricultural policy, the idea of sustainability is not new. For hundreds of years until the mid-nineteenth century, it was a part of English agricultural thought and practice. The phrase sustainable agriculture systems was coined by Northbourn to characterise farming practices. This emphasised the farm as a living, organic whole, harmonious and dynamic. Hence, the phrase has a broad connotation compared to only using live things for agricultural purposes, which is often incorrectly suggested nowadays. The historical study of the relationship between soil quality, food safety, and human health has a significant impact on the growth of sustainable agriculture. Since the beginning of the twentieth century, several members of the medical profession in the U.K. have conducted clinical research tests on the issue. Agroecological research is relatively new, less than 50 years old, and ecology as a scientific discipline is also relatively new. Nonetheless, both fields have made significant contributions to our understanding of the natural world and how human activities impact ecosystems. By studying interactions in natural environments, ecologists and agro ecologists can help us develop more sustainable practices that benefit both human health and the environment. The focus of ecology depends upon the interactions of organisms including people—within ecosystems, as well as the corresponding flows of resources and energy. Agroecosystems and natural ecosystems differ in several ways. Agroecosystems are partially powered by auxiliary energy sources such as human power, fossil fuels, and animals whereas natural ecosystems are not. Human management has reduced species diversity in agroecosystems, and the dominant plant and animal species are artificially selected. In contrast, natural ecosystems have a higher level of species diversity. Agroecosystems are controlled by humans, whereas natural ecosystems are controlled by natural feedback mechanisms. The sociocultural components play a significant role in shaping agricultural systems, as human interactions with these systems are critical factors in determining their shape. Agroecology and ecology are unique in that they study interactions in their natural environments, rather than studying individual components in isolation. This approach allows for a more comprehensive understanding of how ecosystems function, and how human activities impact these systems. Scientists prefer to have a thorough grasp of a subject, and the ecological paradigm is one of the few often-used models that offer a decent chance to do so. Agroecologists influence one's thinking about sustainability, even though they have long been utilised as a tool to help explain why sustainable systems work. It is becoming increasingly evident how agroecological principles can be used to create sustainable farming systems. Our understanding of sustainability in agriculture has improved in recent years, partly due to ideas about sustainable yield in fisheries. The goal in fisheries is to maximise yields by ensuring that harvest rates equal replacement rates, allowing for almost endless harvesting. Similar concepts are being applied to agriculture by focusing on the appropriate replacement rates for soil, soil organisms, soil nutrients and organic matter, water, genetic resources, and energy. By adopting these principles, we can develop more sustainable farming systems that benefit both the environment and human health.

3 Sustainable Approach

The food industry has a large effect on the environment, economy, and society. A sustainable strategy is critical to ensuring the security and nutrition of food for all while conserving natural resources for future generations. A sustainable food system should be financially feasible, socially responsible, and environmentally responsible. This includes reducing food waste, conserving energy and water, employing non-polluting manufacturing techniques, and assisting local farmers (Greentumble 2015).

The following points can be considered to form a sustainable agricultural system:

- The aim should be to fulfil people's need of getting a nutrient-rich diet, including farmers, their families, and communities, and improve the quality of life in rural areas.
- The farming process should necessarily be cost-effective, or else it will lead to incomparable losses.
- Farming practices should be ecological, promoting versatile biodiversity along with judicial management of natural resources.

Regenerative agroforestry and organic farming are examples of sustainable food production techniques that can help minimise the effects of food production on the environment while improving soil quality and biodiversity. Customers can help promote sustainable food systems by purchasing locally sourced, seasonal, and organic foods, minimising food waste, and supporting sustainable food businesses. We can guarantee a healthy and resilient food system that benefits everyone now and in the future by adopting a sustainable approach in the food sector. Organic farming leads to sustainable food production where natural pesticides and fertilisers, crop rotation, and crop diversity are employed to reduce the use of synthetic chemicals and improve soil health. Other sustainable agriculture techniques include permaculture, biodynamic farming, agroforestry, and food forests, which aim to create a self-sustaining ecosystem that replicates natural systems. Cover crops, soil enrichment, and native pest predators are all examples of sustainable agriculture practices that can help improve soil quality with reduced use of synthetic chemicals. Regenerative agriculture is a way of soil conservation that emphasises soil health and biodiversity through practices such as cover cropping, crop rotation, and reduced tillage. We can reduce the environmental impact of food production while ensuring a healthy and resilient food system by implementing these sustainable food production techniques. Everyone cannot become a farmer but it is needed that agriculture must provide expanding populations with affordable food supplies. It is also obvious that this goal cannot be met in the highly industrial and destructive ways that have become the norm in recent years. This has caused environmental pollution and soil degradation in many locations, which harms people, even if they are away from the affected regions.

The sustainable agricultural techniques listed below are just a few of the many ways we can make agriculture much more sustainable.

3.1 Biodynamic Farming

A traditional but contemporary alternative to conventional cultivation is biodynamic farming. It is not, however, widely recognised or applied. It is comparable to organic farming but uses metaphysical principles to treat the soil and promote crop development. It is believed that biodynamic cultivation is "above and beyond organic". Above 5500 farmers worldwide are interested in and use biodynamic farming, and buyers of organic goods strongly favour this farming technique. Demeter-International certified biodynamic activity is now present in 55 nations, with Germany having maximum (1552) biodynamic farms. The use of organic matter to restore the soil, treating it as a living arrangement, constructing a system that maintains the balance of all factors that are essential for life, spreading awareness about the use of green manure, crop rotation, and treating manure and compost in a biodynamic manner, all of these promote biodynamic farming. In addition to a collection of practices, biodynamic farming is also a philosophical approach that affects the overall design of the farm.

Scientific research has shown that biodynamic farming supports sustainable agriculture by enhancing soil quality, leading to an increase in the amount and nutritional content of the product, and controlling pests. Therefore, biodynamic farming is like a ray of hope for a sustainable system shortly (Muhie 2023).

3.2 Hydroponics and Aquaponics

In hydroponics, the soil is replaced by gravel, the clay stone, and nutrients are put into the water. Current agricultural systems depend on high-quality soil, manual removal of weeds and gallons of water which reduces productivity. To overcome these challenges, hydroponics uses controlled environmental parameters with a microcontroller kit connected to a wireless sensor network. According to Gentry (2019), it is estimated that 70% of the population will reside in urban locations by 2050, essentializing the presence of fresh produce, better transportation, and storage methods to ensure quality and nutrition in plants. Aquaponics is a novel solution to the global food demand. With an increase in population, food security and sustainability have to be developed by non-traditional farming methods. Aquaponics is a combination of aquaculture and hydroponics to generate both plants and fish which is nothing but organic food production. Here, the nutrients produced by fish in the water are circulated to the plants for growth and development. This system needs proper care and maintenance to protect plants from root damage and to ensure their proper functioning (Ezzahoui et al. 2021).

3.3 Agroforestry and Food Forests

Agroforestry is a method of farming that involves cultivating trees and shrubs alongside crops or grazing areas. This system integrates both agriculture and forestry techniques to create a diverse productive land that can endure over time. In this system, trees play an important role in creating favourable surroundings that help maintain suitable temperature and moisture levels. Also, they protect crops against environmental stresses. Grazing in agroforestry stabilises the soil, and reduces nutrient runoff to enhance the soil structure. Therefore, agroforestry is a valuable tool for farmers in arid regions where the soil is prone to desertification (Greentumble 2015).

3.4 Urban Agriculture

Urban agriculture is the production of food or other useful crops in or near cities, involving diverse stakeholders and socio-economic conditions (FAO 2018). It involves a wide range of practices, from small-scale urban gardening carried out by individuals or small groups to large-scale urban farming operated as a business (Duží et al. 2017). There is a growing need to localise our food systems, therefore it is good to cultivate food closer to home, even within urban areas. As the majority of people will live in cities in the future, urban agriculture will positively impact global food production methods.

4 Case Study on Soy and Soy Foods Consumption

A recent study conducted a Life Cycle Assessment (LCA) of soy protein and seitan protein-based bacon products. The study evaluated the environmental impact of these products, including global warming, terrestrial acidification, terrestrial toxicity, water consumption, freshwater eutrophication, and human carcinogenic toxicity. The nutritional characteristics of plant-based bacon products were also compared, with seitan protein-based bacon showing a higher protein content than pork bacon. The study found that heating plant-based bacon products with induction, ceramic, and electric stoves before consumption had a lower environmental impact than high-risk factors such as petroleum production and diesel combustion. The study concluded that soy protein and seitan-based bacon alternatives were low in fat content, and seitan protein-based bacon provided more protein content than original bacon. The study also found that the highest risks of environmental and human health effects of bacon substitutes came from side industries that cause the highest amounts of environmental issues crucial for food production and transportation (Yusuf 2023).

Soy-based protein food manufacturers now offer a wide range of food products. The global production of soybeans has significantly increased over the past few decades, with the US accounting for 45% of the total global production, followed by Brazil (20%) and China (12%). The increased demand for soy in the US and its introduction to Brazil in the 1960s led to a global increase in soybean yields.

Table 1 compares populations from different countries consuming soy and soy-based food products and the amount of soy protein products they hold. Soy, the best-suited plant protein source, has been consumed as an animal protein substitute by diverse populations and is cultivated by vegetarian and Asian populations. Although soy protein lacks some of the SAA, it still has the highest protein quality among plant proteins and is almost equivalent to some animal proteins. Soy-based food products have well-established manufacturing processes.

5 Plant-Based Food Alternatives' Health Impacts

Human health and existence are indistinguishably dependent on the environment's health. Sustainable food systems may have a positive impact on the surroundings as they are concerned with almost all resources. Sustainable foods are safe to consume

Table 1 Soy consumption per day

Population	Soy and soy foods	Soy protein
Vegetarian	NA	8.42–9.25
United States (US)	NA	NA
Korea	21.7	7.4–8.5
Japan	50.7–102.1	6–11.3
China	23.5–135.4	2.5–10.3

and have high nutritional value. Today's people are health concerned and need unprocessed or minimally processed foods. Degrading ecological quality has also affected the nutritional quality of fruits and vegetables and grains. Also, extensive hybridization to produce high-yielding varieties has lowered their capacity for absorbing nutrients from the soil as their root system weakens, and therefore, low-nutrient profile foods are produced. If varieties are not made high-yielding, then extensive cropping cycles have to be carried out, which require the use of high amounts of pesticides and fertilisers, which is again detrimental to human health. This is a cycle that can only be excited by changing current food production patterns. In sustainable farming systems, diverse regional varieties are grown, which leads to better adaptation to climate change (FAO). Enhanced consumption of processed and discretionary foods with unbalanced nutrition has led to the deterioration of consumer health over the decades. This can also be conferred to unhealthy ways of living. This is also a challenge for the food industry to produce foods that do not lead to the spread of chronic diseases (Szakály 2017). The key to well-being and disease-free life lies in healthy eating habits because "what we eat is what we become" (Fürediné Kovács 2007).

Meat products are discouraged by environmentalists mainly because of the overuse of water, greenhouse gas emissions, and degradation of land. Meat alternatives of plant-based origin are designed for replicating the sensory characteristics of real meat. Life-cycle analyses point out that plant-based foods' environmental footprints are less in comparison to animal-based foods. Human beings are omnivorous as they derive nutrients like zinc and iron from animal foods. Plant nutrients offer protection against health issues caused due to meat.

Thus, to improve human health, animal and plant foods operate in symbiotic ways. While plant-based meat alternatives may have similar sensory characteristics to real meat, they are not nutritionally equivalent. Plant-based meats are usually fortified with vitamins and minerals, but they may not contain all the same nutrients as real meat. For example, plant-based meats generally have less protein and iron than real meat. However, plant-based meats can still be a healthy choice for those looking to reduce their meat consumption, as they are generally lower in saturated fat and calories than real meat. Ingredients of such foods are focussed on the incorporation of vitamins and minerals like B vitamins, iron and zinc found in meat products, and the use of nutrients of plants like protein from soy, pea, and mycoprotein; fats from coconut, canola, and soybean, etc. and other flavouring extracts or agents (Curtain and Grafenauer 2019). Plant-based diets have become increasingly popular in recent years due to their many health benefits. A well-planned and maintained vegetarian diet can provide humans with essential nutrients and reduce the risk of chronic diseases such as heart disease, diabetes, and cancer. Additionally, plant-based meats are becoming more widely available, and they may also reduce the environmental impact of red meat production. By transitioning to a plant-based diet, individuals can improve their health and reduce their carbon footprint (Fehér et al. 2020).

6 Impact on Environment

People are becoming aware of the impact they are creating on the environment. Anthropogenic actions are posing grave threats to the environment, which need to be addressed and controlled. Not only urbanisation and industrialisation are the cause for the same but also the eating habits of humans. Given the same, there's a rise in the acceptance of veganism by people across the world. Veganism or completely plant-based alternatives are coming up as a solution to the environmental crisis. Even mainstream visual and print media has covered this issue. Meat production and its consumption are believed to damage the environment more than plant cultivation and consumption. Non-vegetarian eating patterns also lead to greenhouse gas emissions, warned by FAO and World watch Institute (Pendergrast 2016).

Sustainable farming, as opposed to intensive agriculture, can benefit nature along with preserving the natural deposits. This is accomplished by

- Adhering to natural cycles
- Recycling nutrients and water
- Avoiding the overuse of farming chemicals
- Reducing agricultural runoff
- Preventing lake and river pollution
- Conserving water and naturally keeping soil fertility by recycling nutrients on the farm
- Soil and perennial plants sequester more carbon
- Increasing agricultural energy efficiency
- Lowering emissions of air pollutants and greenhouse gases
- Creating habitats for pollinators and useful insects
- Ensuring farm animal wellbeing while also allowing for peaceful coexistence with local wildlife (EU 2020)

Climatic changes can also be mitigated by increasing veganism because livestock farming contributes largely to greenhouse gas emissions. However, a sudden and complete shift to plant-based alternatives may have a distressing effect on land and resources. There may be a loss of the animal genetic pool along with some co-dependent plant species. Indeed there are pros and cons to both types of diets, but sustainability can be achieved by balance only. "One basket approach" may lead to some other unknown negative impacts. The dynamics of the economy will also be affected if meat consumption stops completely. This could lead to a threat to food security (Dorgbetor et al. 2022).

7 Future Scope and Challenges

Having sustainable food systems in place has become a necessity given the increasing population and depleting resources, as well as a decline in environmental life. Plant-based alternatives in dietary habits are being researched in the hope of being a sustainable option as compared to meat diets. The main challenge in acceptance of this shift is the satisfaction and mouthfeel of having meat products and the urge to not give up (Lea and Worsley 2003). Graça et al. also reached the same conclusion in their questionnaire-based research. The adversaries of plant-based diets point out the low protein intake because of such dietary patterns, but researchers claim that protein supply is almost similar in both types of diet (Melina et al. 2016; Thomas et al. 2016). However, to ensure necessary protein intake through plant-based diets, there are a lot of foods such as soy products, tofu, seitan, and tempeh which provide protein (Kökény 2009; Szabo et al. 2016). Also, continuous research is being carried out to produce better and more food products that mimic the texture of meat, called vegetarian meat or plant-based meat. A lot of brands are also gaining popularity because this concept is new for people and a boon for those who are willing to give up on non-veg but were not able to do so because of the lack of that texture and flavour in plant foods (Pohjolainen et al. 2015). Furthermore, it is a task to produce meat analogues from plants as there is a lack of profound quality plant-based ingredients and less understanding of the complex structures of meat and fish. The relationship between plant-based ingredients and their ability to mimic eggs, meat, dairy or fish is a complex process. (McClements and Grossmann 2021).

Additionally, plant-based diets can be challenging to balance since they may be deficient in certain micronutrients such as vitamin B12, vitamin D, riboflavin, iron, calcium, and zinc. However, fortification and supplements are one of the many ways to obtain these nutrients. Vitamin B12 is generally introduced via animal products like milk, meat, eggs, etc., but gradually, other alternatives are being researched to fulfil nutrient requirements like single-cell protein and food from algae. There are chances of development of eating disorders and allergies in a few people because of some plant foods. Such risks and challenges need to be resolved for better acceptance by people around the globe.

The major benefit of shifting to plant-based alternatives will be to the innocent animals who suffer a lot in the process. In the majority of places, unethical means are used to produce meat. This will also promote the use of minimally processed or unprocessed food as compared to foods of animal origin. The development of plant-based foods is crucial for our health, well-being, and the sustainability of our planet. Additionally, environmental and ethical concerns are important motivators for people to change or adjust their dietary habits (Graça et al. 2015).

References

Curtain F, Grafenauer S (2019) Plant-based meat substitutes in the flexitarian age: an audit of products on supermarket shelves. Nutrients 11(11):2603

Dorgbetor IK, Ondrasek G, Kutnjak H, Mikuš O (2022) What if the world went vegan? A review of the impact on natural resources, climate change, and economies. Agriculture 12(10):1518

Duží B, Frantál B, Rojo MS (2017) The geography of urban agriculture: new trends and challenges. Moravian Geograph Rep 25(3):130–138

EU (2020). https://ec.europa.eu/agriculture/sites/agriculture/files/events/2012/rio-side-event/brochure_en.pdf. Accessed 15 April 2023

Ezzahoui I, Abdelouahid RA, Taji K, Marzak A (2021) Hydroponic and aquaponic farming: comparative study based on internet of things IoT technologies. Procedia Comp Sci 191:499–504

FAO (2018). http://www.fao.org/3/I9900EN/i9900en.pdf. Accessed 15 April 2023

Fehér A, Gazdecki M, Véha M, Szakály M, Szakály Z (2020) A comprehensive review of the benefits of and the barriers to the switch to a plant-based diet. Sustainability 12(10)

Fürediné Kovács A (2007) A fenntartható táplálkozás az ökoélelmiszerek példáján keresztül [Sustainable nutrition through the example of organic food. Ecol Environ Manag Soc 15:77–103

Gentry M (2019) Local heat, local food: integrating vertical hydroponic farming with district heating in Sweden. Energy 174:191–197

Graça J, Oliveira A, Calheiros MM (2015) Meat, beyond the plate. Data-driven hypotheses for understanding consumer willingness to adopt a more plant-based diet. Appetite 90:80–90

Greentumble (2015) https://greentumble.com/10-sustainable-farming-methods-and-practices. Accessed 20 April 2023

Kökény T (2009) The history of vegetarianism in Hungary. Társadalom 27(2):203–225

Lea E, Worsley A (2003) Benefits and barriers to the consumption of a vegetarian diet in Australia. Pub Heal Nutr 6(5):505–511

McClements DJ, Grossmann L (2021) A brief review of the science behind the design of healthy and sustainable plant-based foods. NPJ Sci Food 5(1):17

Melina V, Craig W, Levin S (2016) Position of the academy of nutrition and dietetics: vegetarian diets. J Acad Nutr Diet 116(12):1970–1980

Muhie SH (2023) Concepts, principles, and application of biodynamic farming: a review. Circular Economy Sustain 3(1):291–304

Pendergrast N (2016) Environmental concerns and the mainstreaming of veganism. In: Impact of meat consumption on health and environmental sustainability. IGI Global, pp 106–122

Pohjolainen P, Vinnari M, Jokinen P (2015) Consumers' perceived barriers to following a plant-based diet. Br Food J 117(3):1150–1167

Szabó Z, Erdélyi A, Kisbenedek AG, Polyák É, Szabó S, Kovács RE, Raposa LB, Figler MA (2016) Növényi alapú étrendről [Plant-based diets: a review]. Orv Hetil 15:1859–1865

Szakály Z (2017) Élelmiszer-marketing. Akadémiai Könyvkiadó, Budapest

Thomas DT, Erdman KA, Burke LM (2016) Position of the academy of nutrition and dietetics, dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. J Acad Nutr Diet 116(3):501–528

Yusuf EH (2023) Comparison of life cycle assessments and nutritional contents of soy protein and wheat protein (seitan) based vegan bacon products for human and environmental health. J Sci Food Agri 103(7):3315–3321

Indigenous Food System for Sustainability: South Pacific Study

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1 Introduction

Food systems significantly impact health and well-being. With the global population expected to reach 9–10 billion by 2050, almost half of the population experiences food shortages and nutrition insecurity leading to undernutrition, micronutrient deficiencies, overweight or obesity (Kuhnlein 2015). Food systems present many opportunities—some yet to be explored—to improve diets (GloPan 2016). However, increasing pressures from population growth, rapid urbanisation, globalisation, economic growth, food industry consolidation and the uncertainties induced by climate change with potential negative impacts on health and nutrition (GloPan 2016; HLPE 2017; Fanzo 2019) present global food system at the centre of a nexus of global problems. The problem stretches from poverty to environmental degradation (Gladek et al. 2017; Rochefort et al. 2021). A food system consists of all the inputs (environment, people, processes, infrastructures, institutions, etc.), activities and actors that relate to the production, processing, distribution, preparation and consumption of food and the outcomes of these activities, namely nutrition and health, economic, social and environmental impacts (HLPE 2014; Caron et al. 2018; Fanzo 2019).

Current food systems are more focused on food quantity with limited focus on quality (GloPan 2016) with an inadequate supply of nutrient-rich, plant-based foods needed for healthier and sustainable diets (Siegel et al. 2014; Willett et al. 2019; Hunter et al. 2019). Since the Green Revolution in the 1960s, agriculture has mainly focused on developing conventional cereal and horticultural crops responsive to additional inputs such as fertilisers and water, giving birth to an agro-industrial food regime (Mabhaudhi et al. 2019). This transition from traditional to modern food

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production systems contributes significantly to major environmental issues, including biodiversity loss, greenhouse gas emissions, contamination and water shortages, ecosystem pollution, and land degradation (Willett et al. 2019; Hunter et al. 2019).

Today, food systems are unsustainable because they cause significant resource depletion and unacceptable environmental impacts (Holden et al. 2018). The sustainability of global food systems has received much attention in recent decades and has been given high visibility by the worldwide community. The definition of sustainability is most frequently quoted from Our Common Future, also known as the Brundtland Report (UN 1987), which implies a state whereby the needs of the present and local population can be met without diminishing the ability of future generations or people in other locations to meet their needs or without causing harm to the environment and natural assets (Allen and Prosperi 2016; Fanzo 2019). Therefore, a sustainable food system (SFS) is a food system that delivers food security and nutrition for all in a manner that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised (HLPE 2014). Global estimates suggest that between 702 and 828 million people in the world (corresponding to 8.9 and 10.5% of the world population, respectively) faced hunger in 2021 (FAO et al. 2022; UN 2022) while one-third of the food produced in the world is lost or wasted (FAO 2011).

In the context of diet, attention given to the sustainability of food systems around the world is primarily driven by concerns related to food insecurity and hunger: the extent of food loss and waste while more than 800 million people still suffer from hunger seems to indicate imbalances, that food systems do not function as required (HLPE 2014). Nevertheless, the concern related to the impact of food loss and waste on natural resources and the environment cannot be ignored in the context of the capacity of ecosystems and natural resources to sustain an increasing demand for food, estimated by FAO, to reach more than 60% by 2050 mainly driven by population, income growth and changing consumption patterns (HLPE 2014). To this effect, the United Nations Zero Hunger Challenge, in implementing the Sustainable Development Goals (SDGs), is driving forward an approach of ‘Transforming our Food Systems to Transform our World’ on the basis that:

> Achieving the Sustainable Development Goals is not possible without ending hunger and malnutrition and without having sustainable and resilient, climate-compatible agriculture and food systems that deliver for people and planet. (GloPan 2016)

Therefore, the increase in food production needed to meet the anticipated demands of the near future cannot be achieved by simply extrapolating current trends in production and consumption (Gladek et al. 2017).

2 Healthy and Sustainable Diet Concept

Sustainable food systems and diets have recently grown important (Fanzo 2019). Despite the substantial contribution that the promotion of healthy diets can enhance sustainability, so far, it has not often been examined within the field of sustainability science, as health is often a peripheral topic (Kajikawa et al. 2014, 2017; Lindgren et al. 2018). Hence, FAO introduced the concept of "sustainable diets", defined as: "*diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable, nutritionally adequate, safe and healthy; while optimising natural and human resources.*" (Burlingame and Dernini 2012; GloPan 2016; Fanzo 2019)

A healthy diet is defined using food groups while considering nutritional adequacy because this most directly connects food production and health and because most dietary guidelines are based primarily on food groups, including other essential constituents of food (Willett et al. 2019).

There has been significant debate around the relationship between healthy and sustainable diets in the context of quality diets from a nutritional and environmental perspective. Countries like Brazil, Germany, Sweden, and Qatar have official food-based dietary guidelines (FBDGs) that include sustainability. In contrast, others like the Netherlands, Norway, Iceland and France have only few components of guidelines that refer to sustainability (GloPan 2016). However, very few countries around the world incorporate sustainability in their FBDGs. Although greenhouse gas emissions represent only one dimension of a diet's environmental footprint, Downs and Fanzo (2015), in their global analysis, reported that the carbon and water footprint of different foods within food groups such as fruits, vegetables, oils and nuts show considerable variation in ecological footprints. Holden et al. (2018) in a review stated:

"The food we eat today is unsustainable for two reasons: the food system causes unacceptable environmental impacts and it is depleting non-renewable resources. Our food can be regarded as 'fossil food' because its production relies on fossil fuel, non-renewable mineral resources, depletion of groundwater reserves and excessive soil loss." Further supported by a recent review by Springmann et al. (2018) which explored the environmental impacts of food systems, highlighted the need for targeted mitigation measures to control the added increase of 50–90% increase in global ecological pressures and destabilisation of key ecosystem processes.

Another review Hunter et al. (2019) investigating the potential of neglected and underutilised species for improving diets and nutrition recommended that a shift towards healthier diets alone could potentially reduce greenhouse gas emissions and other environmental impacts by 29 and 5–9%, respectively, while the adoption of plant-based diets could increase these percentages to 56 and 6–22%, respectively. Consequently, health-promoting and eco-friendly diets have many synergies as long as most sustainable production methods are chosen for each group.

Sustainable diets with low environmental impacts contribute to food and nutrition security and promote healthy lives for present and future generations. These diets should also respect biodiversity and ecosystems, be culturally acceptable, accessible, economically fair, affordable, nutritionally adequate, safe and healthy, and optimise natural and human resources. In other words, sustainable diets should be good for people, the planet, and the economy.

To achieve sustainable diets, sustainable food systems are essential; these can be derived from sustainable cultures and ecosystems. If intact, indigenous Peoples' food systems is deemed sustainable as they have survived for centuries in different ecosystems. These food systems have sustained their cultures for thousands of years in a specific ecosystem. Nonetheless, due to globalisation and open food trading, the food systems of most Indigenous Peoples today are modified and have become heterogeneous of their traditional local foods and foods procured commercially. This modification in the food system will eventually lead to a loss of local biodiversity, dietary quality, unsustainability, and food insecurity in these groups. Further resulting in malnutrition, especially micronutrient deficiency, and overconsumption of dietary energy that drives the growing epidemic of Obesity and Non-Communicable Diseases (NCD's) in indigenous areas today.

Indigenous Peoples' considerations and dialogues on their local food systems should be encouraged, protected and promoted to ensure the sustainability of their cultures and ecosystems. This information contributes to capacity building for Indigenous Peoples and strengthens their ownership of local food security. Knowledge of the perception of indigenous peoples towards sustainability of their food systems will help to overcome challenges of marginalisation, land rights and development needs experienced in various parts of the world.

By studying how specific Indigenous communities improve use their local food systems for food and nutrition security, allows us to gain valuable insights into a more inclusive global picture of sustainable food systems. This understanding can help Indigenous Peoples overcome challenges and strengthen their ownership of local food security. Therefore, promoting the local traditional food biodiversity is an essential driver of food system sustainability, contributing to global consciousness for more broadly protecting food biodiversity and food system sustainability. Encouraging Indigenous Peoples' consideration on their local food systems and taking concerted action can preserve and promote the sustainability of the cultures and ecosystems that derive from their food systems. The South Pacific food system is diverse and encompasses a wide range of traditional cuisines from the countries and island groups of the region. The food systems of the South Pacific are heavily influenced by the region's geography, history, and cultural practices.

Using indigenous plant materials for food is part of indigenous knowledge and practices developed and accumulated over generations. One of the most essential components of the South Pacific food system is the use of local ingredients. Forests or wild plants provide staple food for indigenous people, serve as complementary food for non-indigenous people and offer alternative sources of cash income. Traditional dishes are based on locally available fruits, vegetables, seafood, and meats. Common ingredients include coconut, taro, yams, breadfruit, cassava, fish, and shellfish. These ingredients are often prepared using traditional methods, such as roasting, grilling, and baking.

Another critical aspect of the South Pacific food system is the cultural significance of food. Many traditional dishes are associated with specific occasions and events, such as weddings, funerals, and religious ceremonies. Sharing food is an essential part of social and cultural customs in the South Pacific, and traditional meals are often served family-style, with everyone eating from the same platter.

The South Pacific food system is also heavily influenced by the region's history and the various cultural groups that inhabited the islands over the centuries. Polynesian, Melanesian, and Micronesian cultures have unique culinary traditions and practices.

3 Indigenous Peoples' Food Systems

Indigenous Peoples' traditional food systems have protected human health and natural environments for millennia (Browne et al. 2020). Indigenous food systems represent a treasure trove of knowledge contributing to well-being and health, benefiting communities, preserving rich biodiversity, and providing nutritious food (IFAD 2021).

Indigenous Peoples' food systems are the result of extensive and acute observations of natural processes and effects that have been passed down through personal, communal, and experiential processes and fostered for centuries that have sustained their culture and identity despite the numerous challenges already faced and those that humankind will face in the future (FAO 2021).

3.1 Role of Indigenous and Traditional Food Systems

Indigenous Peoples and local communities have preserved many ecosystems and cultures throughout history, and they continue to be crucial guardians of the world's genetic resources and food supply (Hunter et al. 2020). According to current scientific estimates, Indigenous Peoples' lands and territories contain 80% of the world's remaining biodiversity (FAO 2021). "Traditional food system" of an Indigenous People is defined as all foods within the specific culture that are readily available from local natural resources and culturally accepted, including the sociocultural meanings, acquisition and processing techniques, use, biological composition, and nutritional implications for the people using the food (Elliott et al. 2012; Kennedy et al. 2021; Kuhnlein and Chotiboriboon 2022).

Detailed information on all cultural applications of plants can be found in general ethnographies or ethnobotanical works that discuss traditional food systems. In their contribution, Kuhnlein and Receveur (1996) outlined the various literature sources that support the growing evidence of:

- a wide range of plant and animal species used by Indigenous Peoples, confirming dietary diversity of such food systems;
- Indigenous Peoples' knowledge of a great variety of the sensory qualities of food, and
- the gradually growing literature on nuts. Kuhnlein & Chotiboriboon's study of why and methods for enhancing Indigenous Peoples' food systems in 2022 noted the following:

> The food systems of Indigenous Peoples are known to contain a vast tapestry of riches in food biodiversity, nourishment, and the potential to sustain biocultural knowledge, resilience, and sustainability. However, these internationally recognised and outstanding attributes, historically documented in part, are affected by many challenges of globalisation that threaten their loss and eventual disappearance.

Indigenous Peoples' knowledge, practices, and participation in the transformation of food systems are becoming more widely acknowledged, particularly in relation to how they inform sustainability research, resilience-building tactics, and climate change adaptation (IPCC 2019; Ruckelshaus et al. 2020; FAO 2021). Food serves as more than just a source of nutrition for many Indigenous Peoples; it also serves as a vital link to their social, emotional, and spiritual well-being as well as to their land, family, history, and culture (Browne et al. 2020). Finding treatments that work for Indigenous Peoples' food systems also surfaced in a paper by Kuhnlein et al. (2006).

> Food relates to social needs and local economy. Indigenous Peoples have their own unique perspectives on the relationships between environment and culture, and food, well-being and health, in many dimensions. This knowledge is precious to them. It also has many lessons for industrialised nations and populations.

Consequently, pre-colonial Indigenous food systems were self-determined, ecologically sustainable and provided healthy, varied diets which protected population health (Kuhnlein 2015; Browne et al. 2020). Learning from indigenous food systems can offer holistic, sustainable ways to interact with nature—which must be noted that mankind is a part of, not apart from (IFAD 2021). The significant qualities of the traditional food systems of Indigenous Peoples that require attention are the diversity of species that are accepted as food from the natural environment in diverse climates and latitudes, the technologies developed to harvest and process the food, and the sensory qualities and dietary structures developed for food selection (Kuhnlein and Receveur 1996).

3.2 Indigenous and Traditional Food Crops (ITFCs)

Due to the wide range of foods, fruits, leaves from trees, leafy and root vegetables, and herbaceous plants that it encompasses, indigenous foods can be difficult to define (Akinola et al. 2020). Ayanwale et al. (2016) defined indigenous foods as meals coming from a particular bio-region along with foods that were imported but are now regarded as indigenous since they were incorporated into the regional culinary tradition.

Bhaskarachary et al. (2016), on the other hand, distinguish between “traditional foods” and “indigenous foods” by describing traditional foods as typically consumed within the last few centuries, whilst indigenous foods are not defined by a specific time period. According to van der Merwe et al. (2016), indigenous and traditional food crops (ITFCs) can be thought of as a continuum of foods ranging from completely wild foods (less-conventional crops) like amaranth, pumpkin leaves, and calabash to semi-domesticated foods (conventional crops) like sorghum, cowpeas, and sweet potatoes.

The fact that ITFCs are marginalized by contemporary and modern farming systems may explain why they are also referred to as “wild,” “traditional,” “minor,” “underdeveloped,” “underexploited,” “lost,” “alternative,” “local,” “orphan,” “niche,” “promising,” “novel,” “hidden treasures,” “forgotten,” and “neglected,” among other terms (Padulosi et al. 2002; Li and Siddique 2018; Hunter et al. 2019; Akinola et al. 2020; Kennedy et al. 2021). ITFCs are often relegated to a ‘neglected and underutilised species’—NUS status (IPGRI 2002; Chivenge et al. 2015; Mabhaudhi et al. 2016; Akinola et al. 2020), demonstrating that they are not among the major staple crops of current global food systems (Padulosi et al. 2013).

The NUS notion pertains to significant plant species that researchers, breeders, and governments have marginalized or even neglected (Padulosi et al. 2013; Hunter et al. 2019). NUS are regarded as future smart foods or climate-smart food crops because of their resilience, flexibility, and high potential to ensuring food and nutrition security, according to Imathiu (2021).

Indigenous foods have also gained widespread acclaim over the past 10 years for their ability to contribute to increased biodiversity around the globe (Kapoor et al. 2022). However, the development of ITFCs has been grossly devalued (Bvenura and Afolayan 2015; Akinola et al. 2020) as a result of the green and supermarket revolutions, to mention a few, which have all led to the decline in the diversity of agriculture, food systems, and diets (Guarino et al. 2016; Hunter et al. 2019).

3.3 Erosion of ITFCs in Global Diets

Modern food production technologies have spread mainstream agriculture so far that ITFCs have been overlooked and underutilized. In contrast to ITFCs, which were formerly widely employed, lower nutritional crops and non-indigenous commodities have taken their place (Turner and Turner 2007; Akinola et al. 2020), plainly failing to improve nutrition and the environment (Caron et al. 2018; KC et al. 2018; Willett et al. 2019; Hunter et al. 2019).

The homogenization of global diets is demonstrated by a study of global food supply by Khoury et al. (2014), which shows a 68.8% decrease in variance in national food sources across countries. The study found that over the course of 48 years—from 1961 to 2009—the world’s diets have become more similar, with wheat, rice, and maise taking precedence over other mainstays including sorghum, millets, rye, cassava, sweet potato, and yam.

Furthermore, because colonizers depicted ITFCs as being the meal of poor men, these foods and their foodways were dispersed among Indigenous populations worldwide during the post-colonial period. Due to an excessive reliance on high-yielding, genetically uniform crop monocultures and industrialized agriculture methods and techniques, the modern global food systems have exacerbated the displacement and disappearance of food plant species, their genetic diversity, and biocultural heritage (IPES-Food 2016). Additionally, the inadequate transfer of indigenous knowledge to the younger generation regarding ITFCs may be partially attributed to the decreasing utilisation due to the changing social values and rural-urban migration, where these crops are ignored and neglected in favour of exotic western plant varieties (Njume et al. 2014).

According to research and development programs, non-commodity crops account for the majority of ITFCs worldwide (Sogbohossou et al. 2018). According to a technical assessment by Kew (2016), out of an estimated 300,000 plant species that have ever been documented, only about 5000 have ever been used as food for humans. 75% of the world's food is currently produced by just 12 crops and 5 animal species (Hunter et al. 2019). As such, cultivation of ITFCs has become non-competitive and unattractive compared to the "major" crops promoted through formal seed systems and markets (Chivenge et al. 2015).

4 Importance of ITFCs in Food Systems

ITFCs support sustainable food systems in a variety of ways. In a review, Akinola et al. (2020) divided the advantages of ITFCs into four major categories for enabling more just and sustainable food systems:

- nutritional benefits, such as higher nutrient density than in commodity crops (Penafiel et al. 2011);
- environmental benefits, such as ITFCs' ability to withstand climate change's extreme weather conditions;
- social-cultural benefits, such as the relationship between indigenous knowledge and ITFCs' nutritional value; and
- economic benefits, such as livelihoods and income from the sale of ITFCs (Bharucha and Pretty 2010).

Along with the potentially vital means of living more sustainably, the possibility that information about ITFCs is already being lost is notable. In order to ensure social, economic, and environmental sustainability, ITFCs act as a key link between people and the environment and play a crucial role in fulfilling the Sustainable Development Goals' (SDGs) global objectives (Akinola et al. 2020).

ITFCs are abundant in supplying wholesome, nutrient-dense meals that satisfy dietary needs and encourage healthy diets, ensuring there is no hunger (SDG2) and that people are healthy and happy (SDG3). In order to address climate change and its effects (SDG13) and conserve, restore, and promote terrestrial ecosystems (SDG15), ITFCs can promote genetic variety and environmental preservation while also boosting ecosystem resilience.

ITFCs give people social value in terms of their feeling of self-worth and dignity, as well as a sense of belonging and a connection to their ancestry. Reducing inequality in terms of gender (SDG10), and within- and between-country (SDG12) inequality. ITFCs help generate money to enhance people's quality of life and the potential for economic growth profits, providing sustainable economic growth and decent and productive jobs for everyone (SDG8).

5 ITFCs and Human Health

With greater nutritional applications and advantages, including the possibility for bioactive substances that may help the body's antioxidant activity, ITFCs can surely provide the entire nutrient requirement (Akinola et al. 2020). While ITFCs have added benefit of creating diversification of foods grown and increasing the likelihood of diversified diets (Akinola et al. 2020), many indigenous and traditional vegetables are characterised by their health-protective properties. Through their nutritional effects, the phytochemicals and antioxidants they contain are associated to preventing the onset of illnesses (Mbhenyane et al. 2015).

Many pharmaceutical laboratories are now taking notice of the numerous pharmacological investigations and ethnobotanical analyses that show the pharmacological activities and contribution of diverse ITFCs to people's health as well as their vital function in modern medicine (Koné et al. 2011). International recognition has been given to ITFCs like moringa and rooibos for their therapeutic potential in treating various illnesses, including cancer, diabetes, cardiovascular disorders, and obesity, as well as for their hepato- and nephro-protective properties (Gopalakrishnan et al. 2016; Brilhante et al. 2017; Lin et al. 2018; Smith and Swart 2018). Some indigenous leafy vegetable (ILV) species, including *Telfairia occidentalis, Vernonia amygdalina, Launaea taraxacifolia, Ceiba pentandra* (L.) *Gaertn., Crassocephalum crepidioides (Benth.) S. Moore*, seeds like Garcinia kola, and pulses like Bambara groundnut (*Vigna subterranea*) have been shown to have potential for disease prevention and control like diarrhoea, anaemia, ulcers, cataracts, diabetes, allergic diseases, arthritis, asthma, autoimmune diseases, cancer, leukaemia and lymphoma, based on their alleged anti-oxidant, anti-inflammatory, anti-proliferative, and even reproductive capabilities (Farombi and Owoeye 2011; Eseyin et al. 2014; Kadiri and Olawoye 2015; Kadiri and Olawoye 2016; Bello et al. 2018a, b; Oluwasesan et al. 2019; Raimi et al. 2020).

6 Role of Root Crop in the Food System

Root crops play a significant role in the food system of many countries of the South Pacific, providing a significant source of carbohydrates, dietary fibre, vitamins, and minerals. They are a staple food in many Pacific Island countries, including Papua New Guinea, Fiji, Samoa, and Tonga, and are grown and consumed by both rural and urban populations.

Some of the South Pacific's most cultivated root crops include taro, yam, sweet potato, cassava, and giant taro. These crops are highly adaptable to different growing conditions, including harsh environments such as mountainous regions and small islands, and can be grown in various soil types.

Root crops are used in traditional South Pacific dishes, such as taro pudding, roasted yams, cassava cakes, kava and sweet potato curry. They are also used in other dishes, including soups, stews, and stir-fries. In addition to their food source, root crops have cultural and social significance in many Pacific Island communities. They are often used in traditional ceremonies and rituals, symbolising fertility, growth, and prosperity.

7 Traditional Processing and Sustainability

Traditional food processing in the South Pacific is an integral component of the region's culinary and cultural heritage. Many traditional food processing methods have been abolished from generation to generation and are still utilized alongside modern food processing techniques. Not much scientific work has been done in this field and most of the techniques are poorly recoded in the literature (Malolo et al. 1999; Naika 2020).

Here are some examples of traditional food processing methods used in the South Pacific.

7.1 Fermentation

Food fermentation in the South Pacific has been a vital component of the local culture and cuisine for thousands of years. Fermentation is a process in which microorganisms, such as bacteria or yeast, transform carbohydrates into acids, gases, or alcohol. This process has been utilized to preserve food and create unique flavours and textures in traditional cuisines.

One of the most popular traditional fermented foods in the South Pacific is poi, which is a staple in Hawaii, Samoa, Tonga, and other islands. Poi is made by steaming or baking taro root, then mashing it with water until it forms a smooth, pudding-like consistency. The mixture is left to ferment for a few days, during which natural yeasts and bacteria break down the carbohydrates in the taro into lactic acid, which gives poi its distinctively tangy taste. Poi is often served as a side dish or used as a base for other dishes.

In Fiji and other islands, kokoda is a popular dish that is made by marinating raw fish in coconut cream and lemon or lime juice. The acid in the citrus juice effectively "cooks" the fish, while the coconut cream adds a rich, creamy texture. The dish is often served as an appetiser or side dish and is a favourite among tourists and locals.

Another traditional South Pacific fermented food is leafy vegetables that are based on sauerkraut. While sauerkraut is often associated with European cuisine, it has been adapted to local tastes in Fiji and other islands. In Fiji, vakasakera (sauerkraut) is made by fermenting shredded cassava (and other green leafy vegetables) and cabbage with salt and water (Naika 2020). The resulting product is a tangy, slightly sour condiment that is often served with grilled meats or fish.

Fermented breadfruit is a traditional food in some cultures, especially in Fiji and Vanuatu (Malolo et al. 1999). Nearly all breadfruit fermentation techniques feature a pit. Ripen breadfruits are skin off and then buried inside the pit lined with coconut tree leaves. Pit may be covered with additional leaves, sometimes earth, and stones. In few scenarios breadfruit was first soaked in salt or brackish water for a period of time before being plated in the pits. The fermentation process can take from 2 to 6 months and result in yellow mash with a pungent smell. The paste is removed from the pit, dried and kneaded.

Fermented cassava in the South Pacific refers to a traditional food made from cassava root that is widely consumed in the Pacific Island region. In this region, it is made by pit fermentation similar to breadfruit or soaking the peeled tuber under the running fresh water (Lancaster et al. 1982; Naika 2020). Fermentation produces a tangy, slightly effervescent food. The fermentation process imparts a unique flavour and aroma to the cassava and can also increase its nutritional value. During fermentation the detoxification of cyanide from the bitter cassava is an additional benefit. The exact preparation and ingredients of fermented cassava in the South Pacific may vary between islands and communities.

Fermented coconut, also known as kota/kora, is a traditional food in pacific islands made by fermenting grated coconut under sea water (*Traditional Food Preservation Methods*) (*The Fiji Times Kora, a Fijian delicacy* 2023). The mixture is then strained and used as a base for various dishes, such as stews and curries. The fermentation process imparts a unique flavour and aroma to the coconut and can increase its nutritional value. It is often used as a condiment or as an ingredient in traditional Fijian dishes. Fiji's exact preparation and ingredients of fermented coconut may vary between regions and communities.

Different parts of Fiji, have different methods of preparing Kora. For the island of Qoma, kora is prepared by scrapping coconut, and squeezing out its milk. The squeezed grated coconut will then be wrapped in banana leaves and soaked in sea water. Large stones are placed over the kora bundle to press down the wrapped product and hold it in place during high tide. Some parts of Fiji use nylon sacks for storing grated coconut before placing in sea. Sea water helps soften the grated coconut and add salt to the mixture. At low tide, women identify suitable places at the foreshore to place the prepared kora bundle. Some prefer to place kora in tidal pools or rock pools; some on foreshore while those far way from the ocean prepare the mixture at home. It is said that the difference in salt concentration determines the taste of Kora. Therefore, it is placed in areas with little to no human interaction where sea water is clean with no pollutants.

7.2 Sun Drying

Due to high humidity and frequent rain, traditionally sun-drying is not very popular method used for preserving food in the South Pacific islands. Method mainly used during dry season when there is good wind flow. This method involves exposing the food to the sun's rays and letting it dry naturally, with solar dryer or without the use of any mechanical or electrical equipment (Naika 2020). This method is gaining popularity in the region, particularly in rural areas.

The traditional sun-drying method is used to preserve a variety of foods, including fish, meat, seaweed, fruits, and vegetables. In most of the cases, the food is first marinated in salt or other seasonings before being laid out in the sun to dry. The sun-drying process can take anywhere from a few days to several weeks, depending on the type of food and the weather conditions.

One of the most common sun-dried products in the South Pacific is fish. Fish is a staple food in many island communities, and the sun-drying method allows it to be preserved for long periods without refrigeration. The most commonly dried fish species include tuna, mullet, and shark. The fish are cleaned, salted, and then hung on lines or racks to dry in the sun. Once dry, the fish can be stored for months and are often eaten as a snack or used as a base for soups and stews. Another popular sun-dried product is meat, particularly beef and pork. The meat is sliced into thin strips, seasoned with salt and other spices, and then laid out in the sun to dry. The drying process can take several days, during which time the meat develops a chewy texture and a distinct flavour. Once dry, the meat can be stored for months and is often used as a protein source in soups and stews.

Root crops, seaweed, fruits and vegetables are also commonly sun-dried in the South Pacific. Dalo, cassava and sweet potato are generally steamed, peeled and cut into thin slices for sun drying while roots of kava are generally dried directly. Breadfruit, mangoes, papayas, bananas, pandanus and pineapples are some of the most commonly dried fruits, while pumpkin, eggplants, and chilies are popular dried vegetables. Dried fruits and vegetables are often used in salads, stews, and other dishes, and are also eaten as snacks. In addition to food, other products such as coconut fibers, pandanus leaves, and bark are also sun-dried in the South Pacific for use in traditional crafts and building materials.

7.3 Smoke Drying

Traditional smoke-drying more preferred method of preserving food compared to sun drying and has been practiced in the South Pacific for centuries. This method involves exposing food to smoke from burning wood or other materials, which not only helps to preserve the food but also imparts a unique smoky flavour to it (Malolo et al. 1999). In the South Pacific, smoke-dried food products are an essential part of the region's culinary culture, and they are still widely consumed today.

There are several types of food products that are traditionally smoke-dried in the South Pacific. One of the most common is fish, particularly tuna (Mcgeever 1968). Tuna is abundant in the waters surrounding the South Pacific islands, and it is often caught fresh and then immediately smoked to preserve it. The smoke-dried tuna is usually cut into thin slices and eaten as a snack or used as an ingredient in various dishes. Another popular smoke-dried food product in the South Pacific is pork. In many cultures in the region, pigs are considered a symbol of wealth and are often raised for special occasions such as weddings and funerals. When a pig is slaughtered, it is typically smoked and then sliced into thin pieces. The resulting smoke-dried pork is a staple food item in many South Pacific countries, and it is often eaten with rice or used as a flavouring in soups and stews. Other types of food that are traditionally smoke-dried in the South Pacific include coconut, taro, and breadfruit. Coconut is smoked to make coconut cream, which is an essential ingredient in many South Pacific dishes. Taro and breadfruit are smoked and then pounded into a paste, which can be used as a base for many different types of dishes.

The smoke-drying process itself varies depending on the food product being preserved. In general, the food is first cleaned and then cut into the desired size and shape. It is then placed on a rack or suspended from a hook and exposed to smoke from burning wood or other materials. The smoke not only helps to preserve the food but also adds flavour and colour to it. One of the key advantages of smoke-dried food products is that they can be stored for long periods without refrigeration. This is particularly important in the South Pacific, where access to refrigeration is often limited. Smoke-dried food products also have a unique flavor that is highly valued in the region's culinary culture.

7.4 Pounding

Pounding is a traditional food processing technique that is widely used in the South Pacific, particularly in Melanesia and Polynesia. The process involves pounding or beating food items, such as roots, tubers, and vegetables, with a wooden or stone pestle and mortar until they are soft and pliable. Pounding is an essential part of the traditional cuisine of the South Pacific, and the resulting food products are used for various culinary purposes. Some of the most popular pounded foods in the region include taro, yams, sweet potatoes, and cassava. These foods are usually peeled, sliced, and then pounded into a paste-like consistency. The process of pounding involves a series of repetitive motions that require physical strength and endurance. In traditional communities, pounding is often a communal activity, with women and children working together to prepare food for the entire community. The pounding of food is accompanied by singing and chanting, which serves to create a sense of community and shared purpose. One of the primary benefits of pounding as a food processing technique is that it helps to break down the complex carbohydrates present in many root crops. This makes the nutrients in these foods more accessible to the human body, improving their nutritional value. Additionally, pounding can help to remove toxins and other harmful substances from certain foods, making them safer to eat.

Kava is a traditional drink in many South Pacific countries, made from the kava plant's roots. Kava has been used for centuries in ceremonies and social gatherings and is believed to have relaxing and calming effects. Making kava involves pounding of sun dried the kava root into a powder, soaking it in water, and kneading it to extract the active compounds. The resulting liquid is strained and consumed. In addition to its nutritional benefits, pounding is also valued for its cultural significance in the South Pacific. The traditional techniques and equipment used in pounding have been passed down from generation to generation, and they are an important part of the region's cultural heritage. Pounding also plays a significant role in many traditional ceremonies and rituals, particularly those related to food and feasting.

7.5 Pit Cooking

Traditional pit-cooking, also known as earth oven or hangi, is a cooking method that has been used in the South Pacific for centuries. This method involves digging a pit in the ground, heating stones in the pit with firewood, placing food wrapped in banana leaves or other similar materials on the hot stones, and covering it with more banana leaves and soil to trap the heat. The food then cooks slowly in the pit for several hours, resulting in a unique smoky flavour and tender texture.

This method of cooking is still widely practiced in many South Pacific countries, including New Zealand, Fiji, Samoa, and Tonga, and is often used for special occasions and celebrations such as weddings, funerals, and festivals. Some of the traditional food products that are cooked in pit ovens in the South Pacific include:

1. ***Hangi***—a traditional Maori dish from New Zealand that typically includes meat (lamb, pork, or chicken), kumara (sweet potato), potatoes, pumpkin, and cabbage. The meat and vegetables are wrapped in damp muslin or cheesecloth and placed on the hot stones in the pit, covered with more cloth and soil, and left to cook for several hours.
2. ***Umu***—a similar dish from Samoa that typically includes taro, yams, breadfruit, and fish or meat, wrapped in banana leaves and cooked in a pit oven.

3. ***Lovo***—a traditional Fijian dish that typically includes meat (chicken, fish, or pork), cassava, taro, sweet potato, and other vegetables, wrapped in banana leaves and cooked in a pit oven.
4. ***Ota ika***—a traditional Tongan dish that consists of raw fish marinated in lemon juice and coconut cream, wrapped in banana leaves and cooked in a pit oven.

These traditional pit-cooked dishes are not only delicious but also culturally significant, as they are often prepared and enjoyed as part of important social and cultural events. The process of preparing and cooking the food in the pit oven is also seen as a communal activity, bringing people together to work and share in the experience.

8 Conclusion

These traditional food processing methods are still used in many South Pacific communities and play an essential role in preserving the region's culinary and cultural heritage. These traditional food preservation methods are time-honoured practice that has been used for thousands of years to preserve food, enhance flavours, and create unique culinary experiences. These preservation methods not only provide sustenance but also serve as a symbol of cultural identity and heritage. Consuming traditional processed food products instead of refined Western starches will be a move to healthier traditional diets and also a measure of independence if used during food crises rather than relying on overseas aid. The introduction of Western influences has also impacted the South Pacific food system. While traditional dishes and cooking methods are valued, the region has adopted new foods and culinary practices. For example, the introduction of rice, noodles, and other staples from Asia has greatly influenced the region's cuisine. Overall, the South Pacific food system is a complex and diverse system that is deeply rooted in the region's culture, history, and geography. While it continues to evolve and change, traditional practices and ingredients remain essential to the region's culinary heritage.

References

Akinola R, Pereira LM, Mabhaudhi T et al (2020) A review of indigenous food crops in Africa, the implications for more sustainable, healthy food systems. Sustain 12:1–30. https://doi.org/10.3390/SU12083493

Allen T, Prosperi P (2016) Modeling sustainable food systems. Environ Manage 57:956–975. https://doi.org/10.1007/s00267-016-0664-8

Bhaskarachary K, Vemula SR, Gavaravarapu SRM, Joshi AKR (2016) Traditional foods, functional foods and nutraceuticals. Proc Indian Natl Sci Acad 82:1565–1577. https://doi.org/10.16943/ptinsa/2016/48888

Bello OM, Abiodun BO, Tijjani A (2018a) Lipoxygenase (Lox) Inhibitory Activity of Leaves of Ceiba Pentandra (L.) Gaertn: a neglected vegetable from Nigeria. FUDMA J Sci 2:79–87

Bello OM, Abiodun BO, Uduma AU (2018b) Launaea taraxacifolia; a neglected vegetable from nigeria, its anti-inflammatory and antioxidant activities. Chem Search J 9:9–12
Ayanwale AB, Amusan CA, Adeyemo VA, Oyedele DJ (2016). Analysis of household demand for underutilized indigenous vegetables. Int J Veg Sci 22:570–577. https://doi.org/10.1080/19315260.2015.1103350
Bharucha Z, Pretty J (2010) The roles and values of wild foods in agricultural systems. Philos Trans R Soc B Biol Sci 365:2913–2926. https://doi.org/10.1098/rstb.2010.0123
Brilhante RSN, Sales JA, Pereira VS et al (2017) Research advances on the multiple uses of Moringa oleifera: a sustainable alternative for socially neglected population. Asian Pac J Trop Med 10:621–630. https://doi.org/10.1016/j.apjtm.2017.07.002
Browne J, Lock M, Walker T et al (2020) Effects of food policy actions on Indigenous Peoples' nutrition-related outcomes: a systematic review. BMJ Glob Heal 5:1–15. https://doi.org/10.1136/bmjgh-2020-002442
Burlingame B, Dernini S (2012) Sustainable Diets and Biodiversity: Directions and solutions for policy, research and action. In: International scientific symposium, biodiversity and sustainable diets united against hunger, FAO Headquarters, Rome, Italy, 3–5 November 2010. Food and Agriculture Organization of the United Nations (FAO)
Bvenura C, Afolayan AJ (2015) The role of wild vegetables in household food security in South Africa: a review. Food Res Int 76:1001–1011. https://doi.org/10.1016/j.foodres.2015.06.013
Caron P, Ferrero y de Loma-Osorio G, Nabarro D et al (2018) Food systems for sustainable development: proposals for a profound four-part transformation. Agron Sustain Dev 38. https://doi.org/10.1007/s13593-018-0519-1
Chivenge P, Mabhaudhi T, Modi AT, Mafongoya P (2015) The potential role of neglected and underutilised crop species as future crops under water scarce conditions in sub-Saharan Africa. Int J Environ Res Public Health 12:5685–5711. https://doi.org/10.3390/ijerph120605685
Downs SM, Fanzo J (2015) Is a cardio-protective diet sustainable? A review of the synergies and tensions between foods that promote the health of the heart and the planet. Curr Nutr Rep 4:313–322. https://doi.org/10.1007/s13668-015-0142-6
Elliott B, Jayatilaka D, Brown C, Varley L, Corbett KK (2012) We are not being heard: Aboriginal perspectives on traditional foods access and food security. J Environ Public Health. https://doi.org/10.1155/2012/130945
Eseyin OA, Sattar MA, Rathore HA (2014) A review of the pharmacological and biological activities of the aerial parts of Telfairia occidentalis Hook.f. (Cucurbitaceae). Trop J Pharm Res 13:1761–1769. https://doi.org/10.4314/tjpr.v13i10.28
Fanzo J (2019) Healthy and sustainable diets and food systems: the key to achieving sustainable development goal 2? Food Ethics 4:159–174. https://doi.org/10.1007/s41055-019-00052-6
FAO (2011) Global food losses and food waste—extent, causes and prevention. Rome
FAO (2021) The White/Wiphala paper on indigenous peoples ' food systems. Rome
FAO, IFAD, UNICEF et al (2022) The state of food security and nutrition in the World 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome
Farombi EO, Owoeye O (2011) Antioxidative and chemopreventive properties of Vernonia amygdalina and Garcinia biflavonoid. Int J Environ Res Public Health 8:2533–2555. https://doi.org/10.3390/ijerph8062533
Gladek E, Fraser M, Roemers G et al (2017) Global food system: an analysis—Metabolic
GloPan (2016) Food systems and diets: facing the challenges of the 21st century
Gopalakrishnan L, Doriya K, Kumar DS (2016) Moringa oleifera: a review on nutritive importance and its medicinal application. Food Sci Hum Wellness 5:49–56. https://doi.org/10.1016/j.fshw.2016.04.001
Guarino L, Cherfas J, Hunter D (2016) Revolutions, food and diets, and shrinking diversity. Dublin Gastron Symp. https://arrow.tudublin.ie/dgs/2016/June1/16
HLPE (2014) Food losses and waste in the context of sustainable food systems. A report by the high level panel of experts on food security and nutrition of the Committee on World Food Security

HLPE (2017) Nutrition and food systems. HLPE. 2017. Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome

Holden NM, White EP, Lange MC, Oldfield TL (2018) Review of the sustainability of food systems and transition using the Internet of Food. npj Sci Food 2. https://doi.org/10.1038/S41538-018-0027-3

Hunter D, Borelli T, Beltrame DMO et al (2019) The potential of neglected and underutilised species for improving diets and nutrition. Planta 250:709–729. https://doi.org/10.1007/s00425-019-03169-4

Hunter D, Borelli T, Gee E (2020) Biodiversity, food and nutrition: a new agenda for sustainable food systems. Issues in Agricultural Biodiversity, 1st ed. Routledge, Oxon (UK), 296 p. ISBN: 9780367141516

IFAD (2021) Indigenous food systems are at the heart of resilience

Imathiu S (2021) Neglected and underutilized cultivated crops with respect to indigenous african leafy vegetables for food and nutrition security. J Food Secur 9:115–125. https://doi.org/10.12691/jfs-9-3-4

IPGRI 2002 (2002) Neglected and underutilised plant species: strategic action plan, 1–30

IPCC (2019) Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Cambridge University Press. https://doi.org/10.4337/9781784710644

IPES-Food (2016) Uniformity diversity from uniformity 96. http://www.ipesfood.org/_img/upload/files/UniformityToDiversity_FULL.pdf

Kadiri O, Olawoye B (2015) Underutilised Indigenous Vegetable (UIV) in Nigeria: a rich source of nutrient and antioxidants—a review. Ann Food Sci Technol 16:2

Kadiri O, Olawoye B (2016) Vernonia amygdalina: an underutilized vegetable with nutraceutical potentials—a review. Turkish J Agric—Food Sci Technol 4:763. https://doi.org/10.24925/turjaf.v4i9.763-768.570

Kajikawa Y, Tacoa F, Yamaguchi K (2014) Sustainability science: the changing landscape of sustainability research. Sustain Sci 9:431–438. https://doi.org/10.1007/S11625-014-0244-X/METRICS

Kajikawa Y, Saito O, Takeuchi K (2017) Academic landscape of 10 years of sustainability science. Sustain Sci 12:869–873. https://doi.org/10.1007/S11625-017-0477-6/METRICS

Kapoor R, Sabharwal M, Ghosh-Jerath S (2022) Indigenous foods of India: a comprehensive narrative review of nutritive values, antinutrient content and mineral bioavailability of traditional foods consumed by indigenous communities of India. Front Sustain Food Syst 6. https://doi.org/10.3389/fsufs.2022.696228

KC KB, Dias GM, Veeramani A, et al (2018) When too much isn't enough: does current food production meet global nutritional needs? PLoS One 13:e0205683. https://doi.org/10.1371/journal.pone.0205683

Kennedy G, Kanter R, Chotiboriboon S et al (2021) Traditional and indigenous fruits and vegetables for food system transformation. Curr Dev Nutr 5:1–5. https://doi.org/10.1093/cdn/nzab092

Khoury CK, Bjorkman AD, Dempewolf H, et al (2014) Increasing homogeneity in global food supplies and the implications for food security. Proc Natl Acad Sci USA 111:4001–4006. https://doi.org/10.1073/pnas.1313490111

Koné M, Paice AG, Touré Y (2011) Bambara groundnut [Vigna subterranea (L.) Verdc. (Fabaceae)] usage in human health. Nuts Seeds Heal Dis Prev 189–196. https://doi.org/10.1016/B978-0-12-375688-6.10022-2

Kora, a Fijian delicacy. https://www.fijitimes.com/kora-a-fijian-delicacy/. Accessed 16 Aug 2023

Kuhnlein H, Erasmus B, Creed-Kanashiro H, Englberger L, Okeke C, Turner N, Allen L, Bhattacharjee L (2006). Indigenous peoples' food systems for health: finding interventions that work. Public Health Nutr 9:1013–1019. https://doi.org/10.1017/PHN2006987

Kuhnlein HV (2015) Food system sustainability for health and well-being of indigenous peoples. Public Health Nutr 18:2415–2424. https://doi.org/10.1017/S1368980014002961

Kuhnlein HV, Receveur O (1996) Dietary change and traditional food systems of indigenous peoples. Ann Rev Nutr 16:417–442. https://doi.org/10.1146/annurev.nu.16.070196.002221
Kuhnlein HV, Chotiboriboon S (2022) Why and how to strengthen indigenous peoples food systems with examples from two unique indigenous communities. Front Sustain Food Syst 6:1–20. https://doi.org/10.3389/fsufs.2022.808670
Lancaster PA, Ingram JS, Lim MY, Coursey DG (1982) Traditional Cassava-based foods: survey of processing techniques. Econ Bot 36:12–45
Li X, Siddique KHM (2018) Future smart food: rediscovering hidden treasures of neglected and underutilised species for zero hunger in Asia
Lin M, Zhang J, Chen X (2018) Bioactive flavonoids in Moringa oleifera and their health-promoting properties. J Funct Foods 47:469–479. https://doi.org/10.1016/j.jff.2018.06.011
Lindgren E, Harris F, Dangour AD et al (2018) Sustainable food systems—a health perspective. Sustain Sci 13:1505–1517. https://doi.org/10.1007/s11625-018-0586-x
Mabhaudhi T, O'Reilly P, Walker S, Mwale S (2016) Opportunities for underutilised crops in Southern Africa's post-2015 development agenda. Sustain 8:1–16. https://doi.org/10.3390/su8040302
Mabhaudhi T, Chibarabada TP, Chimonyo VGP et al (2019) Mainstreaming underutilized indigenous and traditional crops into food systems: a south african perspective. Sustainability 11. https://doi.org/10.3390/su11010172
Malolo M, Matenga-Smith T, Hughes R (1999) The staples we eat: Pacific foods. Secretariat of the Pacific Community
Mbhenyane XG, Mushaphi LF, Mabapa NS et al (2015) The consumption of indigenous fruits and vegetables and health risk in rural subjects of Limpopo province, South Africa. Indilinga African J Indig Knowl Syst 12:160–168. https://doi.org/10.4314/indilinga.v12i1
Mcgeever MB (1968) Practical Fish-smoking in Fiii. South Pac Bull 34–36
Naika A (2020) Preserve your own food. Promoting healthy eating through home food processing and preservation, 1st edn. FAO, Rome, Italy
Njume C, Goduka NI, George G (2014) Indigenous leafy vegetables (imifino, morogo, muhuro) in South Africa: a rich and unexplored source of nutrients and antioxidants. African J Biotechnol 13:1933–1942. https://doi.org/10.5897/ajb2013.13320
Oluwasesan MB, Abiodun B, Uduma A (2019) Antioxidant and lipoxygenase inhibitory activity of Crassocephalum crepidioides (Benth.) S. Moore; an underutilised vegetable from Nigeria. FRsCS 1:27–31
Padulosi S, Thompson J, Rudebjer P (2013) Fighting poverty, hunger and malnutrition with neglected and underutilised species
Padulosi S, Hodgkin T, Williams JT, Haq N (2002) Underutilised crops: trends, challenges and opportunities in the 21st century. In: Managing plant genetic diversity. Proceedings an international conference, Kuala Lumpur, Malaysia, 12–16 June 2000 323–338. https://doi.org/10.1079/9780851995229.0323
Penafiel D, Lachat C, Espinel R, Van Damme P, Kolsteren P (2011) A systematic review on the contributions of edible plant and animal biodiversity to human diets. Ecohealth 8(3):381–399. https://doi.org/10.1007/S10393-011-0700-3
Traditional Food Preservation Methods—Toni Kora (Fermented Grated Coconut). https://www.ichlinks.com/archive/materials/photosV.do?nation=FJ&ichDataUid=13870493285131553332. Accessed 16 Aug 2023
Raimi CO, Oyelade AR, Adesola OR (2020) Phytochemical screening and in-Vitro antioxidant activity on Vernonia Amygdalina (Ewuro-Bitter Leaf). Eur J Agric for Res 8:12–17
RBG Kew (2016) The state of the world's plants. In: State of the world (Issue October). https://doi.org/10.5822/978-1-61091-756-8
Rochefort G, Lapointe A, Mercier A-P et al (2021) A rapid review of territorialized food systems and their impacts on human health, food security, and the environment. Nutrients 13:1–13
Siegel KR, Ali MK, Srinivasiah A et al (2014) Do we produce enough fruits and vegetables to meet global health need? PLoS One 9. https://doi.org/10.1371/journal.pone.0104059

Smith C, Swart A (2018) Aspalathus linearis (Rooibos)—a functional food targeting cardiovascular disease. Food Funct 9:5041–5058. https://doi.org/10.1039/C8FO01010B

Sogbohossou EOD, Achigan-Dako EG, Maundu P, et al (2018) A roadmap for breeding orphan leafy vegetable species: a case study of *Gynandropsis gynandra* (Cleomaceae). Hortic Res 5:1–15. https://doi.org/10.1038/s41438-017-0001-2

Ruckelshaus MH, Jackson ST, Mooney HA, Jacobs KL, Kassam KAS, Arroyo MTK, Báldi A, Bartuska AM, Boyd J, Joppa LN, Kovács-Hostyánszki A, Parsons JP, Scholes RJ, Shogren JF, Ouyang Z (2020) The IPBES global assessment: pathways to action. Trends Ecol Evol 35:407–414. https://doi.org/10.1016/j.tree.2020.01.009

Turner NJ, Turner KL (2007) Traditional food systems, erosion and renewal in Northwestern North America. Indian J Tradit Knowl 6:57–68. https://nopr.niscpr.res.in/bitstream/123456789/828/1/IJTK%206%281%29%20%282007%29%2057-68.pdf

UN (1987) Report of the World Commission on Environment and Development: Our common future

UN (2022) The Sustainable Development Goals Report 2022

van der Merwe JD, Cloete PC, van der Hoeven M (2016) Promoting food security through indigenous and traditional food crops. Agroecol Sustain Food Syst 40:830–847. https://doi.org/10.1080/21683565.2016.1159642

Willett W, Rockström J, Loken B et al (2019) Food in the anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393:447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Sustainability in Food Process Development: A Comprehensive Carbon Footprint Analysis Tool

Sally Lukose and Karuna Singh

1 Introduction

In recent years as the world faces increasing concerns about climate change and its environmental consequences, the concept of carbon footprints has garnered significant attention. A carbon footprint is referred as the total amount of greenhouse gas emissions, which is expressed in terms of carbon dioxide equivalent (CO_2e), which is produced either directly or indirectly by an individual, any organization, event, or product throughout its life cycle. This measurement is mainly to help in quantifying the impact of human activities on the earth's climate and provide an important tool for determining the environmental sustainability of various processes, in addition to those involved in food production and processing.

According to the Food and Agriculture Organization (FAO) of the United Nations (FAO 2020), the food industry is considered to be one of the major contributors to the greenhouse gas emissions, contributing for approximately 25% of the global emissions. The processes involved in a food industry involves a wide range of activities, including agricultural production, food transportation, processing of food items, and finally packaging, and distribution of these food items. Varying amounts of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are released into the atmosphere during each of these stages.

The significance of assessing the carbon footprint of food processes lies in its ability to provide valuable insights into the environmental impact of the food industry. By quantifying greenhouse gas emissions at each stage, food processors can identify areas of high emissions, or "hotspots," and implement targeted strategies to reduce

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their carbon footprint. This approach aligns with the broader goal of promoting sustainability and environmental responsibility within the food industry.

Several studies have shown that at certain stages of food production there is a significant environmental impact. For example, in agricultural activities involving livestock production, a potent greenhouse gas, methane is emitted which contribute significantly to the carbon footprint. Furthermore, the transportation of food products over long distances contribute to the release of large amounts of carbon dioxide, impacting the industry's overall carbon footprint (Birch 2014). As depicted in Table 1 food systems is one of the major drivers of greenhouse gas emission contribute around 53.2 billion tonnes of CO_2 equivalents (Deconinck 2018; Scarborough et al. 2014). Food system contribute around 26% of global emission of greenhouse gasses. The details of greenhouse gas emission by different food system activities have been depicted in Table 1. These "hotspots" can be identified by the concerned companies and targeted actions can be taken to curb emissions at critical points in the food supply chain process.

The carbon footprint analysis will help the companies to make informed decisions about adopting sustainable practices and technologies such as shifting to renewable energy sources, optimizing transportation routes, and implementing energy-efficient technologies can lead to reduced emissions and improved overall environmental well-being (Tukker et al. 2011). Furthermore, in present times, studies have shown that consumers are becoming more environmentally aware and are willing to pay a premium for products with lower environmental impacts, making sustainability a compelling marketing advantage (Vermeir and Verbeke 2006).

Table 1 Greenhouse gas emission in food system

Food system	Activities	Percentage emission
Land use		24
	Land use for human food	8
	Land use for livestock	16
Crop production		27
	Crop for human food	21
	Crop for animal feed	6
Livestock and fisheries		31
	Livestock and fish farms	30
	Wild catch fisheries	1
Supply chain		18
	Food processing	4
	Transport	6
	Packaging	5
	Retail	3

(*Source* Bending the Curve: The Restorative Power of Planet-Based Diets; Loken 2020)

2 Challenges Faced by the Food Industry in Reducing Carbon Emissions

The food industry plays a very crucial role in contributing to global carbon emissions due to the complex and interconnected nature of its supply chains and diverse processes. The food industry encounters several challenges in achieving the desired carbon footprint reductions. These Challenges need to be understood in order to develop effective strategies to promote sustainability within this sector (Fig. 1).

Some of the key challenges that are faced by the food industry to reduce carbon emissions are as given under:

- Food supply chains involve multiple stakeholders, such as farmers, processors, distributors, and retailers, operating across different regions and hence are fragmented in nature. It would be challenging to coordinate among these entities, hindering the implementation of sustainability measures. Additionally, each stakeholder in this supply chain may have varying levels of awareness and commitment to sustainability, making it all the more difficult to establish stable carbon reduction strategies.
- The transportation, refrigeration, and processing involved in the food industry relies heavily on fossil fuels. While Fossil fuels are a significant contributor to carbon emissions, but alternative energy sources are neither easily accessible nor affordable. Hence, transitioning to other forms of renewable energy options would require hefty investments and changes in infrastructure.
- Methane is considered as a potent greenhouse gas in the process of livestock production. Looking for sustainable solutions to reduce emissions from livestock while meeting the growing demand for animal-based products is a complex issue (Garnett 2011).
- Expanding agricultural activities and food production often lead to increased carbon emissions due to change in land use and deforestation. Deforestation for agriculture, especially in sensitive ecological regions results in release of stored carbon into the atmosphere. Hence the harmonizing the need for increased food production with conservation of our natural resources poses a major challenge for the food industry (Searchinger et al. 2018).
- Food waste and loss throughout the supply chain account for a significant portion of carbon emissions in the food industry. The food wasted or lost is directly

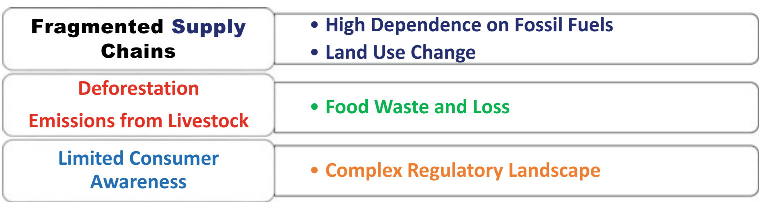

Fig. 1 Challenges faced by the food industry in reducing carbon emissions

proportional to the all the resources and energy invested in its production, transportation, and processing. Reducing food waste is a challenge which requires systemic changes and collaboration across the supply chain (Singh 2020).
- Prioritizing factors like price and convenience by consumers over environmental considerations makes the food industry hesitant to invest in sustainability initiatives that could raise costs without a guarantee of increased market share. Therefore, raising consumer awareness about the importance of sustainable food choices is essential for bringing about industry-wide change.
- Complex regulatory frameworks define the operational setups of the food industry that can vary significantly between countries and regions. Traversing through these regulations but at the same time attempting to implement sustainability measures may pose significant challenges for multinational food companies. It is thus essential to harmonize these regulations and set global sustainability standards to facilitate progress in reducing carbon emissions.

A collaborative approach and effort are required from all the stakeholders such as governments, businesses, farmers, consumers, and civil society organizations involved in the food industry. They must work together to promote sustainable practices, support research and innovation, and create a conducive environment for reducing carbon emissions. By overcoming these challenges, the food industry can make considerable strides towards achieving a more sustainable future.

3 Current Approaches to Sustainability in Food Processing

Sustainability has become a matter of grave concern for the food industry as it delves in to seeking solutions to reduce its environmental impact and promote responsible practices. Various approaches have been adopted to ensure sustainability in food processing, focussing on energy efficiency, waste reduction, and integration of renewable energy. Some of these approaches have shown potential in reducing the industry's carbon footprint and are discussed below:

1. ***Energy-Efficient Technologies***: Technologies such as energy-efficient lighting, advanced refrigeration systems, and improved heat exchangers have been implemented in the food processing facilities to minimize energy consumption during operations. This would not only ensure reduction in their carbon emissions but also significantly cut down the operational costs. The effectiveness of such energy-efficient technologies may however vary depending upon the scale of the facility and the availability of resources at hand. The smaller businesses may face financial barriers in adopting such technologies, hence limiting their effective widespread implementation.
2. ***Waste Reduction***: Food processing industry are increasingly adopting waste reduction measures into their operations. By minimizing food waste and utilizing by-products, processors can reduce greenhouse gas emissions associated with

waste decomposition and their disposal (Khedkar and Singh 2018). Initiatives such as waste-to-energy, like biogas production from organic waste, offer opportunities to generate renewable energy. However, effective waste management requires significant investment in infrastructure and may face regulatory impediments depending on the region.

3. ***Renewable Energy Integration***: Renewable energy offers a long-term and environmentally-friendly energy solution in any setting. The incorporation of renewable energy sources, such as solar, wind and biomass has gained momentum in sustainable food processing. Food companies are installing solar panels and biomass boilers to reduce their dependency on fossil fuels and lower emissions (Koppelmäki et al. 2022). However, the intermittent nature of certain renewable sources, like solar and wind, poses challenges for continuous food processing operations. Hence, to ensure a stable energy supply, solutions its storage and grid integration are needed.
4. ***Sustainable Packaging Solutions***: Sustainable packaging alternatives, such as biodegradable and compostable materials, are being explored by the food processing industry to reduce the environmental impact of packaging waste (Panou and Karabagias 2023). However, there would be limitations in the availability of sustainable packaging materials along with higher production costs. Hence a balance has to be established between sustainability and economic viability. Additionally, banning single-use plastics for packaging can significantly lower carbon emissions.
5. ***Supply Chain Optimization***: Optimization of supply chains is another approach adopted by the food industry to enhance sustainability. By reducing transportation distances, implementing efficient logistics and supporting local sourcing, lower emissions associated with food distribution can be achieved (Ghosh et al. 2020). However, achieving supply chain optimization may be challenging due to the complex nature of global food distribution networks. Balancing local sourcing with meeting consumer demand for diverse products can be logistically complex.

While there are various approaches that contribute to reducing carbon emissions in food processing, yet there are quite a few limitations that exist in achieving a comprehensive carbon footprint analysis. It has been observed that the analysis of carbon footprint is often limited to only the direct emissions within any given facility. However, emissions associated with the entire supply chain, which includes upstream activities like agricultural production and downstream activities like consumption of products and their disposal are neglected areas. Hence it becomes a challenging task to obtain accurate data on emissions throughout the supply chain.

Another challenge is the process of gathering comprehensive and standardized data on the carbon emissions from varied processes within the food industry. The variability in data collection and reporting practices may hamper consistent carbon footprint analysis thus making comparisons between facilities and products more challenging. The multiple and interconnected processes in the food processing industry may lead to unintended consequences, for example, the increasing energy efficiency

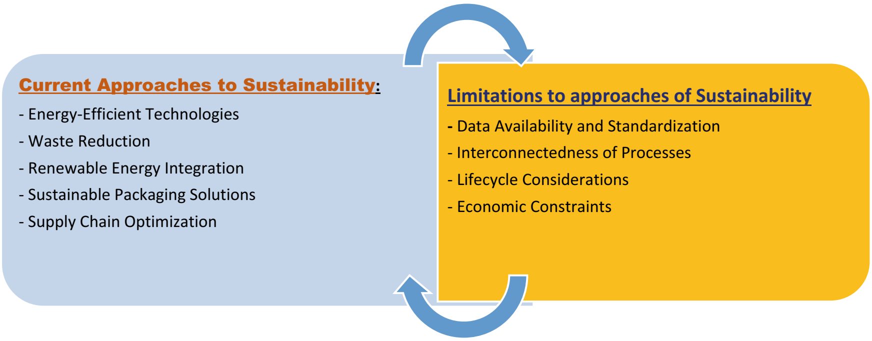

Fig. 2 Different approaches and limitations to sustainability in food processing

in one process may lead to increased demand for raw materials in another, thereby counterbalancing potential reduction in emissions.

It has been observed that carbon footprint analyses often focus on the immediate operational emissions but may disregard the long-term impacts of processes such as extraction, product life cycles, and end-of-life disposal. Hence, a more comprehensive lifecycle analysis is required for a holistic understanding of the impacts that it may have on the environment.

Additionally, sustainable practices, if adopted and practised by the food processing requires significant financial investments. This may be all the truer for small and medium-sized enterprises (SMEs) wherein the financial burden faced may be significant and hence may be an impediment in implementing these sustainability measures. Addressing these limitations through better data collection, lifecycle considerations, and targeted policies will enable the food industry to make more informed decisions and advance toward a more sustainable future (Fig. 2).

4 Developing a Customized Carbon Footprint Analysis Tool for Food Processing: Addressing the Unique Characteristics

As the food industry pursues to take on sustainability measures to reduce its environmental impact, the development of a specialized carbon footprint analysis tool custom-made for the food processing is essential (Dutilh and Kramer 2000). While the traditional carbon footprint analysis tools are unable to capture the intricacies and unique characteristics involved in the diverse processes in food production (Sharma et al. 2021), a customized tool can offer a suitable solution to the carbon emissions associated with the entire food supply chain, from farm to fork (Centre for Sustainable Systems 2022). Conducting GHG verification is essential for quantifying these emissions and identifying hotspots. Several international standards are applicable for measuring, managing, and reporting GHG emissions, including the Greenhouse Gas Protocol (GHG Protocol), (ISO 14064 2018), ISO 14067, PAS 2050, and PAS 2060 (Liu et al. 2023). The usefulness of these approaches depends on the specific goals, resources, and commitment to sustainability and emissions reduction of food industry stakeholders. Here, we discuss the need for such a specialized tool and explore the key parameters that should be included in it.

5 The Need for a Specialized Tool

- A specialized tool can assess the complexities involved in several operations, ranging from agricultural production and raw material sourcing to transportation, packaging, and distribution and provide a detailed breakdown of emissions, enabling targeted sustainability efforts.
- It can integrate data from different points, often spanning across multiple regions and involving various stakeholders and ensure a holistic analysis.
- A specialized tool can accommodate diverse food products each with its unique production processes and raw materials and their specific attributes.
- A customized tool can consider the carbon impact of waste management practices, followed in a food processing industry, such as composting or energy recovery, to provide a more accurate assessment.
- A specialized tool can help to identify carbon "hotspots" within food processing operations. By recognizing these high emissions areas, the concerned companies can prioritize targeted mitigation strategies and hence optimizing adequate resource allocation for obtaining the maximum impact.

6 Key Parameters to Include in the Tool

- Measurement of Energy Consumption: The tool should be able to measure energy consumption across all stages of food processing, including electricity, fuel, and other forms of energy which would be used for either heating, cooling, and/or processing.
- Raw Material Sourcing: Assess the carbon emissions associated with sourcing raw materials, accounting for transportation, land use change, and agricultural practices.
- Transportation: Calculate the emissions linked to the transportation of raw materials to the processing facility and the distribution of finished products to consumers and retailers.
- Packaging: Include the emissions arising from the production and disposal of packaging materials, considering alternatives for more sustainable packaging.

- Waste Generation and Management: Account for emissions from waste generation and analyse the carbon impact of various waste management methods, such as recycling or anaerobic digestion.
- Water Usage: Evaluate the carbon footprint of water usage throughout food processing, as water-intensive processes can indirectly contribute to emissions.
- Processing Techniques: Consider the carbon intensity of specific processing techniques and explore more energy-efficient alternatives.
- Renewable Energy Integration: Assess the potential for integrating renewable energy sources into food processing operations, such as solar panels or biomass boilers.
- Emission Factors: Utilize updated emission factors for different activities and processes to ensure accuracy in calculating emissions.
- Lifecycle Assessment: Adopt a lifecycle approach to assess emissions from the entire food supply chain, from agricultural production to the end of product life.

These key parameters when incorporated into a customized carbon footprint analysis tool, the food industry can obtain valuable data regarding its environmental impact and make suitable evidence-based decisions to enhance sustainability (Thyberg and Tonjes 2016; Thakur et al. 2021) adopt innovative practices, and ultimately contribute to a more sustainable future for food processing.

7 Measuring Carbon Emissions in Food Processing and Methodologies and CO_2 Equivalent Conversion

Measuring carbon emissions at each stage of food processing is very important and it involves various methodologies and calculation models. Accurate measurements of these emissions are crucial for understanding the impact of the various processes on the environment and to devise sustainability aspects within the food industry. These emissions need to be converted in to into a standardized unit of CO_2 equivalent (CO_2e), which plays a vital role in enabling comparisons and benchmarking, thus helping the concerned stakeholders to effectively assess their carbon footprints. Products of animal origin, such as meat and dairy, have on average higher emissions per kilogram than vegetable products and fruits. Beef and lamb meat have exceptionally high CF, followed by cheese, due to the contribution of CH_4 from enteric fermentation in ruminants. Meat from monogastric animals, such as pigs and poultry, shows lower CF values than products from ruminants, but still higher than most foods of vegetal origin, due the large amount of feed needed in livestock production and emissions from manure handling (Pandey et al. 2011) (Fig. 3).

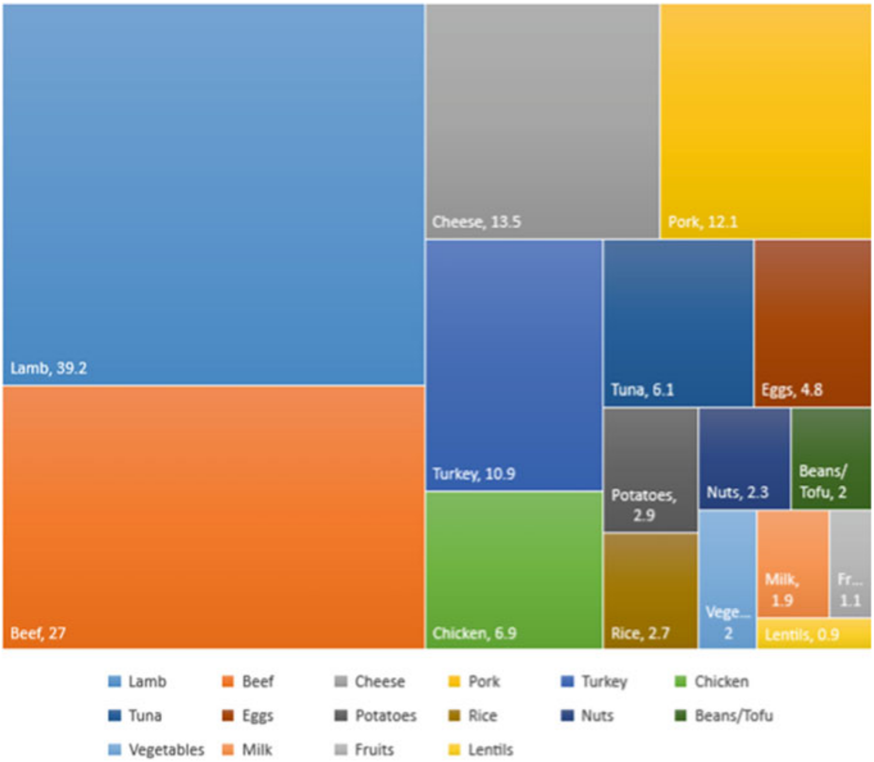

Fig. 3 The carbon footprint of different types of food

7.1 Methods for Quantifying Carbon Emissions

7.1.1 Direct Emissions

These emissions are released directly from sources owned or controlled by the company. Within the food processing industry, these emissions mainly arise from on-site combustion of fossil fuels for energy, emissions from refrigerants, and waste material treatment. Accordingly, measurement methods for direct emissions involve using emission factors specific to fuel types, equipment, or waste handling processes (IPCC 2013).

7.1.2 Indirect Emissions—Purchased Energy

Indirect emissions come from the generation of purchased electricity, heating, and cooling. To quantify such emissions in food processing, the concerned companies rely on data provided from utility providers or use standard emission factors for the regional energy mix (Cederberg and Stadig 2003; IPCC 2000; World Business Council for Sustainable Development and World Resources Institute 2005).

4.6.1.2.1 Indirect Emissions—Supply Chain

These emissions include all indirect emissions upstream and downstream in the food supply chain, which encompasses emissions from production of raw materials, transportation, packaging, distribution and also consumer use. The calculation of these emissions often requires collaboration with suppliers for obtaining data, transportation companies, and retailers. This makes it more complex and dependant on industry-specific data sets (International Organization for Standardization 2006).

8 Calculation Models for Carbon Emissions

- **Inventory–Based Approach**: This approach is most commonly used for direct and indirect emissions associated with energy use. This method involves compiling comprehensive data on activities, processes, and inputs involved in food processing. Emission factors are then applied to these data to calculate emissions.
- **Process–Based Approach**: This approach focuses on detailed process modelling to estimate emissions. This method is especially useful for complex processes with diverse emissions sources, such as livestock production, where enteric fermentation and manure management are significant sources of methane (Cederberg and Stadig 2003).
- **Input–Output Analysis**: This analysis employs economic data to estimate emissions based on the consumption of goods and services within the food industry. This method is valuable for assessing the upstream emissions embedded in the products used by a company (Cheng et al. 2022; Khasreen et al. 2009).

9 Significance of Converting Emissions to CO_2 Equivalent

Expressing emissions in a standardized unit like CO_2e is essential for facilitating comparisons and benchmarking across different processes, products, and companies. The conversion to CO_2e accounts for the varying global warming potentials (GWPs) of different greenhouse gases (GHGs) relative to carbon dioxide. For example, methane has a significantly higher GWP than carbon dioxide over a 20-year timespan, while nitrous oxide has a much higher GWP. This conversion of emissions to CO_2e allows the food industry for a fair comparison of the climatic impact of different gases and supports the companies to assess their overall carbon footprint more carefully and make informed decisions regarding emissions reductions, and compare performance against industry benchmarks. Utilizing appropriate methodologies and standardized units ensures transparent and accurate reporting, fostering a sustainable and environmentally responsible food supply chain.

10 Identifying Hotspots and Reduction Strategies for Carbon Footprint in Food Processing Industry

The carbon footprint analysis tool plays a very significant role in identifying emission "hotspots" in food processes, enabling companies to prioritize reduction efforts in the most impactful areas. By pinpointing the stages with the highest emissions, organizations can develop effective strategies for carbon footprint reduction and make substantial progress towards achieving their sustainability goals. In the section below discusses how the analysis tool facilitates hotspot identification and present effective reduction strategies, including energy-efficient technologies, sustainable sourcing, and waste management practices.

10.1 Identifying Hotspots Through the Analysis Tool

- **Collection of Granular Data**: The analysis tool allows for granular data collection from different stages of food processing, including energy consumption, transportation, raw material sourcing, and waste generation. This comprehensive data enables a detailed evaluation of emissions, helping identify stages with the most significant carbon footprints (ISO 14044 2006).
- **Life Cycle Assessment (LCA)**: The tool employs LCA principles to evaluate emissions across the entire food supply chain, from "farm to fork". This holistic approach uncovers indirect emissions and hidden hotspots that may not be apparent when only considering direct emissions (Dutilh and Kramer 2000).
- **Supply Chain Analysis**: By incorporating the indirect emissions upstream and downstream of a company's operations, the tool assesses emissions from suppliers, logistics, and distribution channels. This analysis helps identify emission hotspots beyond a company's immediate control (Greenhouse Gas Protocol 2023).

10.2 Effective Strategies for Carbon Footprint Reduction

- **Energy-Efficient Technologies**: Adopting energy-efficient technologies in food processing facilities can significantly reduce emissions. Implementing LED lighting, optimizing HVAC systems, and utilizing advanced machinery with low energy consumption are examples of effective measures.
- **Sustainable Sourcing**: Working with suppliers who adhere to sustainable agricultural practices can reduce the carbon footprint of raw materials. Companies can support farmers using eco-friendly techniques, such as regenerative agriculture, organic farming, and low-emission fertilizers.
- **Transportation Optimization**: Efficient transportation planning can lower emissions in the supply chain. Employing alternative transportation methods, route

optimization, and consolidating shipments can lead to reduced carbon emissions from distribution.

- **Waste Management Practices**: Implementing waste reduction and recycling programs can minimize emissions from waste disposal. Companies can explore options like composting organic waste, recycling packaging materials, and investing in anaerobic digestion to convert organic waste into energy (Elginoz et al. 2020).
- **Renewable Energy Integration**: Incorporating renewable energy sources, such as solar panels or wind turbines, into food processing facilities can significantly decrease carbon emissions associated with electricity consumption (Kliaugaite and Kruopienė 2018).
- **Process Optimization**: Conducting process-level analyses can identify opportunities for emissions reduction. Companies can modify or replace specific steps in food processing with more sustainable alternatives.

By utilizing the carbon footprint analysis tool, companies in the food processing sector can identify emission hotspots and implement targeted strategies for reduction. These strategies, ranging from energy-efficient technologies to sustainable sourcing and waste management practices, enable businesses to make significant strides towards a more environmentally sustainable and responsible food supply chain.

11 Challenges and Barriers in Implementing the Carbon Footprint Analysis Tool in Food Processing

While the carbon footprint analysis tool holds immense potential for driving sustainability in the food processing sector, its successful implementation may encounter certain challenges and barriers. Addressing these obstacles is crucial to ensure that companies can effectively utilize the tool to reduce their environmental impact. Some of the key challenges and barriers in implementing the carbon Footprint analysis tool in food processing are as given below:

- **Data Accuracy and Availability:**

Obtaining accurate and comprehensive data from various stages of the food supply chain can be challenging as the data may be distributed among the various stakeholders which may result in inconsistencies and may affect the accuracy of the analysis. This however can be overcome by collaborating with suppliers, industry partners and other relevant stakeholders to collect standardized data and maintaining transparency and reliability in the data obtained. Data management systems and making use of technologies like block chain for data verification can aid in maintaining the integrity of the data (Kamilaris et al. 2019; Xiong et al. 2020).

- **Cost Implications:**

Initial investments in the implementation of the carbon footprint analysis tool and subsequent sustainability are something which every company will have to take on themselves which will be perceived as a financial burden for them. However, if these companies can consider this prospect as a long-term investment, it may lead to cost savings in the long run. An example of this prospect would be if an adoption of energy-efficient technologies can lower operational costs through reduced energy consumption (Naud et al. 2020).

- **Resistance to Change:**

A common barrier that is often encountered when adopting new sustainability practices and tools is the *r*esistance to change. There would an initial hesitation to adjust to new processes or adopt sustainable strategies. This however can be addressed via effective communication, providing training and involving employees in the decision-making processes (World Health Organization 2016).

- **Lack of Expertise:**

The concerned companies may lack expertise in conducting carbon footprint analysis and interpreting the results in-house. Such issues can be addressed by seeking external experts or consultants from other institutes or research organizations and Universities to bridge this knowledge gap and ensure accurate analysis.

- **Limited Industry Standards:**

There is a lack of uniform industry standards for measuring and reporting carbon footprint. This may pose as a challenge for measuring and reporting carbon footprints and may hinder benchmarking and comparison among different companies. The active engagement with industry associations and participation in sustainability initiatives can help drive the establishment of standardized methods and benchmarks. Encouraging industry-wide adoption of reporting frameworks, such as the Greenhouse Gas Protocol, can promote consistency and comparability (World Business Council for Sustainable Development and World Resources Institute 2005).

12 Future Prospects and Industry Adoption of the Carbon Footprint Analysis Tool in the Food Industry

The widespread adoption of the carbon footprint analysis tool in the food industry holds immense potential to drive transformative change, improve sustainability practices, and contribute significantly to global efforts in mitigating climate change. As more companies embrace the tool, it can stimulate innovation, facilitate informed decision-making, and foster a collective commitment to reducing carbon emissions.

The analysis tool can serve as a catalyst for innovation within the food industry. By identifying carbon emission hotspots and inefficiencies, companies are encouraged to explore new technologies, processes, and materials that offer lower environmental impacts. This drive for innovation can lead to the development of energy-efficient equipment, sustainable packaging solutions, and novel waste management practices (Elginoz et al. 2020; Garcia-Garcia et al. 2019). Sustainable practices are likely to become a key competitive advantage for companies. With consumers increasingly valuing sustainability and demanding eco-friendly products, companies that actively reduce their carbon footprint and demonstrate commitment to environmental stewardship will gain a positive brand image, enhanced consumer loyalty, and increased market share (Gareth Edwards-Jones et al. 2010).

The analysis tool provides valuable data and insights that empower companies to make well-informed decisions about their operations and supply chain. Armed with comprehensive information on carbon emissions, organizations can optimize transportation routes, choose eco-friendly suppliers, and streamline production processes to minimize environmental impacts. Transparency across the supply chain becomes more attainable with the tool's adoption. Companies can collaborate with suppliers and stakeholders to collectively address emissions hotspots, fostering a shared commitment to sustainability throughout the food supply chain (Lundie and Peters 2005).

The food industry plays a significant role in global greenhouse gas emissions. By adopting the carbon footprint analysis tool and implementing reduction strategies, the industry can make substantial contributions to global climate change mitigation efforts. Collectively, these efforts can help nations achieve their targets outlined in international climate agreements (Göbel et al. 2015; Sharma et al. 2021). As the adoption of the analysis tool becomes more widespread, aggregated data from multiple companies can offer valuable insights into industry-wide emission trends and inform policymakers about the most effective measures for reducing emissions in the food sector (Ghosh et al. 2020).

The adoption of the analysis tool can foster collaborative initiatives among companies, industry associations, and governments to address broader sustainability challenges. Companies may work together to establish industry-wide carbon reduction targets, share best practices, and develop sustainable sourcing initiatives (IPCC 2013). The impact of the tool's adoption is not limited to the food industry alone. Similar analysis and sustainability practices can be extended to other sectors, creating a broader cross-industry impact in combating climate change (Scarborough et al. 2014).

The widespread adoption of the carbon footprint analysis tool has the potential to revolutionize the food industry's sustainability practices, stimulate innovation, and make significant contributions to global climate change mitigation. By promoting informed decision-making, fostering collaboration, and inspiring cross-industry impact, the tool can pave the way for a more sustainable and environmentally responsible future for the food industry and beyond.

References

Birch EL (2014) A review of "Climate change 2014: impacts, adaptation, and vulnerability" and "Climate change 2014: mitigation of climate change." J Am Plann Assoc 80(2):184–185. https://doi.org/10.1080/01944363.2014.954464

Cederberg C, Stadig M (2003) System expansion and allocation in life cycle assessment of milk and beef production. Intern J Life Cycle Assess 8(6):350–356. https://doi.org/10.1007/BF02978508

Centre for Sustainable Systems (2022) Carbon footprint factsheet. University of Michigan Pub. No. CSS09-05. https://css.umich.edu/publications/factsheets/sustainability-indicators/carbon-footprint-factsheet. Last Accessed 14 Aug 2023

Cheng B, Lu K, Li J, Chen H, Luo X, Shafique M (2022) Comprehensive assessment of embodied environmental impacts of buildings using normalized environmental impact factors. J Clean Produ 334:130083. https://doi.org/10.1016/j.jclepro.2021.130083

Deconinck K (2018) Carbon footprints for food systems. Diet to save: our food system is fuelling climate change; are we ready to switch to a new diet? https://www.downtoearth.org.in/news/climate-change/diet-to-save-our-food-system-is-fuelling-climate-change-are-we-ready-to-switch-to-a-new-diet--74726. Last Accessed 16 Aug 2023

Dutilh CE, Kramer KJ (2000) Energy consumption in the food chain: comparing alternative options in food production and consumption. AMBIO J Human Environ 29(2):98–101. https://doi.org/10.1579/0044-7447-29.2.98

Edwards-Jones G, Edwards-Jones G, Jensen MF (2010) Carbon footprint and food systems: do current accounting methodologies disadvantage developing countries? World Bank 1:57

Elginoz N, Khatami K, Owusu-Agyeman I, Cetecioglu Z (2020) Life cycle assessment of an innovative food waste management system. Front Sustain Food Syst 4:57. https://www.frontiersin.org/articles/. https://doi.org/10.3389/fsufs.2020.00023

FAO, IFAD, UNICEF, WFP and WHO (2020) The state of food security and nutrition in the world 2020. In: Transforming food systems for affordable healthy diets, vol 1. Rome, FAO pp 1–237. https://doi.org/10.4060/ca9692en

Garcia-Garcia G, Stone J, Rahimifard S (2019) Opportunities for waste valorisation in the food industry–a case study with four UK food manufacturers. J Cleaner Prod 211:1339–1356. https://doi.org/10.1016/j.jclepro.2018.11.269

Garnett T (2011) Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Pol 36:S23–S32. https://doi.org/10.1016/j.foodpol.2010.10.010

Ghosh P, Jha A, Sharma R (2020) Managing carbon footprint for a sustainable supply chain: a systematic literature review. Mod Supp Chain Res Appl 2(3):123–141. https://doi.org/10.1108/MSCRA-06-2020-0016

Göbel C, Langen N, Blumenthal A, Teitscheid P, Ritter G (2015) Cutting food waste through cooperation along the food supply chain. Sustainability 7(2):2. https://doi.org/10.3390/su7021429

Greenhouse Gas Protocol (2023) World resources institute. https://www.wri.org/initiatives/greenhouse-gas-protocol. Last Accessed 14 Aug 2023

IPCC (2000) Good practice guidance and uncertainty management in national greenhouse gas inventories. Intergovernmental Panel on Climate Change p 35

IPCC (2013) Climate change 2013: the physical science basis. In: Stocker TF, Qin D, Plattner GK, Tignor MM, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom, New York, USA, p 1535. https://www.ipcc.ch/report/ar5/wg1/. Last Accessed 14 Aug 2023

ISO 14044:2006 (2006) Environmental management—life cycle assessment—requirements and guidelines. https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en. Last Accessed 14 Aug 2023

ISO 14064-1:2018 (2018) Greenhouse gases: specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals, vol 2, p 45. https://www.iso.org/standard/66453.html. Last Accessed 14 Aug 2023
Kamilaris A, Fonts A, Prenafeta-Boldú F (2019) The rise of blockchain technology in agriculture and food supply chains. Trend Food Sci Technol 91. https://doi.org/10.1016/j.tifs.2019.07.034
Khasreen MM, Banfill PG, Menzies GF (2009) Life-cycle assessment and the environmental impact of buildings: a review. Sustainability 1(3):28. https://doi.org/10.3390/su1030674
Khedkar R, Singh K (2018) Food industry waste: a panacea or pollution hazard? In: Jindal T (ed) Paradigms in pollution prevention, vol 1. Springer International Publishing pp 35–47. https://doi.org/10.1007/978-3-319-58415-7_3
Kliaugaite D, Kruopienė J (2018) Food waste generation and prevention measures in retail sector: a comparative study. Environ Res Engg Manag 73. https://doi.org/10.5755/j01.erem.73.4.19941
Koppelmäki K, Hendriks M, Helenius J, Kujala S, Schulte RPO (2022) Food-energy integration in primary production and food processing results in a more equal distribution of economic value across regional food systems: Nordic case study from circular perspective. Circul Econ Sustain. https://doi.org/10.1007/s43615-022-00233-2
Liu TC, Wu YC, Chau CF (2023) An overview of carbon emission mitigation in the food industry: efforts, challenges, and opportunities. Processes 11(7):7. https://doi.org/10.3390/pr11071993
Loken B et al (2020) Bending the curve: the restorative power of planet-based diets by WWF. WWF, Gland, Switzerland. https://www.worldwildlife.org/publications/bending-the-curve-the-restorative-power-of-planet-based-diets. Last Accessed 16 Aug 2023
Lundie S, Peters GM (2005) Life cycle assessment of food waste management options. J Clean Prod 13(3):275–286. https://doi.org/10.1016/j.jclepro.2004.02.020
Naud O, Taylor J, Colizzi L, Giroudeau R, Guillaume, Bourreau E, Crestey T, Tisseyre (2020) Support to decision making. In: Castrignanò G, Buttafuoco G, Khosla R, Mouazen A, Moshou D, Naud O (eds) Agricultural Internet of Things and decision support for precision smart farming. Academic Press pp 183–224. https://doi.org/10.1016/B978-0-12-818373-1.00004-4
Pandey D, Agrawal M, Pandey JS (2011) Carbon footprint: current methods of estimation. Environ Monit Assess 178(1):135–160. https://doi.org/10.1007/s10661-010-1678-y
Panou A, Karabagias IK (2023) Biodegradable packaging materials for foods preservation: sources, advantages, limitations, and future perspectives. Coatings 13(7):7. https://doi.org/10.3390/coatings13071176
Scarborough P, Appleby PN, Mizdrak A, Briggs ADM, Travis RC, Bradbury KE, Key TJ (2014) Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Climc Chan 125(2):179–192. https://doi.org/10.1007/s10584-014-1169-1
Searchinger TD, Wirsenius S, Beringer T, Dumas P (2018) Assessing the efficiency of changes in land use for mitigating climate change. Nature 564(7735):249–253. https://doi.org/10.1038/s41586-018-0757-z
Sharma VK, Sachdeva A, Singh LP (2021) A meta analysis of sustainable supply chain management from different aspects. Intern J Supply Oper Manag 8(3). https://doi.org/10.22034/ijsom.2021.3.4
Singh K (2020) Sustainable food waste management: a review. In: Thakur M, Modi VK, Khedkar R, Singh K (eds) Sustainable food waste management: concepts and innovations, vol 1. Springer pp 3–19. https://doi.org/10.1007/978-981-15-8967-6_1
Thakur M, Modi V, Khedkar R, Singh K (2021) Sustainable food waste management: concepts and innovations. Springer. https://doi.org/10.1007/978-981-15-8967-6
Thyberg KL, Tonjes DJ (2016) Drivers of food wastage and their implications for sustainable policy development. Technol Soc Fac Publ 1–29. https://commons.library.stonybrook.edu/techsoc-articles/11
Tukker A, Goldbohm RA, de Koning A, Verheijden M, Kleijn R, Wolf O, Pérez-Domínguez I, Rueda-Cantuche JM (2011) Environmental impacts of changes to healthier diets in Europe. Ecol Econ 70(10):1776–1788. https://doi.org/10.1016/j.ecolecon.2011.05.001

Vermeir I, Verbeke W (2006) Sustainable food consumption: exploring the consumer "Attitude–behavioral intention" Gap. J Agricul Environ Ethics 19(2):169–194. https://doi.org/10.1007/s10806-005-5485-3

World Business Council for Sustainable Development, World Resources Institute (2005) The greenhouse gas protocol: the GHG protocol for project accounting. World Business Council for Sustainable Development; World Resources Institute

World Health Organization (2016) Global strategy on human resources for health: workforce 2030. World Health Organization. https://apps.who.int/iris/handle/10665/250368

Xiong H, Dalhaus T, Wang P, Huang J (2020) Blockchain technology for agriculture: applications and rationale. Front Blockchain 3. https://www.frontiersin.org/articles/. https://doi.org/10.3389/fbloc.2020.00007

Food Sustainability: Challenges and Strategies

Shalini Sehgal, Sunita Aggarwal, Pragya Kaushik, Shalini Trehan, and Deepanshu

1 Introduction

Food sustainability encompasses multiple aspects and key issues related to ecology, economy, and society. Developing countries often prioritize food safety, while developed countries focus on trade and regional approaches (Brown et al. 1987). Common features associated with sustainability include the support of human life on Earth, the long-term preservation of biological resources and agricultural productivity, stable human populations, limited growth economies, an emphasis on small-scale and self-reliance, and the maintenance of environmental quality and ecosystems. Improving the sustainability of food production is of utmost importance. It is suggested that food multinationals transfer some democratic control over their global environmental policies to achieve this. The World Commission on Environment and Development emphasizes that sustainable development must consider the environment's ability to meet present and future human demands, along with the concept of social justice, while addressing ecological, economic, and sustainability aspects (Langhelle 2000).

It is crucial to view sustainability as a challenge rather than an unchanging state, as it involves preserving the resilience and adaptability of natural systems (Tilman et al. 2002). Environmental pressures linked to food sustainability are influenced by system

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boundaries. Analytical tools such as Life Cycle Analysis (LCA) can help assess the technological feasibility and societal acceptability of sustainability measures.

Promoting food sustainability ensures that the Earth can provide for current and future generations. Additionally, it leads to healthier outcomes for both humans and the environment. There is a growing recognition of the need for sustainable diets and food systems that support human health while addressing interconnected challenges related to food production, procurement, preparation, consumption, and waste (Downs et al. 2020). Shifting dietary patterns to protect the environment is a key objective while providing healthy, culturally appropriate, and desirable food (Ahmed et al. 2020).

Sustainability has become increasingly important in response to pressing global issues such as poverty, climate change, environmental pollution, and the finite nature of natural resources (Buerke et al. 2017). Over time, various definitions and perspectives on sustainability have emerged.

2 Defining Sustainability and Its Importance

Sustainability, as defined by the United Nations, refers to the practice of agriculture and food preparation that minimizes waste of natural resources and ensures the ability to continue these practices without harm to the environment or human health. Food sustainability is dependent on the development of sustainable food systems, which encompass various interconnected subsystems such as farming, waste management, and supply chains. It is a global concern for present and future generations, encompassing all living species on Earth. The concept of sustainability was first introduced in the Brundtland Report (1987), which emphasized the goal of meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. However, sustainability has also been associated with the idea of "green and good," representing efforts to build community-based, healthy food systems (Kloppenburg et al. 2020).

3 Food Sustainability Challenges

The complex nature of food systems requires a coordinated approach. The main problems to be addressed in terms of food security and nutrition necessitate collaborative solutions across disciplinary, divisional, and institutional boundaries. In increasingly globalized food systems, these challenges arise from interactions across different scales and levels, demanding integrated actions by all stakeholders at local, national, regional, and global levels. This applies to both public and private sectors, encompassing various fronts, including agriculture, trade, policy, health, environment,

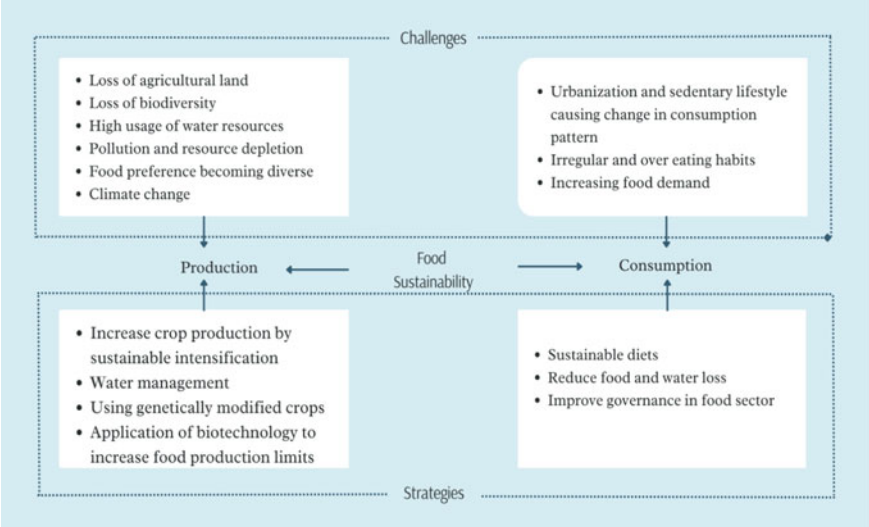

Fig. 1 Food sustainability—challenges and strategies

gender norms, education, transport, infrastructure, and more. Achieving food sustainability requires a synergistic merging of ideas from these various angles, rather than a destructive clash (Fig. 1).

3.1 Food Production

The challenge can be conceptualized as follows: the human population is growing and urbanizing. We are increasingly becoming net consumers, and a diminishing proportion of the world's population will engage in farming, at least as their primary activity, in the coming years. As incomes rise, people's food preferences are changing, with an increasing demand for meat and dairy products. Meeting this demand may require a 60–110% increase in food production by 2050 overall (Tilman et al. 2011; Alexandratos and Bruinsma 2012). Simultaneously, it is crucial to reduce environmental damage caused by food production, including both direct impacts and those related to deforestation. More food must be produced to feed urban consumers on existing farmland in ways that minimize excessive environmental costs. Technological innovations and managerial changes are considered key factors in reducing environmental impacts and increasing supply. In agriculture, the main strategies include measures to improve efficiency, such as precise matching of inputs (fertilizers, water, and pesticides) to outputs (plant or livestock requirements), technologies for recovering energy from agricultural waste (such as anaerobic digestion), and farming practices that sequester carbon in soils (Shafer et al. 2011). Furthermore, postharvest emissions can be reduced through the development of refrigeration, manufacturing, and transport technologies that are more energy efficient or based on renewable energy sources. Waste can be minimized through better inventory management, modifications to packaging and portion sizes, and other approaches that prolong the shelf life of foods or help consumers reduce food waste in other ways (Garnett 2013). Currently, this perspective dominates the discourse on food sustainability.

3.2 Food Consumption

In a second framing of the food sustainability challenge, the focus shifts to the end point in the supply chain—the consumer. This perspective emphasizes that excessive consumption, particularly of high-impact foods such as meat and dairy products, is a leading cause of the environmental crisis we face. Technological improvements alone will not be sufficient to address this problem. This view is shared by many within the animal welfare and environmental movements (Hamerschlag 2011; Thomas 2010). By 2050, the growth of the livestock sector could push the planet to a point where humanity's biological existence is threatened. It is therefore concluded that per capita meat consumption in 2050 may need to be between 20 and 40% of current levels (Pelletier and Tyedmers 2010). While demand may need to be restrained for environmental reasons, this perspective also highlights research findings that reduced consumption of livestock products would benefit human health (Friel et al. 2009). Unlike the production efficiency framing, the demand restraint perspective explicitly links the health and environmental agendas, often considering the relationship as synergistic. Stakeholders advocating for demand restraint argue that predominantly plant-based diets are healthier, citing studies showing that people who consume fewer animal products, including vegetarians, tend to be healthier across various indicators, although the reasons for this may be complex (Millward and Garnett 2010). They also refer to studies demonstrating that plant-based diets can provide an adequate balance of key nutrients at a lower greenhouse gas "cost" than meat-dominated diets (Carlsson-Kanyama and González 2009; Davis et al. 2010, Edwards and Roberts 2009). Measures to address this problem could yield both environmental and health benefits. Notably, this perspective strongly emphasizes diet-related chronic diseases associated with animal products and prevalent in many parts of the world, particularly cities (Popkin 1999). It places less emphasis on the on-going problem of hunger and micronutrient deficiencies that still affect millions of impoverished people worldwide, especially in rural communities. Importantly, the context for studies comparing vegetarians or low-meat eaters with their high meat-eating counterparts assumes that citizens typically have access to a diverse range of plant-based foods, including vegetables, fruits, legumes, and meals specifically formulated for vegetarians. The situation is vastly different in low-income developing countries, where diets are often monotonous and lack diversity. Reorienting dietary patterns in these regions would require fiscal and regulatory measures, such as taxes and subsidies on certain foods, and potentially even bans on specific foods or farming practices like intensive livestock production.

3.3 Socioeconomic Challenges

The production efficiency perspective focuses on changing production patterns, while the demand restraint perspective addresses excessive consumption. The food system transformation perspective considers both production and consumption in terms of the relationships among sectors in the food system, viewing the problem as an "imbalance." The concern lies not only with production or consumption alone but with the unequal relationships between producers and consumers, both across and within countries and communities. This inequality leads to the dual problems of excess and insufficiency, evident in both environmental issues (over- and under-application of agricultural inputs) and health (obesity and hunger). These problems are socio-economic in nature, stemming from dynamic interactions among natural, technological, behavioral, and economic systems, rather than being merely technical or a consequence of individual decisions (Lang 2009). This perspective encompasses a wide range of opinions, with some analyses of the problems and visions for solutions being more radical than others. Some adopt a macro perspective, focusing on trading relations between nations, while others concentrate on local contexts (Foresight, U. K. 2011). However, they all argue that achieving food system sustainability requires changing the socio-economic governance of the food system. A comprehensive range of interventions will be necessary, including "hard" measures such as regulations and fiscal instruments, as well as "soft" approaches like voluntary agreements, awareness-raising, and education (Kassam 2008; Bailey 2011). Given that food sustainability problems stem from imbalances and inequities, focusing solely on increasing production is unlikely to improve food security.

4 Strategies to Address Sustainability Challenges

Addressing sustainability challenges is crucial for the well-being of our planet and future generations. With the increasing complexities of global issues such as climate change, resource depletion, and social inequalities, it is imperative to develop effective strategies that can drive meaningful change. These strategies encompass a wide range of approaches and actions, involving various sectors and stakeholders. By adopting a multi-faceted and integrated approach, we can tackle sustainability challenges at local, national, and global levels. In this context, this article explores key strategies that can contribute to a more sustainable future, including agroforestry, transgenic technology, and food loss prevention and control, and policy regulations. By implementing these strategies, we can pave the way for a resilient, thriving, and environmentally conscious world.

4.1 Agroforestry

Agroforestry, the intentional integration of trees, agricultural or horticultural crops, and/or animals on the same land, has evolved over the past four decades from a traditional practice to a science-based solution for efficient resource management. While specific practices may vary across countries based on farmers' needs and circumstances, the primary objective remains maximizing land utilization while providing ecological and environmental benefits (Jose 2009). Agroforestry practices, such as maintaining year-round vegetative soil cover and preserving soil organic matter, contribute to soil fertility (Boffa 1999). Additionally, nutrient cycling through nitrogen fixation enhances nutrient supply (Barnes and Fagg 2003). The presence of deep-rooted trees improves soil physical conditions and promotes soil microbial activity (Ramachandran et al. 2009). By reducing pressure on natural forests, agroforestry also aids in tropical biodiversity conservation. Farmers value the system not only for its ability to generate revenue through the sale of tree products but also for its capacity to produce various other products that would otherwise need to be purchased (Ashley et al. 2006). Recognized for its potential to ensure food security in impoverished nations and contribute to global environmental sustainability, agroforestry offers numerous benefits.

4.2 Transgenic Technology

Scientific research has opened the way to technological innovations that have deeply impacted society and one field that has emerged as a standout is biotechnology. Biotechnology involves harnessing biological systems, live organisms, or their derivatives to create or modify products and processes for specific purposes (Bell 1992). Within this realm, transgenic technology has gained prominence, where genetic material from one organism is transferred to another without the need for sexual mating. Since the mid-1990s, the commercial production of transgenic crops has experienced significant growth, with proponents claiming potential benefits such as improved food security through higher yields and increased income for farmers. This growth has been extraordinary, witnessing an astounding 80-fold increase between 1996 and 2009 (Vij and Tyagi 2007). At present, transgenic technology finds wide application in plant breeding, covering approximately 134 million hectares across 25 countries, with an annual growth rate of 7%. The potential of this technology to revolutionize agricultural practices and ensure a secure and sustainable food supply is widely anticipated.

One notable advantage of transgenic crops lies in their ability to develop drought-tolerant varieties. Advances in functional genomics have enabled scientists to identify genes involved in abiotic stress, such as cold or heat, and incorporating these genes into crops like maize and rice has shown promising results in achieving high yields with reduced water consumption (Nelson et al. 2007; Hu et al. 2006;

Oerke 2006). Additionally, transgenic Bacillus thuringiensis (Bt) crops have demonstrated increased resistance against insect pests, nematodes, and rodents, leading to improved yields and profitability compared to non-Bt varieties (Raybould and Quemada, 2010; Duan et al. 2008). The decreased reliance on pesticides in Bt fields has also contributed to enhanced biodiversity. Currently, the most prevalent genetically modified traits in transgenic crops are herbicide tolerance and pest resistance, which are found in soybean, cotton, maize, and canola (Wolfenbarger et al. 2008).

Beyond sustainable food production, transgenic technology holds promise in addressing nutritional deficiencies. Studies have shown that through multi-gene metabolic engineering, the levels of essential nutrients, such as carotenoids, can be boosted in edible plant tissues. The absence of these nutrients in staple foods contributes to preventable blindness affecting millions of people each year (Akhtar et al. 2003). Furthermore, transgenic crops have the potential to mitigate climate change by reducing greenhouse gas emissions through a decreased reliance on fossil-based fuels associated with lower pesticide and herbicide usage. Moreover, adopting conservation tillage practices in biotech crops contributes to increased soil carbon sequestration. These examples underscore the substantial potential of transgenic crops in reducing poverty, enhancing food security, and promoting environmental sustainability. While concerns persist regarding the long-term impacts of transgenic food, no compelling evidence has emerged to substantiate these concerns since its introduction 15 years ago.

4.3 Food Loss Prevention and Control

Food loss prevention and control are crucial strategies aimed at reducing the amount of food wasted throughout the entire food supply chain, from production to consumption. Food loss refers to the decrease in the quantity or quality of food caused by inefficiencies or failures at any stage of the supply chain, excluding intentional decisions to reduce the amount of food available for consumption. Food waste, on the other hand, refers to the discarding of edible food by retailers, food service establishments, and consumers.

Addressing it as a paramount importance due to its significant social, economic, and environmental implications. It is estimated that approximately one-third of the food produced globally is lost or wasted, which amounts to around 1.3 billion metric tons per year. This staggering number leads to alleviate hunger and malnutrition but also has adverse consequences on natural resources, greenhouse gas emissions, and climate change.

Implementing effective strategies to prevent and control food loss requires a comprehensive approach that involves various stakeholders, including farmers, processors, retailers, consumers, and policymakers.

Addressing food loss and waste is of utmost importance due to its significant social, economic, and environmental implications. Globally, it is estimated that approximately one-third of the food produced is lost or wasted, amounting to around

1.3 billion metric tons per year. This wastage occurs during postharvest mishandling, spoilage, and household waste. Such a staggering amount of food loss and waste not only represents missed opportunities to alleviate hunger and malnutrition but also has adverse consequences on natural resources, greenhouse gas emissions, and climate change.

The complexity of the problem of postharvest loss varies widely from place to place. However, a substantial portion of these losses can be prevented or controlled. A crucial first step towards an appropriate strategy for prevention or control is obtaining a thorough understanding of the production and handling systems in the food supply chain. In developing countries, the lack of infrastructure has been identified as a major contributing factor to food loss. Therefore, it is imperative for governmental bodies to support the construction of facilities like cold storage in areas that currently lack such infrastructure, thus preventing future losses. Similarly, non-functional facilities in need of maintenance should receive adequate funding for repairs and maintenance, ensuring their proper operation with regular monitoring plans (Hodges et al. 2011).

Implementing effective strategies to prevent and control food loss requires a comprehensive approach that involves various stakeholders, including farmers, processors, retailers, consumers, and policymakers. To address transportation challenges, for example, the development of networks of all-weather feeder roads can provide cheaper and faster access to markets, thereby reducing potential future losses, particularly in regions like Africa where transportation costs are significantly higher than in other parts of the world (Celata 2009). Introducing mechanized systems in production methods can also help reduce time and labor, contributing to decrease losses. Developed countries, with their advanced handling technology, can offer assistance to developing nations in adopting more efficient practices.

Furthermore, food waste generated by developed countries can be better managed through system plans. Food industries and supermarkets can implement computerized stock control systems that promptly alert them to stock volumes, enabling timely stock rotations (Houghton and Portougal 1997). Encouraging studies on national-level food waste generation can help categorize household wastes as “avoidable,” “possibly avoidable,” and “unavoidable” (WRAP 2009). Improving consumer knowledge through awareness campaigns about the consequences of food waste is vital in minimizing wastage. By addressing these aspects and promoting collaboration among stakeholders, it is possible to make significant strides in preventing and controlling food loss and waste. This concerted effort will not only help tackle hunger and malnutrition but also contribute to resource conservation, reduced greenhouse gas emissions, and a more sustainable food system.

4.4 Policy Regulations

Food security is not solely dependent on the capacity for food production but also on the principles of equity and environmental sustainability (Martins 2009). Policy regulation plays a crucial role in providing guidance and actions to combat food insecurity. However, in many developing countries, despite the existence of food security policies, there is often a lack of effective implementation to achieve the desired goals. Successful policy implementation, as highlighted by Garn (1999), depends on factors such as effective communication, adequate financial resources, the attitudes of implementers, and bureaucratic structures.

One of the challenges is that food is often perceived as a business commodity rather than a fundamental human right. The sharp increase in food prices in 2008 and the subsequent impact of the 2009 global economic crisis further exacerbated the issue of food insecurity, pushing an additional 100–200 million people into hunger. While the problem affected both developed and developing nations, developed nations were able to mitigate the insecurity levels through food aid in the form of direct relief and subsidized food production. It is essential for policymakers in developing nations to implement similar approaches, ensuring that they are driven by a genuine intention to benefit the population as an immediate remedy.

Long-term strategies should focus on reducing domestic food prices through changes in food policies, tax cuts on staple food imports, and the creation of job opportunities for vulnerable populations. Cooperation between nations and compassionate policy approaches targeting the global vulnerable population can significantly reduce hunger levels. Moreover, policy regulations that impose unnecessary restrictions on beneficial technologies should be relaxed, allowing for the utilization of science-based technological innovations to address food insecurity issues (Premanandh 2011). As there is no central governing agency authorized to ensure global food security, efforts from organizations such as the World Food Programme (WFP), the Food and Agriculture Organization (FAO), and the United Nations Children's Fund (UNICEF) should be further strengthened by involving more voluntary organizations to address the issue. Global food security strategies and policy implementations should identify food-surplus and food-deficit countries and structure interventions accordingly. Stringent restrictions on the import/export of food commodities may need to be temporarily relaxed, with the aim of establishing more permanent agreements through comprehensive reviews.

4.5 Sustainable Intensification

The concept of sustainable intensification recognizes the need to meet the growing global demand for food while addressing the challenges of climate change, land degradation, water scarcity, and biodiversity loss. It emphasizes the integration of sustainable agricultural practices, such as precision farming, agro ecology, conservation agriculture, and improved livestock management, with the goal of achieving higher yields and economic returns without compromising long-term sustainability (Royal Society 2009; Garnett and Godfray 2012; Smith 2013).

Key principles of sustainable intensification include:

(A) ***Productivity***: Increasing agricultural productivity through the use of improved crop varieties, modern farming techniques, and efficient resource management. This can involve precision agriculture technologies, such as satellite imagery, soil sensors, and GPS or AI-guided machinery, to optimize inputs and reduce waste (Pretty 2008)

(B) ***Efficiency***: Enhancing resource use efficiency by minimizing waste, reducing water consumption, improving nutrient management, and optimizing energy use. This involves adopting practices such as drip irrigation, nutrient recycling, and energy-efficient machinery to minimize environmental impacts.

(C) ***Resilience***: Building resilient agricultural systems that can withstand climate variability and shocks. This includes practices such as crop diversification, agroforestry, and conservation measures to enhance ecosystem services, improve soil health, and reduce vulnerability to pests, diseases, and extreme weather events.

(D) ***Environmental conservation***: Conserving and enhancing biodiversity, protecting natural habitats, and promoting sustainable land and water management practices. This can involve the preservation of natural areas, the restoration of degraded lands, and the promotion of sustainable agro-ecosystems that support biodiversity and ecological balance (Milder et al. 2012)

(E) ***Socioeconomic considerations***: Ensuring that sustainable intensification practices are socially and economically viable for farmers, contribute to rural development, and support equitable access to resources and benefits. This includes providing access to knowledge, technologies, markets, and financial services for smallholder farmers and promoting inclusive and participatory approaches to decision-making.

According to FAO (2013) Sustainable intensification is seen as a pathway towards achieving global food security while reducing the environmental footprint of agriculture. By adopting innovative and sustainable practices, farmers can increase agricultural productivity, improve livelihoods, reduce greenhouse gas emissions, protect biodiversity, and conserve natural resources. However, it is essential to tailor sustainable intensification approaches to local contexts, considering specific agro ecological conditions, socio-economic factors, and cultural considerations to ensure their effectiveness and acceptance.

5 Food Production Challenges

The ever-growing human population affects the food demand which is increasing drastically. The rising urbanization is also a challenge. As people's incomes are on a rise, their food preferences are becoming diverse, hence various meats and dairy foods are required. It is assumed that this demand will rise by 60–110% by 2050 and in the upcoming years more people will be working in the agriculture sector to fulfill the consumers' needs. Concurrently, environmental damages caused due to food production have to be dealt (Tilman et al. 2011; FAO 2012).

The major risks to sustainability food security are the loss of agricultural land, loss of biodiversity, high usage of water resources, pollution and resource depletion. These challenges have an impact of climate change which further changes the geography of food production globally.

Loss of agricultural land: By the emergence of competing pressures on land, linked to the search for the alternative forms of energy like biofuels, urban expansion and the loss of biodiversity, the issues of land loss have been enraged. During farming, if not considering the soil conservation techniques, the land degradation starts due to soil erosion, deforestation, pollution, and overgrazing (Stocking and Murnaghan 2001). This causes the loss of at least 16–40% (Chappell and LaValle 2011) of land area which affects 1.5 billion people.

Loss of biodiversity: During the green revolution, a huge proportion of genetic diversity of agricultural crops was lost which resulted in variations of the pattern of intraspecific diversity (Aarnink et al. 1998). These losses majorly affect the species overall fitness and adaptive potential which limits its recovery. The extinction of non-agricultural biodiversity also affects the food production by disturbing the ecosystem as in natural control on crop pests and diseases.

High usage of water resources: 70% of total water resources is used for irrigation (Foley et al. 2011; FAO 2011). It is proposed that in upcoming years, the usage of water resources will be increased and in some regions like sub-Saharan Africa, this figure will be doubled as compared to 1997. This concludes that by 2050, 90% of 3 billion people will be living in water stressed conditions, because the water demand in agriculture, industries and households will be continuously increasing.

Pollution and resource depletion: Fertilizers and pesticides play a huge role in agricultural practices but also have harmful effects on the ecosystem health like eutrophication and contamination of water sources, disruption of nutrient cycle. Production of fertilizers and pesticides deplete the non-renewable resources like phosphorus ores (Cordell et al. 2009). The emission of harmful gases like methane and nitrous oxide by the agricultural sector have increased by 17% from 1990 to 2005 (Smith et al. 2007). Even 12% of total anthropogenic emissions of greenhouse gases is contributed by agriculture. Hence, it causes a significant impact on climate change.

6 Strategies to Address Sustainability Challenges

6.1 Sustainable Intensification

Currently, Sustainable Intensification (SI) is being a powerful productivism discourse in the food security debate due to the competing pressures on the land and the awareness of environmental impacts of food production. The main principle of SI is to increase agricultural production without harming the environment and also by not occupying more non-agricultural land (Pretty and Bharucha 2014).

The main three components supporting SI are:

1. For increased crop production, SI advises a systematic way to use the natural resources like land, water, seeds and fertilizers, without damaging the environment (FAO 2010). It assures improved soil and water management, with high soil fertility by utilizing various agro ecological processes like biological nitrogen fixation, carbon cycling and nutrient cycling. These processes play a vital role in crop production, addressing these also help in biodiversity conservation (Gibson et al. 2007) and the natural life cycle (De Backer et al. 2009).
2. Secondly, SI links agro-industrial/biotech with agroecological propositions (Dibden et al. 2013). Theoretically, in food production SI promises to benefit small farmers by increasing the production, reducing cost, building durability and strengthening their resistance to environmental stress.
3. For the success of sustainable intensification projects on food production, SI emphasizes on the importance to consider traditional knowledge to solve local needs (Garnett and Godfray 2012). By acknowledging the local environmental and socio-economic conditions, local farmers will also be included on this path of innovation.

Innovation and management are the factors important to decrease harmful environmental impacts and to increase production. Hence, to improve the efficiency of crop production some strategies to consider should be accuracy in matching of fertilizers, water and other inputs, with the outputs like livestock or crop requirements. Producing energy from agricultural waste and other technologies to replenish soil with carbon must be used. Refrigeration can be used to reduce post-harvest emissions. For the manufacturing and transport, energy efficient or renewable energy sources dependent technologies must be used. Waste produced during this whole process can be reduced by inventory management, or by modifying packaging material. It is also necessary to prolong the shelf life of food and help consumers reduce food waste.

6.2 Increasing Production Limits

The aim of the sustainable food production is to obtain higher yield, hence debates over the theoretical limits for gaining the maximum yield of the most productive crops like sugarcane growing under the different conditions which can be obtained for livestock rearing are still in advancement. Although, it is an appreciable outlook to maximize the crop production.

In the Green revolution, hybrid varieties of maize and semi dwarf, disease resistant varieties of wheat and rice were developed by the help of conventional breeding. Hence, in these crops there was less risk of yield loss caused by lodging or rust epidemics, even if there is extra water or fertilizer supply. Although, in genetically modified crops (GMC), gene insertions can provide pest-insect toxin or resistance to individual diseases. Eventually, with the help of more advanced technologies, a combination of desirable and new traits will be able to be introduced. Gene insertion can also be useful in animal feed, as genetically modified crops could be fed which can increase the efficiency of meat production and decrease methane emissions.

Biotechnology is an emerging field, and increasing the sustainable food production limit with the help of it seems attainable but, the underdeveloped and poor nations have to be supported by making new alliances of business or civil society organizations.

7 The Consumption Challenges

Urbanization and sedentary lifestyle in recent years has led to a change in consumption pattern that has a negative impact on the health and wellbeing of individuals. As estimated, in 2018, about 2 billion adults, 207 million adolescents and more than 44 million children below the age of five were overweight, of which one-third adults and adolescents and 44% children were obese, and their number is increasing at an alarming pace (FAO 2019). Eating an excessive amount of food, particularly animal products, is one of the major causes of negative health outcomes besides adversely affecting the environment (Garnett 2013). Currently, there is increased consumption of energy rich diets, high in fat, oil, dairy products, red meat, processed meat and processed food, more so in developed countries and urban areas. It results in an alarming increase in obesity, overweight and non-communicable diseases like cardiovascular diseases (CVD), diabetes and hypertension. Association has been observed between the high intake of livestock products and weakens/ill health (Sinha et al. 2009). Moreover, the current eating habits are not environmentally friendly as well as have a toll on the natural resources. The livestock farming emits a much higher amount of greenhouse gas (GHG) as compared to crop cultivation. Also, about half of the agriculture produce is used as animal feed which can be a major source of food for humans by transition to plant-based diets (Willett et al. 2019).

The type and quantity of food consumed has a relevance to both health and environment. If the current dietary trend is continued, mitigation measures deployed for increasing production would fail in future and GHG emission will continue to rise. For sustainability in the food sector, there is a need to control the production of animal products and also decrease per capita consumption of meat to 20–40% of the present one by 2050. Also, one is needed to shift to more plant-based diets with emphasis given on eating as much as required by the body (Pelletier and Tyedmers 2010, Popp et al. 2010). This would help in maintaining the health as well as prevent environmental damage.

Today worldwide people are suffering from obesity and being overweight on one side and from hunger and micronutrient deficiency on the other side. The number of both undernourished and obese people are increasing at a great pace. According to the State of Food Security and Nutrition in the World Report, over 820 million people worldwide are experiencing hunger and 2 billion people have food insecurity of moderate to severe level and rarely have access to nutritious and sufficient food, thus having undernourished and poor health (FAO, IFAD, UNICEF, WFP, WHO). In developing countries, particularly poor ones and in rural areas, people usually have access to diets without much diversity and there the availability of minerals like calcium, zinc, iron and magnesium from animal products become important (Dror and Allen 2011). As argued by advocates, enough food is available to feed all but there is inequality in resource usage and consumption patterns. Need is for equalization of the resources, much better utilization of already available food, changes in the consumers' attitude, designing 'sustainable healthy diets' and avoiding food losses and wastage. By 2050, the world is required to feed a population of 9.7 billion (UN 2019). So, both food security and food safety have to be aimed for a sustainable future and to meet the SDGs United Nations. For this, different approaches/strategies may be used including intensification of food production without use of antimicrobials, setting up circular food production systems, artificial intelligence and intelligent packaging, changed diet, and limiting/reducing food loss. Multiple challenges have to be addressed to meet sustainability in the food system.

8 Strategy to Address Consumption Challenges

8.1 The Concept of Sustainable Diets

Sustainability in diet means it should be available to the present as well as to future generations for their health and wellbeing. Gussow and Clancy were the first to use the term 'sustainable diet' in their article 'dietary guidelines for sustainability' on the concern of malnutrition and environmental degradation (Johnston et al. 2014). To address the issue of healthy and sustainable diet and provide the uniform guidelines on it, FAO and WHO hold the joint meeting of international experts in Italy in July 2019. As defined by FAO in 2019, "*Sustainable Healthy Diets are dietary patterns that promote all dimensions of individuals' health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable*" (FAO and WHO). It is a complex term including social, economic and environmental aspects.

Our current consumption behavior impacts the environment negatively and is a challenge to the sustainability of the planet earth. About 13.7 billion tons of carbon dioxide equivalents are released in the food system from its farming to consumption (Poore and Nemecek 2018). There is a need that all the stakeholders including government, industries and consumers come together to bring changes in production, processing and consumption patterns of food. Increasing attention is being paid on the consumption and shopping aspect of the food in a sustainable manner. Number of technologies like carbon footprint calculators, apps on smartphones, and websites have been designed for food sustainability which provide the information as well as assist in making sustainable decisions during consumption and purchasing

(Kalnikaite et al. 2011). One has to consider a number of factors like food type (local/organic), food miles, climate footprints, food waste, supply chain, food management etc. while dealing with sustainability in food choices (Lindrup et al 2021). Moreover, factors like size of the family, budget, taste, shopping mode, transportation, and needs consideration during sustainable shopping (Clear et al. 2015). Despite its complexity and time driven process, 'Pioneer' or 'sustainability-conscious' people give more emphasis on locality, organicity and food miles while buying food (Clear et al. 2016).

To save the adversity of current diet on humanity in future, and to save the environment and health at present, BDA, the association of UK dietitians in 2018 launched the 'one blue dot project' for sustainable eating under which a nine-point plan was given for a sustainable diet for the individuals of all age groups (BDA 2023). There they emphasize that through altered food consumptions and diet it is possible to achieve SDGs to a large extent, particularly goals on no poverty, zero hunger, clean water, good health and wellbeing, Quality education, gender equality, responsible production and consumption, mitigating climate change, sustainable land use, and sustainable life on land and water. It gives more emphasis on production and use of plant-based diet and reduction in animal products, particularly red meat.

Organic food consumption is the way to move towards sustainability in the food sector. Several countries in Europe have set policies on the utilization of organic food as an alternative to move towards the goal of more sustainable production and consumption. Despite adopting measures such as food labelling, awareness to consumers, market development support, there was only a marginal increase in organic food consumption (Vittersø and Tangeland 2014). Measures like subsidies on some food items or ban of some may be taken for reorienting the dietary patterns (Garnett 2013). Politicians, researchers and other advocates have largely been concerned with how consumers can be influenced in order to develop the markets for sustainable food products. Both the transition of the eating habits as well as realization by the consumers of their responsibility towards the family, society and climate is required. Policy makers should try to find out the reasons for inhibition in habit change and the ways to bring this transformation for sustainability in food consumption (Tuscano et al. 2021).

8.2 Reducing Food Loss or Waste

Food waste is any food, or its inedible parts that is removed from the food supply chain to be recovered or disposed of (Östergren et al. 2014). As defined by Food and Agriculture Organization (FAO) of the United Nations (UN), food loss is the loss of food from the supply chain at any step from production to consumption and food waste is disposal of safe nutritious food (FAO 2011). Food loss or waste (FLW) is a massive problem globally, causing food insecurity, climate and ecological damage, thus has to be tackled urgently for food sustainability. In addition, it negatively impacts socio-economic growth resulting in low income, hike in food prices, and poverty (Gills et al. 2015). Annual FLW occurring at any stage of the food supply chain (FSC) is about 1.3 billion tons. According to FAO in 2011, around one third of the food is wasted in a food chain because of preharvest failure or at the time of harvest or post-harvest (handling, storage, transportation, processing, packing, delivery, retail and consumption) which is finally discarded in landfills. The reasons for food losses may be food spoilage and damage because of inadequate harvesting time, climatic conditions, insufficient storage conditions, faulty cold chains, improper packaging and transportations, difficulties in marketing of produce, technical faults in equipment, human errors or delay in custom clearance during export and so on. Food wastage may be because of incomplete or peeling off of labelling, confusing 'best before' labels, inappropriate product information, overstocking of products, recalled foods by the producers and leftover edible food on preparing oversized portions, which is often discarded by the retailers, restaurants and households. In 2019, a total 337 recalls were made in the U.S. Food and Drug Administration (FDA) and U.S. Department of Agriculture Food Safety and Inspection Service (USDA FSIS) because of the presence of microbial contamination, undeclared allergens or foreign material. Moreover, the factors responsible for food loss or waste may vary for developing and developed countries. While in the former 40% food loss happens during production, in latter 40% food waste is generated during distribution, marketing and consumption (Wunderlich and Martinez 2018). The highest loss or waste of food occurs at the consumer end both at home and outside home, estimated levels are 27% of grain, 33% of seafood, 28% of fruits and vegetables, 12% of meat and 17% for milk products and so on (Chen et al. 2020).

Food loss or waste constitute for 8% GHG emission and 28% total global area under agriculture (Vågsholm et al. 2020). This indicates not only the depletion and wasteful use of natural resources but also has negative consequences on the environment, adversely causing damage to soil and water sources, biodiversity and forest. FLW poses a threat to the food sector globally and calls for adequate measures to be taken to minimize preventable food waste and valorization of the non-preventable waste (Morone et al 2019). Its reduction is one of the sustainable development goals adopted by the UN in 2015. As per SDG 12.3, the target is to reduce the waste of food to half (50%) by 2030 at the retail and consumption level. It is a collective task, requiring collaborative efforts and improved connectivity among all the stakeholders including politicians, policy makers, engineers, IT personnels, economists, social and physical scientists and others. To meet the set goal as a whole, the alliance called 'Champions 12.3' was constituted of government officials, international organizations executives, researchers, civil society, and personnel involved in the food supply chain. The alliance interpreted the SDG 12.3 and provided the guidelines on monitoring indicators for observing the progress in 2017 (World Research Institute WRI and Ministry of Economic Affairs of the Netherlands 2016). As data available presently on FLW is incomparable because of small sample size and use of different methods in computation, there is a requirement to have a robust approach to quantitate FLW accurately for designing better policy and intervention, and also monitoring implementation and reduction in food waste. Five challenges were faced while planning for FLW reduction that include assessment of actual FLW, estimation of benefits and cost, planning policies and initiatives under insufficient data, understanding of the interaction among different supply chain steps, and preparing for income transitions (Cattaneo et al. 2021).

Many other initiatives have also been taken for harmonized accounting and reporting standards of food loss or waste at different stages in the food chain such as ‘Food Loss and Waste (FLW) Protocol’ which was launched in 2016; FUSIONS (Food Use for Social Innovation by Optimising Waste Prevention Strategies) project was financed; EU Platform on Food Losses and Food Waste was established in 2016; workshop on “FW accounting: methodologies, challenges, and opportunities”, was organized in 2017 and so on. The problem of food losses and waste can be addressed to some extent by reducing losses at source, reprocessing excess or unused food, reusing leftovers for biofuels, compost, animal feed, or compost, and lastly for energy recovery through incineration (Vågsholm et al. 2020). As suggested by Unilever (2017) a five-step program can be employed to limit food loss or waste which includes:

1. Awareness should be raised among the public about the magnitude of the problem and its impact on GHG emission, on rotting of food, and the economic loss due to the use of resources like energy, water, land, and labor in its production. As estimated, the annual global loss is approximately $940 billion and after China and USA, food loss and waste is the third emitter of GHG. Consumers’ behavior would have a great impact on food loss or waste as they are the key contributor in its generation, so should be told about their role in achieving the goals of “zero loss or waste of food” (Alamar et al. 2018).
2. The target of reduction has to be set. To meet SDGs, the UN has set the target that by 2030, the global food loss or waste should reduce to its present half.
3. The amount of food loss or waste in each region or country should be known to decide the policies and programs to be undertaken to solve the problem. The ‘Global Food Loss and Waste Accounting and Reporting Standard’ is the first to be developed by a Steering Committee of seven expert institutions for quantification and reporting of food loss or waste by governments and countries as per the FLW Standard.
4. Action plans need to be developed and implemented including intensifying crop harvest, adoption of novel technology for reprocessing and recycling, consumer campaigns and public–private partnerships. The ‘Global Think.Eat.Save’ food waste prevention guidance to reduce loss and waste in food include measuring the quantity of loss and waste, formulating the regional and national policies, actions to be taken to reduce the waste in food chain and consumer campaigns to increase their awareness.
5. Collaboration is needed at all the levels involving farmers, agribusinesses, retailers, households, local authorities, governments and so on. The decision makers in public, private and non-governmental organizations can collaborate to design and implement the innovative solutions to improve the food system in a sustainable manner,

Fig. 2 The influence of Food wastage on sustainability Shafiee-Jood and Cai 2016 (*Source*)

Further 'smart packaging (SP) systems' can be employed to keep the food safe and improve its quality and sustainability. SP allows the monitoring of changes happening internally and externally in the food and responds to it through an external interface. This would avoid spoilage, extend the freshness and shelf life and keep the product safe. Integration of food packaging with emerging advanced technologies such as electronics and wireless communication and cloud data solutions increases its traceability across the FSC and reduces food loss and waste (Chen et al. 2020). In addition, dynamic shelf-life systems which can tell the status of food inside the packet is a better option than the label stating 'best before' or 'use by' (Poyatos-Racionero et al. 2018).

Though avoiding complete food loss and waste is not possible, limiting would help in the better management of resources like land, water and would also provide the food available to one billion more people. Furthermore, it will lead to climate sustainability and improve food security worldwide (Fig. 2).

9 The Socio-economic Challenges in Food Sustainability

Sustainability has long been a major combination of social (people), ecological (planet), and economic (profit) concerns. According to Drewnowski (2017), sustainable food consumption means consuming nutrient-dense, cost-effective, and socially acceptable meals while protecting the environment. Thus, we can say that sustainable food consumption involves four major domains, i.e., socio-economic, dietary, cultural, and environmental. Here, the socio-economic factor focuses on food affordability while emphasizing the social acceptability of foods, while the rest focuses on nutrient-rich foods, culturally acceptable foods, and the prevention of greenhouse gas emissions, respectively.

The current food system is unsustainable, owing to a shift in consumption patterns towards more dietary animal protein, the emergence of heavily processed foods, the widening gap between rich and poor, a lack of food security despite an abundance of food, an increase in food waste, etc. (Ifeanyichukwu and Nwaizugbo 2019); thus, this system results in starvation, loss of resources, agricultural waste, pollutants, unfairness, and so on. Also, the current coronavirus pandemic shows the vulnerability of our global food supply systems to disturbances that may result in threats to consumer safety, shortages of workers, and other manufacturing concerns, as well as shortfalls of internationally traded food products (Brunori et al. 2020).

In recent years, most emerging and undeveloped economies have experienced recessions and high inflation rates, resulting in rising food prices, specifically for sustainable items. In addition, organic items are more expensive than conventional alternatives in today's market. High prices for food are also reported to pose substantial issues for highly susceptible low-income families that invest a large portion of their earnings on food items. It is also worth noting that over 2 billion individuals in underdeveloped countries spend up to 70% of their disposable income on food (Ifeanyichukwu and Nwaizugbo 2019).

Ensuring safe, nutritious, and inexpensive food for both present and future generations while maintaining natural resources and supporting livelihoods poses several socioeconomic issues. Some of the significant challenges are discussed below.

9.1 Poverty and Food Insecurity

Poverty and food insecurity are intertwined issues that undermine food sustainability. Inadequate income and resources restrict access to nutritious and sufficient food, resulting in malnutrition and hunger. Since 2014, the number of persons affected by hunger has been continuously increasing. According to current estimates, about 828 million people, or 9.8% of the world's population, are hungry (The State of Food Security and Nutrition in the World 2022). The lack of financial resources also makes it challenging to invest in sustainable farming practices, modern technologies, and the infrastructure required for sustainable food production. Furthermore, a lack of knowledge about nutrition, food safety, and sustainable consumption practices could exacerbate unhealthy eating patterns and increase food waste. Eliminating poverty by means of fair economic expansion, safety net initiatives, and alleviating poverty measures is vital for enhancing food availability and sustainability (Wezel et al. 2020).

9.2 Food Waste

According to FAO (2018), around 1.3 billion tons of food are lost or wasted annually in the world. Food loss happens during the processes of harvesting, preservation, delivery, and manufacturing, whereas food waste primarily occurs at the level of the customer. This means that large quantities of resources that are used in the production of food that are lost or wasted, and greenhouse gases produced during various stages of the food supply chain are squandered (Teixeira 2018) and thereby threatening sustainability. In addition, converting natural habitats into agricultural spaces is frequently needed for the cultivation of crops. When food is wasted, these land-use shifts become even more unsustainable, resulting in biodiversity loss and ecological devastation. And, thus results in economic losses, inefficient resource use, and poor environmental consequences (Grote 2014). Accessibility to inexpensive goods, bad purchasing strategies, the fragile nature of foods, improper transportation and storage, etc. are some of the factors contributing to the public sector's food waste (Morawicki and Díaz González 2018), while food losses occur during harvest and post-harvest stages due to issues with processing, handling, packing, transportation, infrastructural deficiencies, cold chains, and unbalanced incentives etc. (Vågsholm et al. 2020).

9.3 Loss of Biodiversity and Genetic Resources

Biodiversity loss in agriculture can reduce agricultural output and economic viability. Monoculture systems are vulnerable to pests, diseases, and environmental changes because they rely on a small number of high-yielding crop varieties. Farmers can experience crop failures and reduced yields as a result, which leads to income losses and financial instability (Hoffmann 2021). Also, loss of genetic resources and crop diversity can increase reliance on external inputs such as fertilizers, herbicides, and water. Lack of crop diversity makes agroecosystems more vulnerable to pests and diseases, which require farmers to employ chemical inputs to combat them. This reliance on external inputs not only contributes to environmental degradation but also raises production costs, threatening the economic sustainability of agricultural systems. Furthermore, small-scale farmers may face difficulties affording and accessing these costly inputs, exacerbating inequalities in agricultural production. Also, decreased genetic diversity may limit trade opportunities since particular crops may not fulfill the quality standards or preferences of international markets.

9.4 Inequality in Food Distribution

Garnett (2013) described that food inequality is an ongoing challenge both within and across countries and communities. This inequality creates the twin challenges of excess and insufficiency, which express themselves in both the environment (over- and under-application of agricultural inputs) and health (obesity and hunger). Because of reasons such as inadequate infrastructure, market inefficiencies, and discriminatory practices, some regions and people have restricted access to affordable and healthy food, while other regions have abundant food access, resulting in obesity and overconsumption (Bhat 2022). More food will be needed to feed an expanding population as well as to maintain the people's surplus weight, and in order to produce these additional calories, more natural resources and fossil fuels will be required (Morawicki and Díaz González 2018). This disparity increases food insecurity and perpetuates the poverty cycle and over consumption causing a major challenge to food sustainability goals.

9.5 Global Trade and Market Dynamics

Global trade and market dynamics can result in unequal access to markets, particularly for small-scale farmers in developing nations. Trade barriers, tariffs, and non-tariff measures can limit their ability to engage in international markets, limiting their potential for economic growth and development. Global trade can also contribute to price volatility in agricultural commodities. Global food price fluctuations can have serious social and economic repercussions for both farmers and consumers. Sharp increases in prices can lead to food price spikes, making food less affordable and exacerbating food insecurity, particularly for vulnerable populations (van Berkum 2021).

According to Morawicki and Díaz González (2018), locally produced foods are usually considered to have a smaller environmental impact than food grown or produced elsewhere and transported. The transportation of food over long distances, often referred to as "food miles," contributes to carbon emissions, energy consumption and food losses. A large amount of energy is used to deliver food via plane, followed by automobiles, trains, and ships. Global trade can destabilize local food systems by encouraging the importation of food from other nations. Local food production, traditional farming practices, and cultural food identities may be jeopardized as a result. Thus, overreliance on imported food can increase vulnerability to supply chain disruptions, price shocks, and market failures, thus threatening the social and economic development of local farmers and small-scale businesses (Zimmermann and Rapsomanikis 2023).

9.6 Changing Dietary Patterns

As incomes rise and populations urbanize, there is often a shift towards diets that are richer in animal-based products, such as meat, dairy, and eggs (Vågsholm et al. 2020). This change in dietary patterns puts additional pressure on agricultural systems to meet the growing demand for animal feed, resulting in increased land use, water consumption, and greenhouse gas emissions, etc. Morawicki and Díaz González (2018) described that changing dietary patterns often drive change in land use, particularly through the expansion of agricultural land for the production of feed crops and grazing land for livestock. Livestock production requires substantial resources and contributes significantly to deforestation, water pollution, and biodiversity loss (Garnett 2013). Meeting the increasing demand for animal-based products in an unsustainable manner can strain natural resources and exacerbate environmental degradation. Additionally, changes in eating habits can affect both nutrition and food availability, especially in low-income nations (Chen et al. 2022). Diets that are high in processed foods, added sugars, and unhealthy fats can contribute to the rise of non-communicable diseases such as obesity, diabetes, and cardiovascular diseases (Fróna et al. 2019). Meeting the nutritional needs of a growing population while ensuring access to affordable, diverse, and nutritious food is a challenge to food sustainability goals.

9.7 Political and Policy Constraints

In many cases, existing policy frameworks may not effectively handle the complex challenges of food sustainability. Agriculture, land use, trade, and food system policies may be outdated, fragmented, or insufficiently aligned with sustainability goals (Vågsholm et al. 2020). This can hinder the adoption of sustainable practices and the advancement of more resilient and equitable food systems. Vågsholm et al. (2020) further described that political instability, conflict, and fragile governance can have severe impacts on food sustainability. In regions experiencing political unrest, food production and distribution systems are often disrupted, leading to increased food insecurity and vulnerability. Food insecurity and famines are also the result of political instability and conflicts, which cause an increase in food prices and thus create a food imbalance (Fróna et al. 2019).

10 Strategies to Address Socio-economic Challenges

The socio-economic challenges in food sustainability are complex and interconnected. Tackling issues such as poverty, inequality, land degradation, climate change, loss and waste, unsustainable practices, and global trade dynamics requires a holistic and multi-faceted approach. Collaboration among governments, civil society organizations, farmers, researchers, and the private sector is crucial for eliminating such challenges to food sustainability (Teixeira 2018). Policy interventions at national and international levels should focus on promoting sustainable agricultural practices, investing in rural infrastructure, enhancing access to finance and markets for small-scale farmers, and improving social protection systems (Kennedy et al. 2020). Fair trade, sustainable production and consumption habits, and improved market access for small-scale farmers are all necessary for a more equitable and sustainable global food system. Local and regional food system strengthening can also help minimize dependency on long-distance food transportation and enhance resilience (Sajid et al. 2017).

Poverty can be addressed through inclusive economic growth, social protection programs, and poverty reduction strategies, which are crucial to improving food security and sustainability (Ifeanyichukwu and Nwaizugbo 2019). Income Generation and Employment Opportunities can be created through investment in rural infrastructure, access to credit and financial services, and support for entrepreneurship and small-scale farming. Wahbeh et al. (2022), described that social safety nets and targeted interventions can be implemented to provide assistance to vulnerable populations. This includes cash transfer programs, school feeding programs, and subsidized food programs to ensure access to nutritious food for those living in poverty. These measures can boost long-term economic growth and decrease poverty while contributing to reducing current food scarcity.

Partnerships that promote fairness, diversity, and solidarity are often established in inclusive and sustainable food systems. These partnerships could include both vertical cooperation in supply chains among privately held businesses and industries as well as horizontal cooperation of government, social, and private entities (Wahbeh et al. 2022). He emphasized further that public–private partnerships (PPPs) aim to advance equitable and long-term growth in the economy through market-focused investments. PPPs allow for the sharing of knowledge, skills, and financing, and the private sector's market-oriented approach can be combined with the knowledge of local demand held by civil society organizations, while research institutes offer expertise and the government supplies crucial legislation and standards (FAO 2018).

Encouraging long-term consumption patterns that prioritize healthy, balanced diets, increasing public understanding of the social and environmental effects of food choices, and supporting measures to prevent food waste can be implemented to achieve food sustainability (Vågsholm et al. 2020). This includes upgrading food transportation and storage infrastructure, encouraging sustainable packaging, and undertaking responsible consumption education initiatives.

Considering food sustainability issues result in inequalities and disparities, focusing solely on improving production is unlikely to enhance food security. Today, hunger is caused by a lack of access rather than a lack of availability, as affordability is the major factor. While some increase in output may be required, it is vital to boost production in specific regions, in connection to specific consumers and producers (Garnett 2013). One of the main strategies to address these challenges of food sustainability is discussed below.

10.1 Improve Governance

Food system sustainability can only be realized by improving the food system's socio-economic governance. Food governance is a necessity for the successful implementation of food policies at the global, regional, and national levels because they operate at multiple levels formed by international, national, and regional agreements (Del Valle et al. 2022). Food systems must become more efficient and inclusive, with policies and legal frameworks addressing income inequality, supporting livelihoods, and ensuring resilience, all while ensuring coherent and effective national and international governance (Kennedy et al. 2020). A wide range of initiatives, including measures like regulations and fiscal instruments, as well as approaches like voluntary agreements, raising awareness, and education, will be required.

For the complete elimination of hunger and food insecurity, explicit political promises must be made, and sufficient resources must be distributed in a timely and effective manner. Coordinated initiatives should be promoted through multidisciplinary approaches and alliances, all while being supported by international norms and agreements, policy discourse, global governance systems, advocacy, and communication (FAO 2018).

Promoting partnerships across governments, civil society organizations, academic institutions, and the commercial sector to boost collaboration and utilize expertise, resources, and innovation can help to facilitate multi-stakeholder collaborations. These collaborations can allow knowledge exchange, collaborative research projects, and the creation of fresh solutions to socio economic challenges in food sustainability (Wahbeh et al. 2022). He further emphasized that the role of the legislature in regulating a nation's agriculture is also seen as an essential component of food availability because it is accountable for a number of things, including developing, evaluating, and putting into effect the best laws and regulations to ensure the social security of its people, as well as giving small-scale agricultural producers the support they need and guaranteeing protection and assistance in all facets of their life. In order to change the population's production role, governments in developing countries must prioritize R&D, agriculture infrastructure (e.g., irrigation and soil preservation technology), expanding services, early warning systems, or subsidized farm income (Fróna et al. 2019).

A consumer-oriented policy should be implemented to increase awareness of the nutritional values of food, the large inefficiencies in the production of some foods, and the massive losses and food waste that occur, which could be avoided. The low awareness of the nutritional values of different foods and hygienic risks is especially prevalent in many developing countries, leading to an unsustainable food system (Grote 2014).

An interdepartmental approach may be employed to encourage cooperation in policy across several policy domains, such as agriculture, the environment, trade, and social welfare, to ensure that policies are linked and mutually beneficial (Byers and Gilmer 2021). This necessitates collaboration among various government departments and agencies (e.g., ministries of agriculture, trade, health, environment, education, transportation, and infrastructure, among others) in order to develop integrated policies to tackle the social, economic, and environmental challenges of food sustainability (FAO 2018).

Improving governance through improved legitimacy and transparency in decision-making processes, traceability in resource allocation, and fair implementation of monitoring and evaluation tools to ensure accountability and tackle any incidents of corruption is critical for addressing numerous food sustainability concerns (Kaiser et al. 2021). He further explained that meaningful engagement of varied stakeholders in decision making processes and governance of the food system, such as farmers, consumers, civil society organizations, and the commercial sector, is required to reflect broad ethical standards and these engagements can be achieved through developing forums for discussions, consultation, and collaboration to ensure that all stakeholders' opinions and viewpoints are taken into account. In both developed and developing economies, Food supply systems should be strengthened, and effective policy enforcement, monitoring, and evaluation systems should be implemented (Brunori et al. 2020). Establishing and enforcing strong legislative and regulatory frameworks to promote sustainable agriculture, food safety, and environmental protection is helpful in achieving food sustainability (Del Valle et al. 2022). Governance appears as both a process and a value that allows the socio-cultural context for food systems to work properly (Berry 2019).

11 Conclusion

The socio-economic issues of food sustainability demand a multifaceted approach that incorporates social, economic, and environmental considerations. Poverty, inequality, food waste, unsustainable practices, biodiversity loss, market dynamics, changing dietary patterns, and political restrictions are all interconnected and require coordinated efforts to overcome. It is feasible to achieve considerable progress towards food sustainability by applying initiatives such as income production, social safety nets, sustainable agriculture, and inclusive governance. These initiatives stress the need for empowering small-scale farmers, promoting sustainable consumption patterns, fortifying institutions and policies, and encouraging collaboration among varied stakeholders. Furthermore, improving governance mechanisms is critical to resolving these challenges. Governments, international organizations, civil society, and the commercial sector must collaborate to implement beneficial programs and promote sustainable food systems. To convert our current food systems into resilient, inclusive, and sustainable ones, we need political will, investment, and a long-term commitment.

We may ensure fair access to nutritious food, reduce environmental consequences, improve rural livelihoods, and contribute to the accomplishment of sustainable development goals by tackling the socioeconomic difficulties in food sustainability. Only by working together can we ensure that everyone has access to safe, healthy, and sustainably produced food while also protecting our planet's resources for future generations.

References

Aarnink W, Bunning S, Collette L, Mulvany P (1998) Sustaining agricultural biodiversity and agroecosystem functions: opportunities, incentives and approaches for the conservation and sustainable use of agricultural biodiversity in agro-ecosystems and production systems. In: Report of the international technical workshop. Headquarters, Rome

Ahmed S, Byker Shanks C, Leal Filho W, Wall T, Azul AM, Brandli L (2020) Supporting sustainable development goals through sustainable diets. In: Good health and well-being. Springer International Publishing, Cham, Switzerland

Akhtar S, Ahmed A, Randhawa MA, Atukorala S, Arlappa N, Ismail T (2003) Prevalence of vitamin A deficiency in South Asia: causes, outcomes, and possible remedies. J Health Popul Nutr 31(4):413–423. https://doi.org/10.3329/jhpn.v31i4.19975

Alamar M del C, Falagán N, Aktas E, Terry LA (2018). Minimising food waste: a call for multidisciplinary research. J Sci Food Agric 98(1):8–11. https://doi.org/10.1002/jsfa.8708

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. FAO Agricultural Development Economics Division

Ashley R, Russell D, Swallow B (2006) The policy terrain in protected area landscapes: challenges for agroforestry in integrated landscape conservation. Biodivers Conserv 15(2):663–689. https://doi.org/10.1007/s10531-005-2100-x

Bailey R (2011) Growing a better future: food justice in a resource-constrained world

Barnes R, Fagg C (2003) Faidherbia albida: monograph and annotated bibliography. Oxford For Ins

BDA (2023) One Blue Dot—sustainable diets [Internet]. Bda.uk.com. https://www.bda.uk.com/news-campaigns/campaigns/one-blue-dot.html. Cited 24 Aug 2023

Bell DE (1992) The 1992 convention on biological diversity: the continuing significance of US objections at the Earth Summit. Geo Wash J Int'l L & Econ 26

van Berkum S (2021) How trade can drive inclusive and sustainable food system outcomes in food deficit low-income countries. Food Secur 13(6):1541–1554. https://doi.org/10.1007/s12571-021-01218-z

Berry EM (2019) Sustainable food systems and the Mediterranean Diet. Nutrients [Internet] 11(9):2229. https://doi.org/10.3390/nu11092229

Bhat R (2022) Emerging trends and sustainability challenges in the global agri-food sector. In: Future foods. Elsevier, pp 1–21

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa (FAO No. 34). Food & Agriculture Organization of the United Nations, Rome

Brown BJ, Hanson ME, Liverman DM, Merideth RW Jr (1987) Global sustainability: toward definition. Environ Manag 11(6):713–719. https://doi.org/10.1007/bf01867238

Brunori G, Branca G, Cembalo L, D'Haese M, Dries L (2020) Agricultural and food economics: the challenge of sustainability. Agric Food Econ 8(1). https://doi.org/10.1186/s40100-020-00156-2

Buerke A, Straatmann T, Lin-Hi N, Müller K (2017) Consumer awareness and sustainability-focused value orientation as motivating factors of responsible consumer behavior. Rev Manag Sci 11(4):959–991. https://doi.org/10.1007/s11846-016-0211-2

Byers V, Gilmer A (2021) The challenge of sustainable consumption for governance and policy development—a systematic review. Sustainability 13(12):6723. https://doi.org/10.3390/su13126723

Carlsson-Kanyama A, González AD (2009) Potential contributions of food consumption patterns to climate change. Am J Clin Nutr 89(5):1704S-1709S. https://doi.org/10.3945/ajcn.2009.26736AA
Cattaneo A, Sánchez MV, Torero M, Vos R (2021) Reducing food loss and waste: five challenges for policy and research. Food Policy 98(101974):101974. https://doi.org/10.1016/j.foodpol.2020.101974
Celata FB (2009) New directions in economic geography. Reshap Econ Geogr World Dev Rep 2(117):498–500
Chappell MJ, LaValle LA (2011) Food security and biodiversity: can we have both? An agroecological analysis. Agric Hum Values 28(1):3–26. https://doi.org/10.1007/s10460-009-9251-4
Chen S, Brahma S, Mackay J, Cao C, Aliakbarian B (2020) The role of smart packaging systems in the food supply chain. J Food Sci 85(3):517–525. https://doi.org/10.1111/17503841.15046
Chen C, Chaudhary A, Mathys A (2022) Dietary change and global sustainable development goals. Front Sustain Food Syst 6. https://doi.org/10.3389/fsufs.2022.771041
Clear AK, Friday A, Rouncefield M, Chamberlain A (2015) Supporting sustainable food shopping. IEEE Pervasive Comput 14(4):28–36
Clear AK, O'neill K, Friday A, Hazas M (2016) Bearing an open "Pandora's box": HCI for reconciling everyday food and sustainability. ACM Trans Comput Hum Interact 23(5):1–25. https://doi.org/10.1145/2970817
Cordell D, Drangert JO, White S (2009) The story of phosphorus: global food security and food for thought. Glob Environ Change [Internet] 19(2):292–305. https://doi.org/10.1016/j.gloenvcha.2008.10.009
Davis J, Sonesson U, Baumgartner DU, Nemecek T (2010) Environmental impact of four meals with different protein sources: case studies in Spain and Sweden. Food Res Int [Internet] 43(7):1874–1884. https://doi.org/10.1016/j.foodres.2009.08.017
De Backer E, Aertsens J, Vergucht S, Steurbaut W (2009) Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA): a case study of leek production. Br Food J 111:1028–1061
Dibden J, Gibbs D, Cocklin C (2013) Framing GM crops as a food security solution. J Rural Stud [Internet] 29:59–70. https://doi.org/10.1016/j.jrurstud.2011.11.001
Downs SM, Ahmed S, Fanzo J, Herforth A (2020) Food environment typology: advancing an expanded definition, framework, and methodological approach for improved characterization of wild, cultivated, and built food environments toward sustainable diets. Foods [Internet] 9(4):532. https://doi.org/10.3390/foods9040532
Drewnowski A (2017) Sustainable, healthy diets: models and measures. In: Sustainable nutrition in a changing world. Springer International Publishing, Cham, pp 25–34
Dror DK, Allen LH (2011) The importance of milk and other animal-source foods for children in low-income countries. Food Nutr Bull 32:227–243
Duan JJ, Marvier M, Huesing J, Dively G, Huang ZY (2008) A meta-analysis of effects of Bt crops on honey bees (Hymenoptera: Apidae). PLoS One [Internet] 3(1):e1415. https://doi.org/10.1371/journal.pone.0001415
Edwards P, Roberts I (2009) Population adiposity and climate change. Int J Epidemiol [Internet] 38(4):1137–1140. https://doi.org/10.1093/ije/dyp172
FAO of the United Nations (2011) Save and grow: a policymaker's guide to sustainable intensification of smallholder crop production. Food & Agriculture Organization of the United Nations (FAO), Rome, Italy
FAO (2010) Sustainable crop production intensification through an ecosystem approach and an enabling environment: capturing efficiency through ecosystem services and management, COAG/2010/3. Food and Agriculture Organization of the United Nations
FAO (2012) Looking ahead in world food and agriculture: perspectives to 2050. Food & Agriculture Organization of the United Nations (FAO), Rome, Italy

FAO (2013) Global Information System on Water and Agriculture (2013) Fao.org.http://www.fao.org/nr/water/aquastat/main/index.stm. Cited 24 Aug 2023

FAO (2018) Sustainable food systems: concept and framework. Rome

FAO (2019) The state of food security and nutrition in the World 2019: safeguarding against economic slowdowns and downturns. Food & Agriculture Organization of the United Nations (FAO), Rome, Italy

FLW Standard (2016) Food loss and waste protocol. https://flwprotocol.org/flw-standard/. Cited 25 Aug 2023

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M et al (2011) Solutions for a cultivated planet. Nature [Internet] 478(7369):337–342. https://doi.org/10.1038/nature10452

Foresight UK (2011) The future of food and farming. The Government Office for Science, London

Friel S, Dangour AD, Garnett T, Lock K, Chalabi Z, Roberts I et al (2009) Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture. Lancet [Internet] 374(9706):2016–2025. https://doi.org/10.1016/S0140-6736(09)61753-0

Fróna D, Szenderák J, Harangi-Rákos M (2019) The challenge of feeding the world. Sustainability [Internet] 11(20):5816. https://doi.org/10.3390/su11205816

Garn GA (1999) Solving the policy implementation problem. Educ Policy Anal Arch [Internet] 7:26. https://doi.org/10.14507/epaa.v7n26.1999

Garnett T, Godfray CH (2012) Sustainable intensification in agriculture: navigating a course through competing food system priorities. Food Climate Research Network and the Oxford Martin Programme on the Future of Food, UK

Garnett T (2013) Food sustainability: problems, perspectives and solutions. Proc Nutr Soc [Internet] 72(1):29–39. https://doi.org/10.1017/s0029665112002947

Gibson RH, Pearce S, Morris RJ, Symondson WOC, Memmott J (2007) Plant diversity and land use under organic and conventional agriculture: a whole-farm approach: whole-farm diversity in different systems. J Appl Ecol [Internet] 44(4):792–803. https://doi.org/10.1111/j.1365-2664.2007.01292.x

Gills R, Sharma JP, Bhardwaj T (2015) Achieving zero hunger through zero wastage: an overview of present scenario and future reflections. Indian J Agric Sci 85(9):1127–1133

Grote U (2014) Can we improve global food security? A socio-economic and political perspective. Food Secur [Internet] 6(2):187–200. https://doi.org/10.1007/s12571-013-0321-5

Hamerschlag K (2011) Meat eater's guide to climate change and health. Environmental Working Group, Washington, DC

Hodges RJ, Buzby JC, Bennett B (2011) Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. J Agric Sci [Internet] 149(S1):37–45. https://doi.org/10.1017/s0021859610000936

Hoffmann I (2021) Declining biodiversity threatens food security. World Food J

Houghton E, Portougal V (1997) Reengineering the production planning process in the food industry. Int J Prod Econ [Internet] 50(2–3):105–116. https://doi.org/10.1016/s0925-5273(97)00036-4

Hu H, Dai M, Yao J, Xiao B, Li X, Zhang Q et al (2006) Overexpressing a NAM, ATAF, and CUC (NAC) transcription factor enhances drought resistance and salt tolerance in rice. Proc Natl Acad Sci USA [Internet] 103(35):12987–12992. https://doi.org/10.1073/pnas.0604882103

Ifeanyichukwu CD, Nwaizugbo IC (2019) The effect of socio-economic factors on sustainable food consumption in developing economies. Br J Market Stud (BJMS) 7(7):13–19

Johnston JL, Fanzo JC, Cogill B (2014) Understanding sustainable diets: a descriptive analysis of the determinants and processes that influence diets and their impact on health, food security, and environmental sustainability. Adv Nutr [Internet] 5(4):418–429. https://doi.org/10.3945/an.113.005553

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst [Internet] 76(1):1–10. https://doi.org/10.1007/s10457-009-9229-7

Kaiser M, Goldson S, Buklijas T, Gluckman P, Allen K, Bardsley A et al (2021) Towards post-pandemic sustainable and ethical food systems. Food Ethics [Internet] 6(1). https://doi.org/10.1007/s41055-020-00084-3

Kalnikaite V, Rogers Y, Bird J, Villar N, Bachour K, Payne S et al (2011) How to nudge in situ: designing lambent devices to deliver salient information in supermarkets. In: Proceedings of the 13th international conference on Ubiquitous computing. ACM, New York, NY, USA

Kassam A (2008) Agriculture at a crossroads: synthesis report of the international assessment of agricultural knowledge, science, and technology for development (IAASTD). In: Mcintyre BD, Herren HR, Wakhungu J, Watson RT (eds) Island Press, Washington, DC, p 95, US$20.00. ISBN 978-1-59726-550-8. Exp Agric [Internet]. 2010;46(1):115–116. https://doi.org/10.1017/s0014479709990676

Kennedy E, Raiten D, Finley J (2020) A view to the future: opportunities and challenges for food and nutrition sustainability. Curr Dev Nutr [Internet] 4(4):nzaa035. https://doi.org/10.1093/cdn/nzaa035

Kloppenburg J Jr, Lezberg S, De Master K, Stevenson G, Hendrickson J (2000) Tasting food, tasting sustainability: defining the attributes of an alternative food system with competent, ordinary people. Hum Organ [Internet] 59(2):177–186. https://doi.org/10.17730/humo.59.2.8681677127123543

Lang T (2009) Reshaping the food system for ecological public health. J Hunger Environ Nutr [Internet] 4(3–4):315–335. https://doi.org/10.1080/19320240903321227

Langhelle O (2000) Sustainable development and social justice: Expanding the Rawlsian framework of global justice. Environ Values [Internet] 9(3):295–323. https://doi.org/10.3197/096327100129342074

Lindrup MVA, Cheon E, Skov MB, Raptis D (2021) One byte at a time: Insights about meaningful data for sustainable food consumption practices. In: Designing interactive systems conference 2021. ACM, New York, NY, USA

Looking Ahead in World Food and Agriculture, 2011Looking Ahead in World Food and Agriculture: Perspectives to 2050. Food and Agriculture Organization, Rome, 2011

Martins A (2009) Possibilities and limits of transgenics in ensuring food security and food sovereignty. 4th GARNET Annual. Rome

Milder JC, Garbach K, Declerck F, Driscoll L, Montenegro M (2012) An assessment of the multi-functionality of agroecological intensification. A report prepared for the Bill & Melinda Gates Foundation

Millward DJ, Garnett T (2010) Plenary Lecture 3 Food and the planet: nutritional dilemmas of greenhouse gas emission reductions through reduced intakes of meat and dairy foods: conference on 'over-and undernutrition: challenges and approaches'. Proc Nutr Soc 69(1):103–118

Ministry of Economic Affairs of the Netherlands (2016) Champions 12(3)

Morawicki RO, Díaz González DJ (2018) Food sustainability in the context of human behavior. Yale J Biol Med 91(2):191–196

Morone P, Koutinas A, Gathergood N, Arshadi M, Matharu A (2019) Food waste: challenges and opportunities for enhancing the emerging bio economy. J Clean Prod 221:10–16

Nelson DE, Repetti PP, Adams TR, Creelman RA, Wu J, Warner DC et al (2007) Plant nuclear factor Y (NF-Y) B subunits confer drought tolerance and lead to improved corn yields on water-limited acres. Proc Natl Acad Sci USA [Internet] 104(42):16450–16455. https://doi.org/10.1073/pnas.0707193104

Oerke EC (2006) Crop losses to pests. J Agric Sci [Internet] 144(1):31–43. https://doi.org/10.1017/s0021859605005708

Östergren K, Gustavsson J, Bos-Brouwers H, Timmermans T, Hanssen OJ, Møller H et al (2014) Fusions definitional framework for food waste—full report

Pelletier N, Tyedmers P (2010) Forecasting potential global environmental costs of livestock production 2000–2050. Proc Natl Acad Sci USA [Internet] 107(43):18371–18374. https://doi.org/10.1073/pnas.1004659107

Poore J, Nemecek T (2018) Reducing food's environmental impacts through producers and consumers. Science [Internet] 360(6392):987–992. https://doi.org/10.1126/science.aaq0216

Popkin BM (1999) Urbanization-lifestyle changes and the nutrition transition. World Dev 27(11):1905–1916

Popp A, Lotze-Campen H, Bodirsky B (2010) Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production. Glob Environ Change [Internet] 20(3):451–462. https://doi.org/10.1016/j.gloenvcha.2010.02.001

Poyatos-Racionero E, Ros-Lis JV, Vivancos JL, Martínez-Máñez R (2018) Recent advances on intelligent packaging as tools to reduce food waste. J Clean Prod [Internet] 172:3398–3409. https://doi.org/10.1016/j.jclepro.2017.11.075

Premanandh J (2011) Global consensus-Need of the hour for genetically modified organisms (GMO) labeling. J Commer Biotechnol 17:37–44

Pretty J, Bharucha ZP (2014) Sustainable intensification in agricultural systems. Ann Bot [Internet] 114(8):1571–1596. https://doi.org/10.1093/aob/mcu205

Pretty J (2008) Agricultural sustainability: concepts, principles and evidence. Philos Trans R Soc Lond B Biol Sci [Internet] 363(1491):447–465. https://doi.org/10.1098/rstb.2007.2163

Ramachandran Nair PK, Mohan Kumar B, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Plant Nutr Soil Sci [Internet] 172(1):10–23. https://doi.org/10.1002/jpln.200800030

Raybould A, Quemada H (2010) Bt crops and food security in developing countries: realized benefits, sustainable use and lowering barriers to adoption. Food Secur 2:247–259

Reaping the benefits: science and the sustainable intensification of global agriculture. The Royal Society, London (2009)

Sajid A, Ayatullah, Khan AN, Iqbal S, Abbas S, Natasha Kashif IA et al (2017) Socio-economic constraints affecting sustainable rural livelihood. Arts Soc Sci J [Internet] 09(01). https://doi.org/10.4172/2151-6200.1000324

Shafer SR, Walthall CL, Franzluebbers AJ, Scholten M, Meijs J, Clark H et al (2011) Emergence of the global research alliance on agricultural greenhouse gases. Carbon Manag [Internet] 2(3):209–214. https://doi.org/10.4155/cmt.11.26

Shafiee-Jood M, Cai X (2016) Reducing food loss and waste to enhance food security and environmental sustainability. Environ Sci Technol [Internet] 50(16):8432–8443. https://doi.org/10.1021/acs.est.6b01993

Sinha R, Cross AJ, Graubard BI, Leitzmann MF, Schatzkin A (2009) Meat intake and mortality: a prospective study of over half a million people. Arch Intern Med [Internet] 169(6):562–571. https://doi.org/10.1001/archinternmed.2009.6

Smith P, Martino D, Cai Z (2007) Agriculture. In: Climate change 2007: mitigation. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY

Smith P (2013) Delivering food security without increasing pressure on land. Glob Food Sec [Internet] 2(1):18–23. https://doi.org/10.1016/j.gfs.2012.11.008

Stocking M, Murnaghan N (2001) Handbook for the field assessment of land degradation. Earthscan Publications, London

Teixeira JA (2018) Grand challenges in sustainable food processing. Front Sustain Food Syst [Internet] 2. https://doi.org/10.3389/fsufs.2018.00019

The state of food security and nutrition in the world 2022. FAO (2022)

Thomas P (2010) Healthy planet eating: how lower meat diets can save lives and the planet

Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. Nature [Internet] 418(6898):671–677. https://doi.org/10.1038/nature01014

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci USA [Internet] 108(50):20260–20264. https://doi.org/10.1073/pnas.1116437108

Tuscano M, Lamine C, Bre-Garnier M (2021) Fostering responsible food consumption: a framework combining practice theories and pragmatism applied to an institutional experimental tool. J Rural Stud [Internet] 86:663–672. https://doi.org/10.1016/j.jrurstud.2021.05.029

Unilever PLC (2017) Five steps to reduce food loss and waste [Internet]. Unilever PLC. https://www.unilever.com/news/news-search/2017/five-steps-to-reduce-food-loss-and-waste/. Cited 25 Aug 2023

United Nations: Department of Economic and Social Affairs: Population Division (2019) World population prospects: highlights, key findings and advance tables. United Nations, New York, NY

Vågsholm I, Arzoomand NS, Boqvist S (2020) Food security, safety, and sustainability—getting the trade-offs right. Front Sustain Food Syst [Internet] 4. https://doi.org/10.3389/fsufs.2020.00016

del Valle MM, Shields K, Alvarado Vázquez Mellado AS, Boza S (2022) Food governance for better access to sustainable diets: a review. Front Sustain Food Syst [Internet] 6. https://doi.org/10.3389/fsufs.2022.784264

Vij S, Tyagi AK (2007) Emerging trends in the functional genomics of the abiotic stress response in crop plants. Plant Biotechnol J [Internet] 5(3):361–380. https://doi.org/10.1111/j.1467-7652.2007.00239.x

Vittersø G, Tangeland T (2015) The role of consumers in transitions towards sustainable food consumption. The case of organic food in Norway. J Clean Prod [Internet] 92:91–99. https://doi.org/10.1016/j.jclepro.2014.12.055

Wahbeh S, Anastasiadis F, Sundarakani B, Manikas I (2022) Exploration of food security challenges towards more sustainable food production: a systematic literature review of the major drivers and policies. Foods [Internet] 11(23):3804. https://doi.org/10.3390/foods11233804

Wezel A, Herren BG, Kerr RB, Barrios E, Gonçalves ALR, Sinclair F (2020) Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. Agron Sustain Dev [Internet] 40(6). https://doi.org/10.1007/s13593-020-00646-z

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S et al (2019) Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet [Internet] 393(10170):447–492. https://doi.org/10.1016/s0140-6736(18)31788-4

Wolfenbarger LL, Naranjo SE, Lundgren JG, Bitzer RJ, Watrud LS (2008) Bt crop effects on functional guilds of non-target arthropods: a meta-analysis. PLoS One [Internet] 3(5):e2118. https://doi.org/10.1371/journal.pone.0002118

World agriculture towards 2030/2050, 2012World agriculture towards 2030/2050: the 2012 revision. Food and Agriculture Organisation, Rome (2012)

Wrap W (2009) Household food and drink waste in the UK

Wunderlich SM, Martinez NM (2018) Conserving natural resources through food loss reduction: production & consumption stages of the food supply chain. Int Soil Water Conserv Res 6(4):331–339

Zimmermann A, Rapsomanikis G (2023) Trade and sustainable food systems. In: Science and innovations for food systems transformation. Springer International Publishing, Cham, pp 685–709

Responsible Consumption and Sustainable Diets

Wild Edible and Wetland Plants of Manipur: Their Sustainable Food Usage

Ringshangphi Khapudang, Lanchenbi Chanu Loukrakpam, Sadhana Jadaun, Usha Sharma, and Saleem Siddiqui

1 Introduction

The wild edible plants (WEPs) and wetland plants (WLPs) refers to plants that have one or more edible parts suitable for consumption as food when harvested at the right stage and prepared correctly (Kallas 2010). They play a significant role in the lives of the indigenous communities around the globe (Reyes-García et al. 2005; Mengistu and Hager 2008) by providing nourishment, dietary variety and medicinal benefits (Fig. 1) (Ogle 2001; Pieroni and Price 2006). However, the current global food production system heavily relies on a limited number of domesticated species contributing to 90% of total food production (Misra et al. 2008). The over-reliance on this small range of crops creates potential vulnerabilities in modern agriculture, making it susceptible to abiotic and biotic pressures and the neglect of numerous wild plants that grow naturally intensify the situation. The incorporation of wild plants in the agricultural practices can crucially enhance the sustainability thereby mitigating the potential of excessive reliance on these crops. The additional advantage is that the usage of wild plants are deeply rooted in the tradition and culture of world's indigenous communities, where it contribute as a means of subsistence and income generation (Purba and Silalahi 2021). The wild plants also offer the dietary diversity by acting as a staple food and providing nutrition, where the plants provide essential nutrients, vitamins and minerals surpassing that of cultivated vegetables. The wild plants also exhibit medicinal or therapeutic properties owing to the biologically active compounds, which are considered not only as food but also high quality nutraceutical.

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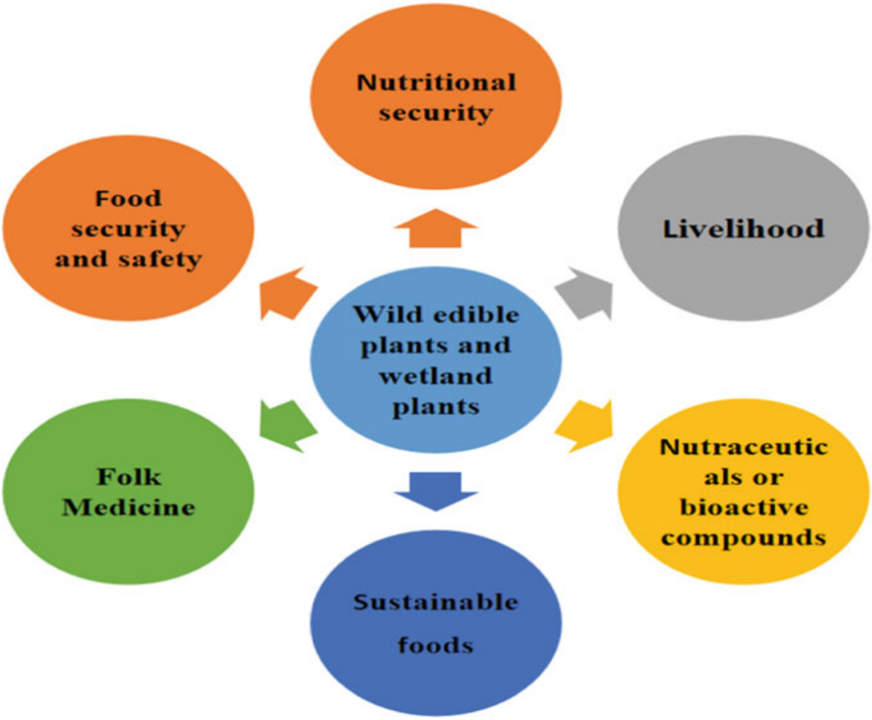

Fig. 1 Importance of WEPs and WLPs

These plants also contribute to the food security by serving as a buffer during the scarcity of conventional food sources (Thakur and Belwal 2022). Apart from these, it also provides an alternative source of income for the marginalized rural population (Medhi et al. 2014).

Harnessing the potential of these plants can significantly enhance the sustainability in agriculture where the need of inputs can reduce the impact on environment because the broad array of genetic traits inherent to these plants can be used to develop new crops through domestication. Despite the immense importance of these plants, it remained widely unknown and underutilized due to its limitation to specific regions or communities. With rapid decline of the traditional knowledge of these plants, limited information on nutritional value and increasing dependence on the processed foods, documenting the diversity, usage, conservation, management and sustainable approach to these plants are crucial. By understanding the potential of these plants, the stakeholders can collaborate to promote sustainable approaches and practices that can facilitate the integration of these plants into the agroforestry and agricultural systems to bolster their dietary value.

The state of Manipur (Fig. 2) is inhabited by various ethnic groups and communities of India following various cultural practices. The Naga, the Kuki and the Mizo tribes in the hills of the state and the valley is populated by the Meitei and the Meitei

Pangal (Khan et al. 2015). Manipur has an area of 22,327 km^2 where hill area accounts for 67% of total land area which serves as a prime habitat of many wild plant species; and wetland area of nearly 592 km^2 which are situated in lowlands comprising of 21 lakes, 2 ox-bows, 2 reservoirs, 130 water logged sites (ENVIS Centre 2015). The region is also a part of the Indo-Burma biodiversity hot spot which is one of the 25 globally recognized biodiversity hot spot (Singh et al. 2009), making it a region blessed with rich endemism of wild plants. It was reported by Chatterjee et al. (2006) that in Manipur there are 13,500 plant species of which 7000 are endemic. Charkraborty et al. (2012) reported that some 2500 species of flowering plant exist in the state.

This chapter aims to explore the main characteristics and consumption pattern of some wild plants highlighting the rich diversity and traditional knowledge of their dietary usage. By understanding these aspects, it facilitates the preservation and conservation of these underutilised plants. The potential and future scope for sustainability will also be addressed and discussed.

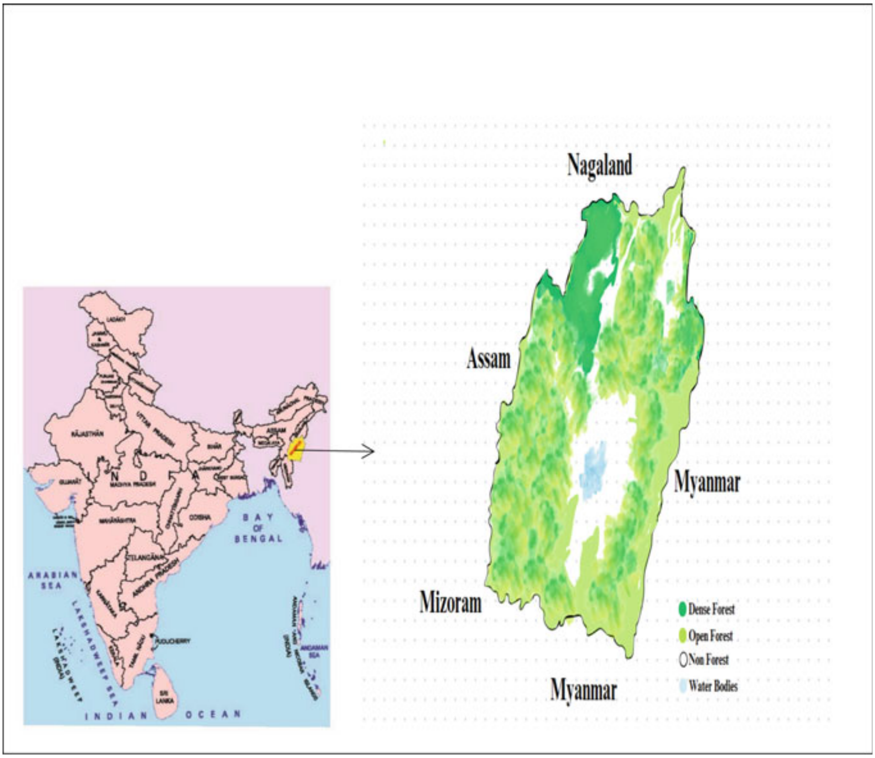

Fig. 2 Map of Manipur

2 Wild Edible Plants

The WEPs with diverse range play a vital role in food security for the ethnic communities of Manipur, particularly in remote villages. Traditionally, these ethnic communities rely on the seasonal WEPs to provide as the necessary source of nutrition. The diverse climate variations of Manipur contribute to its abundant biodiversity which is greatly valued and utilized by the indigenous people. The people of Manipur also possess extensive knowledge about the flora and fauna and their traditional practices often entail the use of forest resources. Furthermore, folk medicine is also prevalent among all the ethnic communities of the state (Deb et al. 2015). While limited research studies have conducted on the nutritional quality and food processing potential of these sources, the existing research indicates that many common WEPs possess high nutritional and nutraceutical properties. In fact, the nutrients such as vitamins, minerals and antioxidant found in these plants often surpass those of commercial crops (Sharma et al. 2013). The rough estimate of all the markets in the major four districts of the state indicates the consumption of approximately 90 tonnes of wild fruits and 90–200 tonnes of WEPs. These fruits and vegetables are not only regarded as the source of sustenance but also believed to have medicinal and health promoting properties. More than 250 different species of wild plants are used as food in this region (Devi et al. 2010). The ethnic communities have developed traditional cuisines that incorporate a wide variety of WEPs. *Singju*, *Eromba/Eronba*, *Ooti*, *Chagaempomba* and *Kangsoi* are some of the traditional dishes that form an essential part of their daily dietary habit which are often prepared by a combination of WEPs and fermented fish called *Ngari*, chilli and other vegetables. While the preparation method is similar, the utilization of these WEPs differs according to the communities based on their taste preference and dietary habit. Including one or more wild edible plants is an integral aspect of the local cuisine. Some of the traditional dishes prepared from them are as follows:

(i) ***Singju***: It is traditional salad, a raw dish that combines various wild leafy vegetables with fermented fish, chilli and other ingredients like cabbage (Fig. 3a).
(ii) ***Eromba/Eronba***: This dish is cooked by boiling plants parts (stems, rhizomes, leaves, inflorescences) and mashing with them potatoes or peas along with chilli, fermented fish resulting in a gravy-like (Fig. 3b).
(iii) ***Ooti***: The preparation involves boiling a mixture of vegetables (stems, leaves) together with rice and a small amount of sodium bicarbonate (Fig. 3c).
(iv) ***Chagempomba***: This traditional dish is cooked by boiling soyabean, rice, and some of leafy vegetables (Fig. 3d)
(v) ***Kangsoi***: This traditional stew is made by boiling a combination of leafy vegetables and potatoes with chilli, salt, fermented fish and small dried fish (Fig. 3e)

Fig. 3 Traditional Manipuri dish (**a**–**e**)

2.1 Classification of WEPs on the Basis of Plant Part Used

The WEPs constitutes a significant portion of around 40% of the vegetables and fruits available in local market throughout the year. The WEPs exhibit diverse life forms including trees, shrubs, herbs, climbers, creeper, weeds and hydrophytes. When it comes to edible parts, leaves are the most dominant, followed by shoots and stems. These parts are consumed as cooked vegetables through boiling, steaming or frying.

The WEPs have classified into following different groups on the basis of the plant part that bear more economic importance and food use.

(i) **Leafy Vegetables**

Numerous WEPs are commonly ingested as a source of leafy vegetables. Konsam et al. (2016) conducted a survey on the WEPs from the 20 major markets of Manipur and reported that for 49% of the total wild plants, leaves were the widely consumed part, being used as vegetable; herbal medicine in treatment of bronchitis, tooth ache, diabetics, etc.; and also as poultry feed, fuel-wood and fencing material. Some of the wild edible leafy vegetables are illustrated in Fig. 4. The information on different types of wild edible plants, where the leaves are used as the major edible part, has been presented in Table 1.

Fig. 4 Some wild leafy vegetables

(ii) Fruits

The fruits obtained from the edible wild plants plays an important function in supporting livelihoods to indigenous people in Manipur. In Fig. 5, some of the wild edible fruits are shown. Table 2 documents the fruits and seeds that are used by the people for various purposes. In rural areas of Manipur, fruits of *Tamarindus indica*, *Zizphus mauritiana*, *Phyllanthus embilica*, *Spondias pinnata*, *Malus baccata* are extensively utilized in preparation of pickle, fruit curry called *hei-thongba*, etc. (Khan et al. 2015; Salam et al. 2019). Similarly, for the preparation of indigenous wine called *Atingba*/*Yu*, *Artocarpus heterophylulus*, A*verrhoa caramhola* and *Pyrus indica* are used. Apart from the dietary use of the fruits, the fruit trees are used as charcoal, firewood, construction timber from *Eugenia jambolana* Lam., *Artocarpus heterophllus* Lamk., *A. lakoocha* Roxb., *Olea ferrguniea* Royle., *Terminalia chebula* Retz., *Tamarindus indica* L. and *Ziziphus mauritiana* Lam. Dyes from some of the fruits such as *Terminalia chebula* Retz., *Eugenia jambolana* Lam., *Rhus semialata* Murr., *Punica granatum* L. and *Phyllanthus embilica* L., are used in local handicraft industries for colouring the traditional attire of men and women. Some of the wild fruits are used to produce oil especially from the peels of *Citrus limon* (L.) Burm. f.

Table 1 List of WEPs used as leafy vegetables

Local names	Scientific name	Family	Mode of utilization or preparation
Anpuinu	*Hiptage* sp.	Malpighiaceae	Consumed either raw or steam with chutney
Ansah	*Spilanthes paniculata* Wall. ex DC.	Asteraceae	Cooked along with other vegetables
Ansingteh	*Lycianthes laevis* (Dunal) Bitter	Solanaceae	Cooked together either with meat or rice
Anthru	*Momordica dioica* Roxb. ex Willd.	Curcurbitaceae	Cooked through boiling, commonly along with rice known as "*chagempomba*"
Awaphadigom	*Eryngium foetidum* L.	Apiaceae	Used as a spice specially in meat curry
BP mana/Khuthap angouba	*Clerodendrum colebrookianum* Walp.	Lamiaceae	Consumed by boiling with salt or cooking them as vegetables
Ching heiyen	*Antidesma acidum* Retz.	Phyllanthaceae	Leaves are edible both in their raw state and when cooked as vegetables
Ching Yensil	*Antidesma diandrum* (Roxb.) B.Heyne ex Roth.	Euphorbiaceace	Prepared and consumed as *eromba*, or cooked alongside potatoes and dry fish
Chuchurngmei	*Sesbania sesban* (L.) Merr.	Leguminosae	Raw leaves added in *singju*
Heiba mana	*Exbucklandia populnea* (R.Br. ex Griff.) R.W.Br.	Hamamelidaceae	Consumed raw in *singju*, eaten as cooked vegetable or used to make chutney
Heibi mana	*Vangueria spinosa* (Roxb. ex Link) Roxb.	Rubiaceae	Leaves are added raw in *singju*
Honghu	*Alocasia macrorrhizos* (L.) G. Don	Araceae	Cooked as a vegetables
Huihu	*Derris wallichii* Prain	Leguminosae	Cooked with potatoes or as *eromba*
Kanghumaan	*Meriandra bengalensis* (Roxb.) Benth.	Lamiaceae	Used as a raw dressing for *singju* and *eromba*
Kongouyen	*Cissus javanica* DC.	Vitaceae	Cooked by boiling together with potatoes and dry fish
Lamthabi	*Cyclanthera pedata* (L.) Schrad.	Cucurbitaceae	Consumed by boiling them in water with a small amount of salt (*Champhut*)
Moirang khanam	*Clerodendrum serratum* (L.) Moon.	Lamiaceae	Steamed and subsequently used to make chutney
Monsaobi	*Chenopodium album* L.	Amaranthaceae	Cooked together with other vegetables

(continued)

Table 1 (continued)

Local names	Scientific name	Family	Mode of utilization or preparation
Morok maan	*Solanum nigrum* L.	Solanaceae	Either boiled and consumed as such or cooked together with meat or with rice
Mukthrubi	*Zanthoxylum acanthopodium* DC.	Rutaceae	Eaten raw with chilli, in fermented fish chutney or as an additive in snail curry (*Tharoi thongba*)
Naosekmanbi	*Zanthoxylum* sp.	Rutaceae	Eaten raw as *singju*, cooked as *kangsoi* or added in meat curry
Oothum	*Wendlandia paniculata* (Roxb.) DC.	Rubiaceae	Tender leaves are consumed as *eromba* along with black pea or for preparation of chutney
Sijou mana	*Eurya acuminata* DC.	Pentaphylacaceae	Cooked as *ooti*, *chagempomba* and *eromba*
Singjwal	*Zanthoxylum budrunga* DC.	Rutaceae	Consumed raw in *singju* and cooked as vegetable dish
Sita phal	*Passiflora edulis* Sims.	Passifloraceae	Eaten as cooked vegetable, added to meat curry
Toninkhok	*Houttuynia cordata* Thunb.	Saururaceae	Leaves are used as accessory additives or spice
Wah-vu	*Polygonum molle* D.Don	Polygonaceae	Cooked and served as vegetable dish
Yendang	*Cycas pectinata* Buch.-Ham.	Cyadaceae	Consumed raw in the form of *singju* and cooked before being eaten as *eromba*

Source Konsam et al. (2016), Pfoze et al. (2011), Salam et al. (2012)

and fruits from *Phyllanthus embilica* L. However, the extraction from these fruits for oil has reduced remarkably owing to readily available of oil products from external market (Hazarika and Singh 2018).

(iii) **Inflorescence**

The consumption of wild edible flower has been a prevalent practice since the early days of human civilization. People have incorporated these flowers into their diets for various purposes such as for garnishing, used to make stir fried, dyes, etc. (Gupta et al. 2018; Rop et al. 2012). These flowers are valued for their natural source of antioxidant and recognized for their diverse biochemical properties including anti-bacterial, anti-inflammatory, antimicrobial, anti-cancerous, anti-fungal etc. (Kumari and Bhargava 2021). In times of famine, the integration of edible wild flower in dietary routine enhances the variety of consumable food options as well as helps

Fig. 5 Some wild edible fruits

alleviate food insecurity. While numerous inflorescences are edible, there remains a lack of proper identification and documentation which is crucial for understanding their usefulness (Gupta et al. 2018). Some of the edible inflorescence are shown in Fig. 6. The information on various flowers of wild plants used as dietary source is presented in Table 3.

(iv) Shoots, Stems, Rhizomes and Tubers

The use of a wide varieties of shoots, stems, rhizomes and tubers of wild plants are reported. Meitei et al. (2022) reported on that the rhizomes of Zingiberaceae were the most widely used as WEPs. It was also reported the use of tubers, stem pith and pseudostem as WEPs. Konsam et al. (2016) reported the use shoots and stem (22%) as the second highest consumed edible parts of the WEPs. Kongouyen (*Cissus javanica*), Torong Khongnang (*Ficus benghalenisis*), Solunche/Jyan/Gariyangei (*Elastostema lineolatum)* are among the highly consumed WEPs due to its unique taste, high abundance, high market value and ease of processing. Khan et al. (2015) also reported the medicinal value of the tender stems as WEPs. Premlata et al. (2020) reported the uses of bamboo shoots consumed as food in the various parts of Manipur in the form of dried, fresh, pickled, boiled and fermented form. The use of shoots, stems rhizomes and tubers of WEPs has been documented in Table 4.

(v) Wild Edible Mushrooms

Wild mushrooms are a potential food reservoir amidst the dwellers of the forest rural villages for their nourishment. Wild edible mushroom are consumed as vegetables and are highly regarded as potential provider of fibers, proteins, phenols, vitamin D2, antioxidant properties as well as essential macronutrients like magnesium and potassium (Valverde et al. 2015). The United Nations and the FAO have acknowledge the importance in integrating the edible wild mushroom as a source for human

Table 2 Dietary use of some wild edible fruits

Local name	Scientific name	Family	Mode of utilization
Ching heiyen	*Antidesma acidum* Retz.	Phyllanthaceae	Eaten as raw
Chingonglei	*Leucaena leucocephala* (Lam.) de Wit	Fabaeceae	Eaten raw as an ingredient of *singju*, cooked as *eromba*
Chorphon	*Elaeocarpus floribundus* Blume	Elaeocarpaceae	Eaten raw, pickled, cooked, fruit beer
Heibi	*Meyna spinosa* Roxb. ex Link	Rubiaceae	Fruits are eaten raw
Heibong	*Ficus auriculata* Lour.	Moraceae	Eaten raw
Heibung	*Garcinia pedunculata* Roxb. ex Buch.-Ham.	Clusiaceae	Eaten as raw or cooked as *hei thongba*, dried
Heijampet	*Rubus ellipticus* Sm.	Rosaceae	Eaten raw
Heijuga	*Juglans regia* L.	Juglandaceae	Eaten raw
Heikhathei (Tangkhul)	*Prunus salicina* Lindl.	Rosaceae	Eaten raw and used to make fruit beer
Heikru	*Phyllanthus emblica* L.	Phyllanthaceae	Eaten raw, pickles. Dried, fruit beer
Heimang	*Rhus chinensis* Mill.	Anacardiaceae	Eaten raw or powdered, juice or candy
Heinoujam	*Averrhoa carambola* (l.) Merr.	Oxalidaceae	Eaten raw and made into jam and candy
Heirikkokthong	*Artocarpus lacucha* Buch.-Ham.	Moraceae	Ripe fruits are eaten raw whereas unripe fruits cooked as vegetables
Heirit	*Ficus semicordata* Buch.-Ham. ex Sm.	Moraceae	Eaten raw, fruit beer
Heithup	*Docynia indica* (Colebr. ex Wall.) Decne.	Rosaceae	Eaten raw, used as pickle, roasted, candy, fruit beer
Jam	*Syzygium cumini* (L.) Skeels	Myrtaceae	Eaten raw and jam
Kathai	*Hodgsonia heteroctita* Hk.f. and Th (Syn. *H. macrocarpa* (Bl.) Cogn. In DC)	Cucurbitaceae	Chutney made from the dried seeds
Lam khamen	*Solanum torvum* Sw.	Solanaceae	Cooked as vegetables
Lam naspati	*Pyrus pashia* Buch.-Ham. ex D.Don	Rosaceae	Eaten raw
Mange	*Tamarindus indica* L.	Leguminosae	Eaten raw
Nonganghei	*Myrica esculenta* Buch.-Ham. ex D.Don	Myricaceae	Eaten raw or pickled or fruit beer

(continued)

Table 2 (continued)

Local name	Scientific name	Family	Mode of utilization
Saharthei (Tangkhul)	*Prunus cerasoides* Buch.-Ham. ex D.Don	Rosaceae	Eaten raw
Theikanthei (Tangkhul)	*Prunus napaulensis* (Ser.) Steud.	Rosaceae	Eaten raw and used to make fruit beer
U-thanjing	*Castanopsis tribuloides* A. DC.	Fagaceae	Seed are roasted and eaten

Sources Khan et al. (2015), Konsam et al. (2016), Salam et al. (2019)

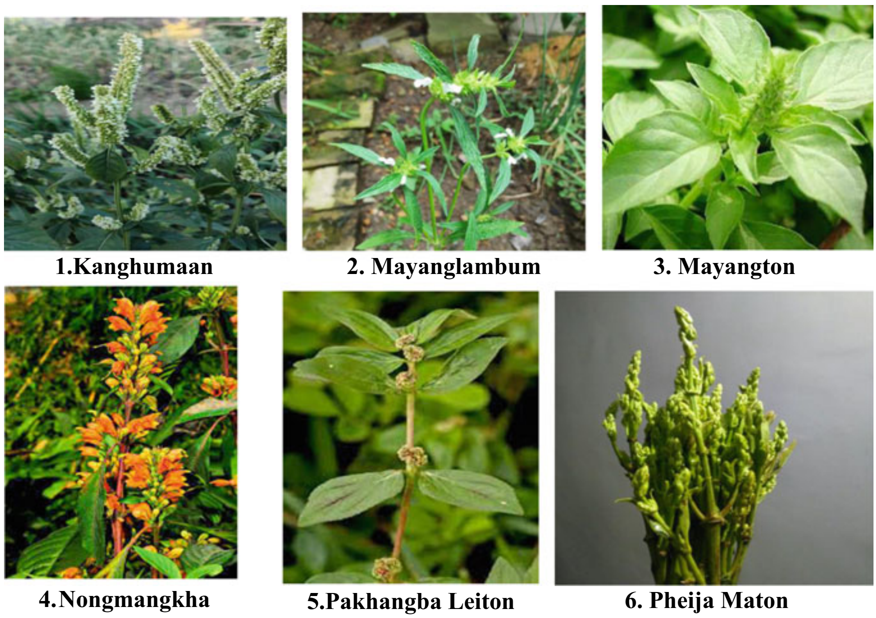

Fig. 6 Some wild edible inflorescences

nourishment, recognizing as a sustainable practices to address the increasing dietary requirements and food insecurity (Toshinungla et al. 2016). Apshahana and Sharma (2018) conducted a market survey at Senapati hill district of Manipur revealing that altogether 8 varieties of macrofungi associated with seven families were found to be traded and consumed. They are mostly used as chutney, salads, in preparing soup and other various dishes. Salam and Jamir (2018) also conducted a market survey in Ukhrul district of Manipur and found 14 varieties of edible wild mushrooms associated with 8 genera under 7 families. Muragkar and Subbulakshmi (2005) reported on the dietary status of wild edible mushroom, where it was reported that the mushrooms contained protein (6.12 g/250 g), fat (0.172 g/250 g), sodium (0.077 mg/250 g) and

Table 3 Dietary use of some wild inflorescences

Local name	Scientific name	Family	Mode of use
Kanghumaan	*Meriandra bengalenis* (Roxb.) Benth.	Lamiaceae	Used as dressing in *eromba* or *singju*
Lam Nongmangkha	*Phlagacanthus curviflorus* (Nees) Nees	Acanthaceae	Cooked as vegetable, boiled with rice
Laphu	*Musa balbsiana* Colla	Musaceae	Cooked as *eromba* or used as ingredient of *singju*
Leibak kundo	*Portulaca oleracea* L.	Portulaceae	Cooked along with dried fish
Lidanipa (Mao-Naga)	*Rhododendron arboreum* Smith	Ericaceae	Eaten raw and nectar is brew to make wine
Mayanglambum	*Leucas aspera* (Willd.) Link	Lamiaceae	Cooked as vegetable
Mayangton	*Ocimum canum* (Sims.)	Lamiaceae	It is consumed raw in the formed of chutney called *morok metpa* or as condiments in *eromba*
Mukthrubi	*Zanthoxylum acanthopodium* DC.	Rutaceae	Used as spice
Nongmangkha	*Phlagocanthes thysiformis* Nees.	Acanthaceae	Eaten as fried or as a sweet chutney
Pakhangba Leiton	*Euphoria hirta* L.	Euphorbiaceae	Eaten raw or cooked
Pheija Maton	*Wendlandia glabrata* DC.	Rubiaceae	Eaten as raw in *singju* or made chutney or cooked as *eromba*
Sarei mapan	*Amomum* sp.	Zingiberaceae	Cooked as vegetable
Siing	*Zingiber officinalis* Roscoe	Zingiberaceae	Used as spices and condiments
Yaipan	*Curcuma angustifolia* Roxb.	Zingiberaceae	Cooked as vegetable
Oosingsha mapan	*Litsea cubeba* (Lour.) Pers.	Lauraeceae	Raw used as chutney cooked as *eromba*

Source Devi et al. (2009), Thockchom et al. (2016)

zinc (3.72 mg/250 g). The information on wild edible mushroom used as dietary source and their mode of utilization is presented in Table 5.

3 Wetland Plants

Wetlands are often referred to as "Wealth lands" or Biological supermarkets due to their vast food chain and diverse biodiversity, which they support (Moirangleima 2010). Despite covering only about 2.5% of Manipur's geographical area, nearly 99% i.e., 153 sites are situated in the valley and the other two wetland situated at

Table 4 Dietary use of stems, shoots, tubers, rhizomes

Local name	Scientific name	Family	Mode of utilization
–	*Ensete glaucum* (Roxb.)	Musaceae	Pseudostem are cooked as vegetables
–	*Hedychium ellipticum* Buch.-Ham. ex Sm.	Zingiberaceae	Rhizomes cooked as vegetables
Laiwa	*Chimonobambusa callosa* (Munro) Nakai	Poaceae	Cooked as *eromba* or as *kanghou* (stir fried)
Langban koukha	*Exallage auricularia* (L.)	Rubiaceae	Young shoots are cooked as vegetables
Laphu	*Musa balbisiana* Colla	Musaceae	Pseudostem are cooked as *eromba* or used as an ingredient of *singju*
Moubi-wa	*Melacanna baccifera* (Roxb.) kurz.	Poaceae	Eaten boiled (*Champhut*) or with meat
Naat	*Cephalostachyum capitatum* Munro	Poaceae	Apical shoots are used to make fermented product '*Soidon*'
Nunggarei	*Asparagus racemosus* Willd.	Asparagaceae	Shoots are cooked or eaten raw, tubers are cooked
Oinam	*Paederia foetida* L.	Rubiaceae	Young shoot are cooked as vegetables
Sembang kaothum	*Cyperus rotundus* L.	Cypereace	Tuber is boiled or eaten raw
Sinthupi	*Dysoxylum gobara* (Buch.-Ham.) merr.	Meliaceae	Tender stem are boiled and strain, cooked as vegetables
Takhellei Hangampal	*Hedychium spicatum* Sm.	Zingiberaceae	Rhizomes cooked as vegetables
Toninkhok	*Houttuynia cordata* Thunb.	Saururaceae	Roots are used as condiments or spice
Ui	*Dendrocalamus manipureanus* Naithani & Bisht	Poaceae	Shoots are used to make fermented product called '*soibum*' and is used to prepared *eromba*
Unap/ Wanap	*Dendrocalamus hamiltonni* Nees & Arn. ex Munro	Poaceae	Shoots are used to make fermented product called '*soibum*' and is used to prepared *eromba*
Utang	*Bambusa tulda* Roxb.	Poaceae	Shoots are cooked as *ushoi ooti* and *usoi kangsu*
Watankhoi	*Dendrocalamus hookeri* Munro	Poaceae	Shoots are cooked as *ushoi ooti* and *usoi kangsu*

Source Premlata et al. (2020), Meitei et al. (2022)

Table 5 Wild edible mushroom and their mode of utilization

Local name	Scientific name	Family	Utilization mode
Sipovar	*Agaricus campetris* L.	Agaricaiae	Eaten fried or cooked with meat
Shiokkhanavar	*Auricularia polytricha* (Mont.) Sacc.	Auriculariaceae	Eaten fried or with dal
Shiokkhanavar (Tangkhul)/Uchina (Meitei)	*Auricularia delicata* (Fr.) Henn.	Auriculariaceae	Cooked with dal
Chengum khomthokpi	*Lactarius princeps*	Russulaceae	Cooked as vegetable with dry fish
Uyen	*Laetiporus sulphureus* (Fr.) Murr.	Polyporaceae	Consumed in the form of *Eromba* mashed with fermented fish
Thangjiyen (Tangkhul)/Uyen (Meitei)	*Lentinula edodes* (Berk.) Pegler	Polyporaceae	Cooked as vegetables in mixed with other vegetables
Thangjiyen	*Lentinula lateritia* (Berk.) Pegler	Polyporaceae	Eaten as *Eromba* (mashed with fermented fish)
Uyen	*Lentinus conatus* Berk.	Polyporaceae	Cooked with pork meat
Uyen	*Lentinus squarrossulus* Mont.	Polyporaceae	Cooked with meat
Uyen	*Pleurotus flabellatus* (Berk. and Br.) Sacc	Polyporaceae	Consumed as simple boiled vegetables along dry fish
Uchekkhong (Tangkhul)	*Ramaria sanguinea* (Pers.) Quel.	Clavariaceae	Eaten fried or cooked with fish
Lengphong (Tangkhul)/ Kanglayen (meitei)	*Schizophyllum commune* Fr.	Schizophyllaceae	Cooked with fish or pork
Varlang	*Termitomyces clypeatus* Heim	Tricholomataceae	Cooked with fish
Shipungvar (Tangkhul)/Narin (Meitei)	*Termitomyces eurrhizus* (Berk.) Heim	Tricholomataceae	Eaten fried or cooked with meat

Source Salam et al. (2019), Khan et al. (2015)

hill district (ENVIS Center 2015). Loktak lake is largest among these wetlands, with an area of 286 km^2, and holds global significance as it is recognized as Ramsar site. Wetlands are exceptionally valuable and highly productive ecosystem on global scale. They play an important function at ensuring health, welfare as well as safety to the communities residing in and around them as these wetlands provide edible plants, useful vegetation, fish and even edible insects for household consumption and medicinal purposes (Fig. 7). Moreover, these local inhabitants sell the abundant

Fig. 7 Some wetland plants

edible plants and fishes at local market to generate revenue and sustenance (Trisal and Manihar 2002).

3.1 Dietary Use of Wetland Plants

A large number of edible WLPs that are supplied by these wetlands acts as a significant function in the lives of the indigenous people. WLPs serve various purposes including food and medicine and also contribute to aesthetic, income, fodder and handicrafts (Meitei and Prasad 2015). As a result, the WLPs hold high socio-cultural significance (Trisal and Manihar 2002).

The traditional Manipuri dishes like *eromba*, *kangsoi*, *kangsu*, *shak*, *singju* and *Ooti* also rely heavily on fresh edible plants from these wetlands. *Eromba* is made by cooking *Alpinia nigra*, *Colocasia esculenta*, *H. coronarium*, chilli and potato. After boiling, the vegetables are then smashed and combined with fermented fish called '*Ngari*'. In preparation of *Kangshoi*, includes *Jussiaea repens*, *Crotalaria juncea* and *Persicaria chinensis* shoots boiled with onion, potatoes, chilli, fermented fish and spices. *Kangsu* is made by boiling *Persicaria posumbu*, *Centella asiatica*, potato, chilli and mashing them with fermented fish. *Shak* involves boiling tender shoots of *Ipomoea aquatica* with fish, potato and spices. *Singju*, a salad, combines *Alocasia cucullata*, *Ipomoea aquatica*, *Neptunia oleracea*, *Oenanthe javanica* with fermented fish and chilli. *Ooti* includes *Alternanthera philoxeroides* and *Colocasia esculenta* leaves boiled with green peas, chilli, spices, fermented fish and sodium bicarbonate. These dishes are an integral part of the daily meals of the local population (Meitei and Prasad 2015). Some of the widely available WLPs of Manipur are shown in Fig. 7. The information on dietary usage of some wetland plants and their mode of utilization is presented in Table 6.

Edible WLPs also provide nutrition to the local inhabitants. The carbohydrate content on the selected species contain between 3.4 and 32.5%, the protein content ranges around 2.6–20.2%, total phosphorus content ranges from 0.4 to 0.991%, sodium, potassium ranges from 0.017 to 0.24% and 0.018 to 0.417%, respectively (Jain et al. 2011). Additionally, edible wetland plant *Lemanea australis* exhibited high micro-nutrient (copper, zinc) content i.e., 31.20 and 62.40 ppm, respectively (Jain et al. 2011).

In addition to being a dietary sources, some WLPs also possess medicinal properties such as the root extract of *Argyreia nervosa* is used to treat rheumatism and nervous disorders while a paste made from *Cynodon dactylon* shoot is applied on cuts, wounds and used in treatment of dropsy and epilepsy. Furthermore, *Z. latifolia* inflorescence extract is used in treating indigestion (Meitei and Prasad 2015). So, the wetlands not only sustain the local communities' nutritional needs but also contributes to their well-being through traditional medicine practices.

4 Importance and Future Scope

Harvesting and selling of WEPs and WLPs directly from their natural habitats may seem cost-effective and effortless, but it possess a serious threat of shortage and even extinction for these plants due to reckless collection (Srivastava et al. 2010). To ensure the sustainable utilization of these wild plants, two conservation strategies are crucial: domestication and processing (Joshi et al. 2015).

(i) **Domestication**: Domestication of wild plants is a logical solution to conserve the threatened wild species and ensure their sustainability. However, it is a challenging process to cultivate these wild plants due to lack of knowledge on suitable agrotechniques and only a tiny fraction (0.5%) of plant species has been

Table 6 Dietary usage of some wetland plants of Manipur and their mode of utilization

Local name	Scientific name	Family	Mode of utilization or preparation
Heikak	*Trapa natans* Linn	Trapaceae	Fruits are consumed either cooked or raw; while petiole are eaten as *eromba* and *singju*
Huikhong	*Viola pilosa* Blume	Violaceae	Shoots are consumed with dried fish
Esing Ikaithabi	*Neptunia oleracea* Lour.	Mimosaceae	Shoots are either consumed as *eromba* or raw as *singju*
Ishingkambong	*Zizania latifolia* Turcz. ex Stapf.	Poaceae	Infected inflorescence is roasted over fire and consumed with molasses and rice
Kabo-napi	*Alternanthera philoxeroides* Griseb.	Amaranthaceae	Tender shoots are cooked as a traditional dish called as *ooti* together with many other vegetables together
Kanghoo	*Alpinia galanga* Willd.	Zingiberaceae	Rhizomes are cooked and smashed with fermented fish, chilli and served as a meal during both lunch and dinner
Kengoi	*Persicaria posumbu* (Buch.-Ham. ex D.Don) H. Gross	Polygonaceae	Aerial parts of the plant cooked together with dry fishes and and consumed as food
Kokthum	*Eleocharis dulcis* Linn.	Cyperaceae	Root cooked with molasses & eaten as snacks
Kolamni	*Ipomoea aquatica* Forsk.	Convolvulaceae	The shoots are cooked and consumed
Komprek	*Oenanthe javanica* (Blume) DC.	Apiaceae	Shoots & leaves are highly regarded and preferred spices for the preparation of *singju*
Komprek tujombi	*Enhydra fluctuans* Lour.	Asteraceae	Shoots are either consumed as *eromba* or raw as *singju*
Koukha	*Sagittaria sagittifolia* Linn.	Alismataceae	Roots are cooked and consumed with molasses, and also used in preparation of *eromba* and also consumed as snacks fried in oil
Langbankoukha	*Hedyotis auricularia* Linn.	Rubiaceae	Tender shoots are cooked and prepared as *ooti*
Lok-lei	*Hedychium coronarium* Koenig	Zingiberaceae	Rhizomes are cooked and prepared as *eromba*
Namra	*Amomum aromaticum* Roxb.	Zingiberaceae	Rhizomes are used as a constituent in the preparation of *eromba*

(continued)

Table 6 (continued)

Local name	Scientific name	Family	Mode of utilization or preparation
Nung-sam	*Lemanea australis* Atkins	Rhodophyceae	The dried and roasted filaments are used to prepared chutney (When roasted over fire the plant produce characteristic fishy smell making it suitable as fish substitute)
Paan	*Colocasia esculenta* (L.) Schott	Araceae	Both the corm and leaves are cooked and consumed as *ooti*
Peruk	*Centella asiatica* (Linn.) Urban	Apiaceae	Whole plant is consumed as *kangsu* (Traditional dish prepared by boiling and mashing with potato and fermented fish)
Pullei	*Alpinia nigra* (Gaertn.) Burtt	Zingiberaceae	Rhizomes are boiled along with potato and used to prepared *eromba* that is mashed with potato, fermented fish and chilli
Singhut kambong	*Narenga porphyrocroma* Bor	Poaceae	Fungus infected inflorescence is roasted over fire and then mashed with molasses and rice before being consumed
Singju-paan	*Alocasia cucullata* Schott	Araceae	Corm is cooked with fermented soybean and consumed or prepared traditional salad called as *singju*
Thambal	*Nelumbo nucifera* Gaertn.	Nymphaeaceae	Flower, tender shoot, leaf and roots are consumed raw as salad; additionally the root is cooked with molasses and eaten as snacks
Thangjing	*Euryale ferox* Salisb.	Nymphaeaceae	Fruit is either cooked or eaten raw as *eromba*; leaf petiole is used in salad
Tharo-angangba	*Nymphaea nouchali* Burma f.	Nymphaeaceae	Petiole used in the preparation and consumed as *singju*
Tharo-angouba	*Nymphaea alba* Linn	Nymphaeaceae	Petiole used in the preparation and consumed as *singju*
Yelang	*Polygonum barbatum* Linn	Polygonaceae	Shoots are either cooked or eaten raw as *singju*
Yempat	*Plantago erosa* Wall	Plantaginaceae	The leaves are occasionally cooked as vegetables

(continued)

Table 6 (continued)

Local name	Scientific name	Family	Mode of utilization or preparation
Yensil	*Oxalis corniculata* Linn	Oxalidaceae	Plant is cooked with seeds of pea (*Pisum sativum*) and consumed
Yerum-keirum	*Stellaria media* (L.) Vill	Caryophyllaceae	Shoots are cooked and consumed as vegetable

Source Meitei and Prasad (2015), Jain et al. (2011), Devi et al. (2022)

successfully domesticated (Kala 2006). In Manipur, the constraint are also due small land holdings in the hill areas where most WEPs are sourced. Though a few these wild plants such as *Eurayle ferox* (Thangjing), *Saggitaria sagitifolia* (Kaokha), *Hibiscus canabinus* (Shougri), have been successful commercialised, but most of them are still collected from the wild. The factors determining for the domestication also depends on the commercial value, palatability and shelf-life (Pfoze et al. 2011; Gangte et al. 2013).

(ii) **Processing**: Processing of these plants into finished products is another method for conservation. By processing, the shelf-lives of these plants can be increased and also allow to overcome seasonality, perishability issues, thereby reducing the dependence on imported food products and contributing to food security and income generation. Most common techniques of traditional food processing in Manipur is sun drying and natural fermentation along with some traditional method of pickling. Some of the processed WEPs are sundried wild mushroom species such as *Schizophyllum commune* (Kanglayen), *Lentinula edodes* (U-yen), *Auricularia auricularia* (Uchina). With regard to the wild fruits, *Spondias pinnata* (Heining), *Rhus* sp. (Heimang) are used in pickling and making candy with brown sugar respectively. *Emblica officinalis* (Heikru), *Eleocarpus floribundus* (Chorphon), *Micrococus paniculata* (Heitup) and *Gracinia penduculata* (Heibung) are boiled and sundried or to made candy or mouth freshener. Starchy WLPs like *Sagittaria sagitifolia* (Koukha), Nymphaea rubra (Lemphu), *Cyperus escluntus* (Kaothum), *Trapa bispinous* (Heikak) are boiled and sold as ready to eat items (Sarangthem et al. 2019). Fermented food products from WEPs are fermented bamboo shoots such as *Dendrocalamus hamiltonii* (soibum) and *Teinostachyum wightii* (soidon), fermented seeds of *Hibiscus cannabinus* (shougri) known as *Gankhiangkhui* and fermented wild *Brassica* sp. (Ankamthu) are major fermented WEPs in the local markets of Manipur (Wahengbam et al. 2020). These traditional fermented foods harbours GRAS (generally regarded as safe) microorganisms with potential source of therapeutic enzyme and other health benefits (Singh et al. 2014).

Despite the benefits of these wild plants consumption, challenges remain in encouraging cultivation and establishing processing industries (Fig. 8). Indigenous

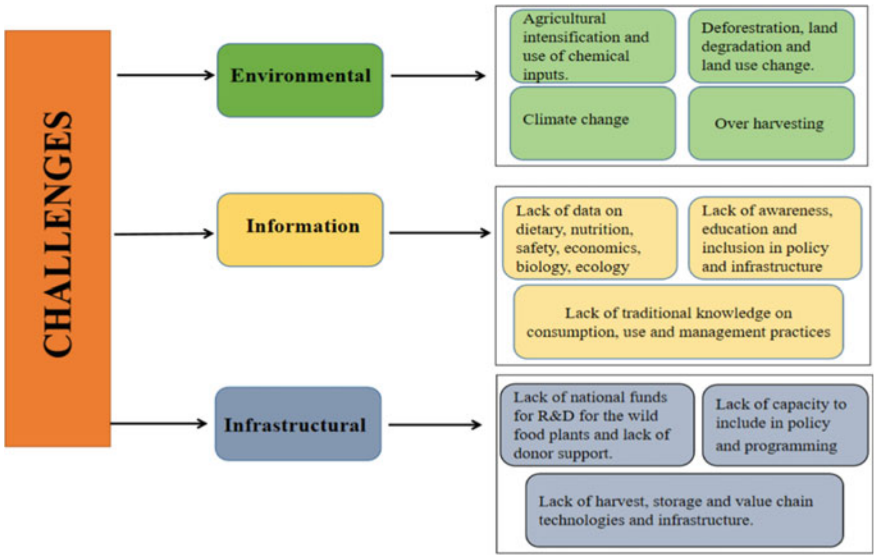

Fig. 8 Challenges faced in conservation and sustainable use of WEPs and WLPs

people in rural areas as well as in tribal areas may be reluctant to switch to cultivation due to various reasons including lack of resources, knowledge (Salam et al. 2012). Additionally, the infrastructure for processing industries in Manipur is limited affecting the consistent quality and quantity of processed wild plants. A significant concern is the large number of endangered plant species in Manipur. Deforestation, cultivation practices, mining, urbanization and other human activities have led to habitat loss and endangerment of many plant species. Propagation and cultivation techniques are urgently needed to reduce the pressure on these plants and prevent their extinction. To unlock the economic potential of Manipur's bio-resources, there is a need for scientific institutions focused on research that can convert these plants to value added products, biotechnological intervention and documentation for sustainable development and proper utilization of these bio-resources (Sarangthem et al. 2019).

5 Conclusion

Wild edible plants and wetland plants of Manipur acts as a significant purpose in the sustenance of the indigenous communities while offering valuable economic opportunities. However, the sustainable utilization along with value addition relies on effective conservation and management efforts involving local communities, industries and government initiatives. Implementing standardized cultivation techniques for high value species can boost income generation and encourage continued cultivation. Promotion of value added techniques with low inputs and technology, along with cost effective processing and packaging technologies can foster a viable small scale industry. This approach will not only ensure better nutritional security but also create employment opportunities in the state. Encouraging research and development in this field can enhance and validate the traditional knowledge of the existing wild plants. Despite the challenges in remote hill areas due to lack of infrastructure, exploiting the potential of these plants can act as a sustainable means for socio-economic development in these areas and in the state too.

References

Apshahana K, Sharma AK (2018) Wild edible mushrooms traded by ethnic communities of Senapati and Kangpokpi district of Manipur, India. J Pharmacogn Phytochem 7(1):2303–2306

Chakraborty R, De B, Devanna N, Sen S (2012) North-East India an ethnic storehouse of unexplored medicinal plants. J Nat Prod Plant Resour 2(1):143–152

Chatterjee S, Saikia A, Dutta P et al (2006) Biodiversity significance of North east India. WWF-India, New Delhi, pp 1–71

Deb L, Laishram S, Khumukcham N et al (2015) Past, present and perspectives of Manipur traditional medicine: a major health care system available for rural population in the North-East India. J Ethnopharmacol 169:387–400

Devi KS, Devi YS, Singh PK (2009) A census on edible flowers found in the valley. J Econ Taxon Bot 33(1):232–239

Devi OS, Komor P, Das D (2010) A checklist of traditional edible bio-resources from Ima markets of Imphal Valley, Manipur, India. J Threat Taxa 2(11):1291–1296

Devi TS, Devi MH, Singh SS, Thokchom R, Singh PK (2022) Studies on the income-generating wild edible wetland plants traditionally consumed by the people of Bishnupur district, Manipur. Pharm Innov J 11(11):915–920

ENVIS (2015) Environmental information system, Directorate of Environment, Government of Manipur. Wetlands. https://manenvis.nic.in/Database/Wetlands_2702.aspx

Gangte HE, Thoudam NS, Zomi GT (2013) Wild edible plants used by the Zou tribe in Manipur, India. Int J Sci Res Publ 3(5):1–8

Gupta YC, Priyanka Sharma, Gitam Sharma, Roshini Agnihotri (2018) Edible flowers, National conference on floriculture for rural and urban prosperity in the scenario of climate change, pp 25–29

Hazarika TK, Singh TS (2018) Wild edible fruits of Manipur, India: associated traditional knowledge and implications to sustainable livelihood. Genet Resour Crop Evol 65:319–332

Jain A, Sundriyal M, Roshnibala S et al (2011) Dietary use and conservation concern of edible wetland plants at indo-Burma hotspot: a case study from northeast India. J Ethnobiol Ethnomed 7(1):1–17

Joshi N, Siwakoti M, Kehlenbeck K (2015) Wild vegetable species in Makawanpur District, Central Nepal: developing a priority setting approach for domestication to improve food security. Econ Bot 69(2):161–170

Kala CP (2006) Problems and prospects in the conservation and development of the Himalayan medicinal plants sector. Int J Sustain Dev 9(4):370–389

Kallas J (2010) Edible wild plants: wild foods from dirt to plate, wild food adventure series, vol I. Gibbs-Smith, Layton, Utah

Khan MR, Kikim A, Yadava PS (2015) Conservation of indigenous wild edible plants used by different communities of Kangchup Hills, Senapati, North East India. Int J Bio-Resour Stress Manag 6(6):680–689

Konsam S, Thongam B, Handique AK (2016) Assessment of wild leafy vegetables traditionally consumed by the ethnic communities of Manipur, northeast India. J Ethnobiol Ethnomed 12:1–15

Kumari P, Bhargava B (2021) Phytochemicals from edible flowers: opening a new arena for healthy lifestyle. J Funct Foods 78:104375

Medhi P, Sarma A, Borthakur SK (2014) Wild edible plants from the Dima Hasao district of Assam, India. Pleione 8(1):133–148

Meitei LR, De A, Mao AA (2022) An ethnobotanical study on the wild edible plants used by forest dwellers in Yangoupokpi Lokchao Wildlife Sanctuary, Manipur, India. Ethnobot Res Appl 23:1–22

Meitei MD, Prasad MNV (2015) Phoomdi—a unique plant biosystem of Loktak lake, Manipur, North-East India: traditional and ecological knowledge. Plant Biosyst 149(4):777–787

Mengistu F, Hager H (2008) Wild edible fruit species cultural domain, informant species competence and preference in three districts of Amhara region, Ethiopia. Ethnobot Res Appl 6:487–502

Misra S, Maikhuri RK, Kala CP, Rao KS, Saxena KG (2008) Wild leafy vegetables: a study of their subsistence dietetic support to the inhabitants of Nanda Devi Biosphere Reserve, India. J Ethnobiol Ethnomed 4:1–9

Moirangleima K (2010) Sustainable management of wetland: central valley of Manipur. B. R. Publishing Corporation, New Delhi, pp 145–196

Murugkar DA, Subbulakshmi GJFC (2005) Nutritional value of edible wild mushrooms collected from the Khasi hills of Meghalaya. Food Chem 89(4):599–603

Ogle BM (2001) Wild vegetables and micronutrient nutrition: studies on the significance of wild vegetables in women's diets in Vietnam. PhD dissertation, Acta Universitatis Upsaliensis. http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-694. Accessed 25 July 2023

Pfoze NL, Yogendra K, Bekington M (2011) Survey and assessment of floral diversity on wild edible plants from Senapati district of Manipur, Northeast India. J Biodiv Environ Sci 1(6):50–62

Pieroni A, Price L (2006) Eating and healing: traditional food as medicine. CRC Press

Premlata T, Sharma V, Bisht MS, Nirmala C (2020) Edible bamboo resources of Manipur: consumption pattern of young shoots, processing techniques and their commercial status in the local market. Indian J Tradit Knowl 19(1):73–82

Purba EC, Silalahi M (2021) Edible plants of the Batak Karo of Merdeka District, North Sumatra, Indonesia. Ethnobot Res Appl 22:1–15

Reyes-García V, Vadez V, Huanca T, Leonard W, Wilkie D (2005) Knowledge and consumption of wild plants: a comparative study in two Tsimane' villages in the Bolivian Amazon. Ethnobot Res Appl 3:201–208

Rop O, Mlcek J, Jurikova T, Neugebauerova J, Vabkova J (2012) Edible flowers—a new promising source of mineral elements in human nutrition. Molecules 17(6):6672–6683

Salam S, Jamir NS (2018) Wild edible fungi sold in local markets of Ukhrul District of Manipur, India. Int J Sci Res Publ 8(1):208–2019

Salam S, Jamir NS, Singh PK (2012) Wild leafy vegetables sold in local markets of Ukhrul District of Manipur, India. Pleione 6(2):298–303

Salam S, Pinokiyo A, Roma M, Jamir NS (2019) Sustainable utilization of edible fruits by Tangkhul Naga Tribe in Ukhrul District, Manipur, North-east India. Pleione 13(1):65–69

Sarangthem N, Sarangi PK, Singh NJ, Singh TA (2019) Value addition of wild edible plants (WEPs) for sustainable utilisation and socioeconomic development of rural areas of Manipur, India. In: Singh TA, Sarangi KP, Sarangthem N (eds) Food bioresources and ethnic foods of Manipur, North East India. Empyreal Publishing House, pp 92–99

Sharma PB, Handique PJ, Devi HS (2013) Antioxidant properties, physico-chemical characteristics and proximate composition of five wild fruits of Manipur, India. J Food Sci Technol 13:1128–1132.

Singh EJ, Singh NS, Singh NR (2009) Biodiversity conservation and natural resources in North East India-with special reference to Manipur. NeBIO 1(1):42–47

Singh TA, Devi KR, Ahmed G, Jeyaram K (2014) Microbial and endogenous origin of fibrinolytic activity in traditional fermented foods of Northeast India. Food Res Int 55:356–362

Srivastava RC, Singh RK, Mukherjee TK (2010) Bioculturally important rare new plant species of Heteropanax Seems (Araliaceae) from Eastern Himalaya, Arunachal Pradesh. Indian J Tradi Knowle 9 (2):242–24

Thakur M, Belwal T (2022) Bioactive components: a sustainable system for good health and well-being, vol I. Springer, Singapore, p 609. https://doi.org/10.1007/978-981-19-2366-1_5

Thokchom R, Hanglem A, Zimisai S et al (2016) Documentation and assessment of wild medicinal and edible flowers of valley districts of Manipur. Int J Res Appl 4(11):13–20

Toshinungla AO, Deb CR, Neilazonuo K (2016) Wild edible mushrooms of Nagaland, India: a potential food resource. J Exp Biol Agric Sci 4(1):59–65

Trisal CL, Manihar T (2002) Management of Phumdis in Loktak lake. In: Proceeding of workshop on management of Phumdis in Loktak lake

Valverde ME, Hernández-Pérez T, Paredes-López O (2015) Edible mushrooms: improving human health and promoting quality life. Int J Microbiol. Article ID 376387. https://doi.org/10.1155/2015/376387

Wahengbam R, Thangjam AS, Keisam S et al (2020) Ethnic fermented foods and alcoholic beverages of Manipur. In: Tamang J (ed) Ethnic fermented foods and beverages of India: science history and culture. Springer, Singapore. https://doi.org/10.1007/978-981-15-1486-9_14

Onion Bulbs: Store House of Potential Phytochemicals for Sustaining Health

Hira Singh, Anil Khar, R. K. Dhall, and Shilpa Gupta

1 Introduction

Being an important bulbous vegetable and condiment crop, onion (*Allium cepa* L.) has been grown for 5000 years because of its uniqueness. Across the globe, bulb onion crop is cultivated in all climatic conditions (Singh et al. 2021b; Khar and Singh 2020). For proper bulb development with specific quality parameters, photoperiod and temperature play critical roles. Since ancient times, several traditional plant-based remedies are being used to cure many human ailments and passed on from one generation to another generation. India has enriched well-established traditions and legacy to use plant-based folk medicines which are well documented in Indian literature. Such practices are regional, local, religious and ethnic group-based (Singh et al. 2022).

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लभते बलवर्णौजः स्वरसौमनस्यतेजसि |

क्षीणशकृतबधिरोऽपि रसोनवत तद्रसंपीत्वा ||

---- पलांडूकल्प

Meaning of the above

"*The consumption of onion makes the man healthy, stout and energetic. His voice turns to melodious and body skin becomes lustrous*"

The importance of onion bulbs is evident from the *Charka-Samhita*—a well-known medicinal treatise written during the sixth century. It would be great to mention here that Indian literature documented the onion therapeutic properties in '*Palandukalp*' as bulb onions are valuable for upkeeping of good health, the energetic and physical strength of the body, and glowing skin (Kolekar et al. 2021; Singh 2017). This bulb crop possessed wide diversity in terms of bulb shape, colour, dry matter content, pungency and other bioactive compounds.

Queen of French cuisine, Julia Child narrated "*It is hard to imagine a civilization without onions*". Onion bio-functional and bioactive compounds are playing a great role in maintaining physical well-being of the human body (Ali et al. 2000). Onion bulbs are used to avoid various seasonal ailments and other related health issues, singly or in combination with other plant-based products. Getting cue from the available traditional knowledge, nutritionists and food scientists assessed further its medicinal and healing properties for a modern society based on the scientific background (Arshad et al. 2017; Suleria et al. 2013; Block 1992; Cazzola et al. 2011; Gulsen and Ayaz 2010). Moreover, World Health Organization (WHO) also documented the use of extracts obtained from onion bulbs to treat cough, cold, bronchitis, relieving hoarseness, appetite loss, asthma, and atherosclerosis. Having higher concentrations of flavonoids and powerful antioxidants, onion bulbs have become a fascinating and interesting vegetable crop (Griffiths et al. 2002).

Taxonomic Classification

Kingdom:	Plantae
Division:	Magnoliophyta
Class:	Liliopsida
Order:	Asparagales
Family:	Amaryllidaceae
Genus:	*Allium*
Species:	*cepa*
Edible Parts:	Bulb and leaves

As per the NHRDF survey, the highest consumption of onion bulbs per capita per day was documented at 56.58 g in Punjab followed by 55.93 g in Himachal Pradesh and 51.34 g in Haryana, while the lowest was recorded at 37.68 g in Tamil Nadu, 40.82 g in Delhi and 41.71 g in Bihar. The national average consumption had been estimated as 45.63 g only. Mountainous state of Himachal Pradesh was recorded to be the minimum-producing state of bulb onions in India (Bhaskar et al. 2018).

Several medicinal properties of onion bulbs have been well mentioned in the *Garuda Purana* and by India's great sage Atreya (Kameshwari 2013). Further, Ayurveda anticipates onions as versatile and multipurpose uses for example cardiovascular diseases, promoting expectoration, diabetes, hypertension, and for reduction of phlegm (Singh et al. 2023a; Kapoor 2018; Nadkarni 1954; Bakhru 1993; Verotta et al. 2015). As documented in *Charaka Samhita and Susruta Samhita*, onion bulbs enhance strength and immunity. *Yogi Bhajan* mentions the therapeutic worth of the combination of three herbs such as onion bulbs, garlic bulbs, and ginger. This combination he called trinity roots (Khalsa and Tierra 2010). Being a strong antioxidant flavonoid, quercetin makes onion bulbs so special and this compound is found near the bulb skin. This compound has been exploited traditionally for preventing several health ailments, for example, regulation of higher blood pressure or lowering of hypertension, diabetes, antibacterial properties, immune stimulant, cardioprotective, anti-inflammatory, antioxidant potential, reducing stroke risk and neuropathy, controlling levels of cholesterol, dyspepsia treatment and anticancer (Batiha et al. 2020). Intake of dietary plant-based flavonoids has potential to reduce the risk of chronic human diseases (Carter and Tourtellotte 2007; Jiang et al. 2006; Choucair et al. 2006; Scalbert and Williamson 2000). Natural diversity in the concentration of various nutrients and phytochemicals is because of genotypic architecture, maturity stage, part of the plant, and storage conditions (Singh et al. 2022, 2023a; Patil et al. 1995).

2 Onion Bulbs as Folk Medicines and Health Functions

In the old literature, medicinal uses of onion bulbs are clearly documented for multiple purposes. With peculiar properties and possessing of an array of biochemical compounds, onion bulbs are used to cure colds, sour throat, cough, asthma, and so on (Singh and Khar 2021; Arshad et al. 2017; Suleria et al. 2013; Cazzola et al. 2011; Gulsen and Ayaz 2010; Block 1992). Now, it is strongly projected to fascinate immense attention and focus on the health advantages of bulb onions and their invariable applications and consumption to prevent and manage various chronic ailments and diseases. Onion bulbs are enriched with a wide array of diverse phytochemicals and phytonutrients having beneficial bio-functional, comprising of sulfur compounds (Zamiri and Hamid 2019; Moreno-Rojas et al. 2018), polysaccharides (Ma et al. 2018), phenolics (Ren et al. 2017; Lee et al. 2017; Viera et al. 2017) and saponins (Dahlawi et al. 2020; Lanzotti et al. 2012). Mixing onion juice with sugar is used to get relief from cough, sour throat, and cold in the children. Being a great source of diverse amino acids like methionine, tryptophan, cysteine, glutamine, asparagine, isoleucine (Gulsen and Ayaz 2010), onion bulbs have immense immunity booster potential as well as anti-asthmatic activities (Arshad et al. 2017; Stajner and Varga 2003).

2.1 Anticancer Properties

Allium species have potential concerns owing to their advantageous properties against cancer. This property is associated due to the presence of various bioactive and functional compounds including organosulfur compounds, saponins and flavonoids (Nohara and Fujiwara 2017; Asemani et al. 2019). Intake of onions in the diet, lowers the risk of various cancers such as gastric cancer (Turati et al. 2015), breast cancer (Desai et al. 2020), colorectal cancer (Wu et al. 2019), and digestive system cancer (Guercio et al. 2016). Various scientific studies were conducted to assess the anticancer properties of bulb onions (Nile et al. 2021; Desai et al. 2020; Yasmin et al. 2017; Zhao et al. 2017; Ravanbakhshian and Behbahani 2018). Further, it was observed that the onion extract anticancer potential was augmented by encapsulating on nano chitosan in multiple cancer cell lines (Alzandi et al. 2022). Moreover, it was also documented that dietary intake of fresh onion bulbs declined blood glucose on fasting and enhanced sensitivity towards insulin in doxorubicin-treated breast cancer patients (Jafarpour-Sadegh et al. 2017). It could be concluded that bulb onions have exceptional anticancer activities. However, its anticancer potential should be further systematically tested and validated by conducting intensive clinical trials.

2.2 Onion Bulbs and Vitamin C

Being a water-soluble vitamin, this vitamin has achieved great attention from food, nutrition, and plant researchers owing to its strong antioxidant activities (Campos et al. 2009). During COVID-19 (SARS-CoV2) pandemic, this vitamin got unexpected popularity among common people as an important immunity booster (Carr and Rowe 2020; Kumari et al. 2020; Singh et al. 2022). The deficiency of Vitamin C results to cause scurvy, anaemia, bleeding gums, neurotic disturbances, muscle degeneration, poor healing of wounds, etc. (Iqbal et al. 2004). Among vegetables, bulbs of onion contain a good amount of Vitamin C (Mitra et al. 2012). Elhassaneen and Sanad (2009) quantified Vitamin C concentrations of 14.63 and 13.84 mg per 100 g of fresh bulb onion portion of red and white varieties, respectively.

Singh et al. (2022) estimated the concentration of Vitamin C in the fresh onion bulbs from forty-five Indian commercial cultivars and observed significant variability for Vitamin C among selected cultivars was recorded. The concentration ranged from 4.94 to 45.05 mg/100 g on a fresh weight basis (FW) and also observed bulb colour influenced the availability of Vitamin C in the fresh bulbs. The Vitamin C levels were relatively low in the white-coloured bulbs compared to light-red coloured bulbs. The variety having red coloured bulbs 'NHRDF-Red' (L-28) possessed the highest amount of Vitamin C (45.05 mg/100 g of FW), followed by 'RO-59' (31.01) and Bhima Dark Red (20.48 mg/100 g). About 9 times difference was determined among the highest and lowest amount recorded. Scientifically, it is well documented that several factors like genotype, physiological stage of the bulb, and seasonal conditions influence the quantity of several phytochemicals significantly possessed by bulbs (Bilyk et al. 1984; Crozier et al. 1997; Sellappan and Akoh 2002).

2.3 Rich Source of Potassium: Hypertension and Blood Pressure

Globally, non-communicable diseases (NCDs) such as hypertension, diabetes, and so on are becoming the great cause of death and count for 80 percent deaths because of NCDs in lower to middle economic countries (WHO 2010). Predominantly, NCDs comprising of diabetes, cardiovascular or heart diseases, cancer and chronic misfunctioning of lungs are the responsible for major untimely and unnatural mortalities. Among all, hypertension or elevated blood pressure, is also considered as silent killer because of non-observable symptoms in several persons which is now become a major health issue worldwide (WHO 2013). An unhealthy and unbalanced diet is a major factor among various causing NCDs and other metabolism-based disorders. This is listed as the major cause of hypertension. According to WHO, the population from lower to middle-income countries intake table salt much higher than the recommended level which is associated with trans-fatty acids and saturated fats. Since the 1980s, the intake of fat has been increasing swiftly in these countries (WHO 2010). According to the WHO, high sodium and low potassium in the Western diet are implicated in the pathogenesis of high blood pressure, which is the basic and foremost cause of myocardial infarction and death. A population-based approach and precision nutrition are needed to prevent and cure IA. Besides genetics, unhealthy diets, lack of exercise, and highly saturated fatty foods have been considered leading factors for causing hypertension. Naturally, sodium content is more in foods, especially processed and snacks. To counter this, identification and selection of plant-based food having higher potassium/sodium ratio is need of the hour. Compared to other vegetables, bulb onions could be a good alternative option since their bulbs possess higher potassium content.

The twenty-first century is working on the principle of "Food as Medicine" and onion bulbs would assuredly play a bigger role in the coming future. Since antiquity, onion bulbs played a significant role in the upkeep of good human health; being used as culinary purposes in every Indian kitchen. Bulbs are possessing augmented levels of Vitamin C, dietary fiber, folic acid, as well as possess a good amount of calcium, iron, zinc, and potassium, whereas lesser contents of sodium and fat (Nile and Park 2013; Abhayawick et al. 2002; Nemeth and Piskula 2007; Singh et al.

2022). Potassium plays a significant role in maintaining balance of water content, heartbeat regulation and neurotransmission (Khan et al. 2019). In US, Metrani et al. (2020) computed 13,550.1 μg/g potassium in red-coloured bulbs. Proper balance of sodium and potassium is utmost important for proper and normal cellular functioning in the body. Since enhancing risks of high blood pressure and hypertension (Zhang et al. 2013; Park et al. 2016), cardiovascular diseases (Cook et al. 2009; Yang et al. 2011) and obesity (Ge et al. 2016; Jain et al. 2014), high dietary sodium and low potassium intake become a challenging global public health issue. The scientific reports displayed that ratio of both electrolytes is powerfully associated with blood pressure and heart functioning (Park et al. 2016; Cook et al. 2009; Okayama et al. 2016). Furthermore, it is reported that the Na:K ratio of dietary intake was an independent risk factor for many metabolic-based disorders. It was suggested that a modified ratio including lower sodium and higher potassium dietary intake to prevent metabolic syndromes (Li et al. 2018). The genetic variability in the concentration of sodium and potassium in the fresh bulbs of onion could be a great contribution to the population suffering from high blood pressure and hypertension eventually leading to cardiovascular diseases (Singh et al. 2023a).

Globally, a large population is suffering from various mental and physical health issues which are unmanageable medical treatment costs, mainly due to unhealthy and lethargic lifestyle, non-communicable diseases (NCD), and metabolic disorders. Among NCD, cardiovascular and coronary diseases particularly hypertension/high blood pressure, heart attack, heart stroke/cerebrovascular and arteries dysfunction are widespread (Mendis et al. 2011). Mortality frequency because of various coronary and cardiovascular diseases have been increasing considerably (Krishnamurthi et al. 2015) and hypertension was considered to be the foremost risk factor (Roger et al. 2012). Astonishingly, about 60% of heart stroke was documented owing to hypertension (WHO 2002; Appel et al. 2011).

Bibbins-Domingo et al. (2010) documented that a decline in intake of sodium in the diet by about 1200 mg/day decreased 32,000–66,000 heart strokes in the United States of America (USA) only. Scientifically, it is established that a decline in sodium dietary intake could decrease the risk of several cardiovascular diseases (Jayedi et al. 2019). The potassium has potential for inhibiting the free radicals in the human body (McCabe et al. 1994). Currently, dietary potassium is gaining popularity because of rising hypertension, high BP, and cardiovascular diseases globally. Henceforward, the identification of plant-based diets having higher potassium concentration and lower sodium amounts could be of immense attention and focus from the public health point of view.

A wide genotypic diversity in sodium, potassium concentrations and their ratio were estimated in the Indian tropical short-day onions. Yellow bulb-coloured varieties such as Pusa Sona and Arka Pitamber exhibited the highest K content. Twenty-three cultivars exhibited higher potassium content than the grand mean value (4679.26 mg per 100 g of fresh weight), which clearly pointed out that Indian onion genotypes possess higher content of potassium. However, this aspect was not even touched to explore a great source of dietary potassium. The results obtained suggested that onion crops may offer a potential source of potassium to fulfill the recommended dietary allowance (Singh et al. 2023a). Further, they recorded the potassium: sodium ratio significantly highest in yellow bulbs than in red and white bulb-coloured varieties.

2.4 Cough, Sore Throat and Asthma

Onion juice is used to relieve and prevent bleeding nose and throat infections. To get relief from malaria fever, Verotta et al. (2015) suggested taking onions with black pepper. For curing cough, an equal mixture of juice of onion and honey (Bakhru 1993; Kapoor 2018) is the best and cheap remedy. Eating raw onion bulbs or drinking fresh onion juice with table salt is a good folklore remedy to treat tuberculosis because of its antimicrobial properties. Inhaling the vapours after or during the crushing of onions is advised as a traditional remedy for getting relief from sore throat, respiratory-related diseases, and lung infections. Licking of a combination mixture of honey and onion juice is used for asthmatic cough. For sneezing and running noses, intake of onion bulbs or juice is a traditional remedy in Indian villages (Singh et al. 2022). In literature, it is well documented that onion juice has potential anti-asthmatic properties (Stajner and Varga 2003).

Scientific studies revealed that onion bulbs could relax tracheal smooth muscle (Memarzia et al. 2019), reduce lung inflammation (Ghorani et al. 2018), ameliorate allergic asthma (El-Hashim et al. 2020), and attenuate lung damage (Zaki 2019). It is verified that onion bulbs and their bio-functional compounds could reduce inflammation in the lungs and provide protection against respiratory diseases. Henceforth, onions and their biochemical properties might have the utmost potential to combat COVID-19 virus infection, yet needs further systematic clinical investigation (Zhao et al. 2021).

2.5 Onion as a Cardiovascular Protectant

The bulb onions are a potential vegetable crop that has the potential to reduce cardiovascular diseases and heart attack risks. Consumption of fresh onions is recommended to reduce triglyceride and cholesterol levels, and lower high blood pressure and hypertension, while increased HDL levels helped to lower CVD, strokes, and diabetes (Singh et al. 2022). Scientific investigations displayed that bulb onions could inhibit platelet aggregation and improve lipid profile (Zhao et al. 2021) and effectively reduce total cholesterol levels (Kang et al. 2016). Further, they reported that quercetin extract elicited high levels of fecal cholesterol and reduce atherogenic index values in high-cholesterol diet-fed mice, with upregulation of LDLR and cholesterol 7-α-monooxygenase (CYP7A1), indicating the cholesterol-lowering effect of onion via fecal excretion. The anti-hyperlipidemic properties of fermented onion and its volatile oils had a positive effect on hyperlipidemia animals (Yang et al. 2018, 2019). To explore this crop as a cardiovascular protectant, more systematic and focused animal-based investigations and clinical studies are required for a clear understanding of associated mechanisms of onion bulbs and their bio-functional compounds.

3 Future Prospective

During the latter half of the twentieth century, there has been a paradigm shift in folklore and traditional medicines toward synthetic drugs and with this change, lots of traditional knowledge related to herb-based medicines has been lost. Nowadays, common people and nutritionists have displayed utmost interest and attention towards herb-based functional foods and folklore remedies to evade various side effects of synthetic medicines for several health problems such as headaches and migraines, allergies, insomnia, arthritis, and anxiety/depression. Undoubtedly, it could be concluded that the use of herb-based phytocompounds and nutraceuticals is better than taking chemical-based drugs for specific diseases. Still, systematic and focused scientific efforts are required to mine out the unexplored health-beneficial properties. Exploitation of modern omics tools, induced mutagenesis, and gene editing technology could be quite convenient to develop new cultivars having specific properties to cure a specific disease (Khar and Singh 2020; Singh et al. 2021a, b; Khar et al. 2022). Under scarcity of resources and lack of modern molecular laboratory, development of F_1 hybrids utilizing cytoplasmic male sterility system could be the best alternative and verified method having higher levels of phytonutrients and bioactive compounds (Singh et al. 2023b). Further, for boosting onion production, widely adapted F_1 hybrids with higher quantities of phytochemicals and functional compounds to address sustainable development goals and to ensure nutritional (Singh and Khar 2021).

4 Conclusions

Post COVID pandemic, the demand of diet enriched with nutrients and bio-functional compounds having therapeutic properties is considerably increased to fight against several non-communicable and lifestyle-based diseases such as hypertension, cardiovascular, diabetes, cancer, and lower immunity. Furthermore, plant-based specific diet supplements are in higher demand owing to its fewer side effects, toxicity and are cheaper. Being a strong antioxidant, onion quercetin has the potential to fight against various health ailments such as free radical scavenging, aging, and inflammation. With the advancement of nutrition and food science, prevention of many health issues and diseases through consuming fruits and vegetables are explored exponentially owing to their peculiar biochemical properties in the form of strong antioxidant activities, higher Vitamin C contents, flavonoids, anthocyanins, and so on. Bulb onions are well suitable for this multipurpose for centuries across the globe.

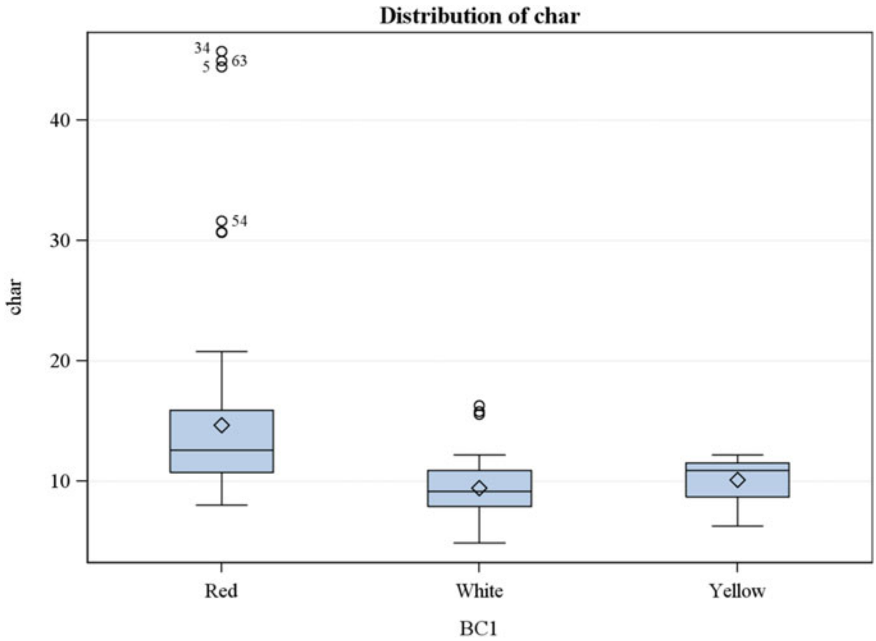

Fig. 1 Boxplot distribution of Vitamin C concentration on the basis of bulb colour (*Source* Singh et al. 2022)

Being a rich source of flavonoids, polyphenols, dietary fibre, thiosulfates, minerals, essential amino acids, and organosulfur, the onion crop has anticancer, antimicrobial, antidiabetic, strong antioxidant, and cardiovascular protectant properties. Because of the burgeoning population specially in lower-middle income countries, intensifying of various new diseases and pandemics, heightened healthcare costs, and awareness of quality and healthy life, all policymakers and related scientists have to emphasize specific phytochemicals and broadly preferred and accepted herbs which have a long history of use for maintenance of health like bulb onion. The twenty-first century is working towards the principle of "Food as Medicine" and systematic research on onion bulbs would undoubtedly play a great role in the future (Figs. 1 and 2; Table 1).

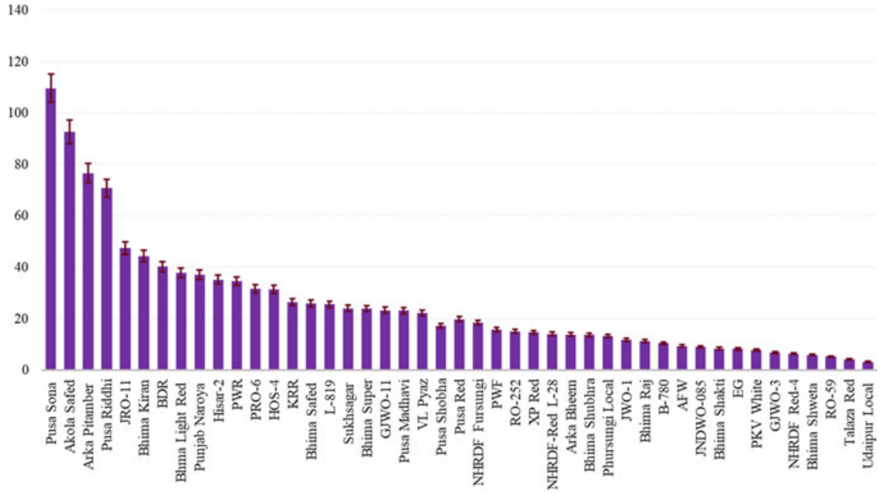

Fig. 2 Potassium to sodium ratio in the 45 Indian short day onion cultivars (*Source* Singh et al. 2023a)

Table 1 An overview of onion used as therapeutic and medicinal purposes

Purpose	References
Oral cavity hygiene to kill germs and treating toothache	Kim (1997), Dorant et al. (1996)
Treating cough, sour throat, flu, cold and asthma	Arshad et al. (2017), Verotta et al. (2015), Suleria et al. (2013), Cazzola et al. (2011), Gulsen and Ayaz (2010), Block (1992)
Jaundice in children	Nadkarni (2002)
Treating acne, pimples, blackheads and burns. Anti-inflammatory, antiallergic and antimicrobial activities. Also used for cosmetic purposes	Aburjai and Natsheh (2003)
Boosting immunity and anti-asthmatic properties	Stajner and Varga (2003), Arshad et al. (2017)
Antithrombotic, antimicrobial, hypolipidemic, antiarthritic, hypoglycaemic, antitumor activities	Ali et al. (2000)
Ascorbic acid or Vitamin C as a strong antioxidant and immunity enhancer	Singh et al. (2022)
Onion juice for treating earache and running ears	Brooks (1986)
Onion as an exceptional aphrodisiac tonic	Gupta and Bhaskar (2020)
Hypertension; high blood pressure: regulating autonomic functioning of the body	Alare et al. (2020)

(continued)

Table 1 (continued)

Purpose	References
Curing of stomach pain, remove stomach gas and bloating	Bhaskar et al. (2018)
For preventing intestine obstructions, gastrointestinal infections, nausea and constipation	Kapoor (2018), Nabavi et al. (2019)
Rich source of potassium and lower concentration of sodium	Singh et al. (2023a)
Anticlotting properties	Kendler (1987), Kleijnen et al. (1989)
Onion juice for curing colic in new born babies and infants	Veretta et al. (2015)
Antiparasitic properties against *Cryptosporidium parvum*, *Giardia*, *Entamoeba gingivalis*, *Leishmaniasis* spp., *Trichomonas vaginalis*, *Blastocystis hominis* etc.	Cheraghipour et al. (2019)
Improving sexual debility/weakness	Nibodhi (2010)
For hair falls and baldness	Brooks (1986), Dweck (1997), Bhil et al. (2020), Kolekar et al. (2021)
For getting relief from piles and haemorrhoids	Nadkarni (2002), Kapoor (2018)
Anticancer properties	Challier et al. (1998), Calucci et al. (2003), Arshad et al. (2017)

References

Abhayawick L, Laguerre JC, Tauzin V, Duquenoy A (2002) Physical properties of three onion varieties as affected by the moisture content. J Food Eng 55:253–262

Aburjai T, Natsheh FM (2003) Plants used in cosmetics. Phytother Res 17:987–1000

Alare K, Alare T, Luviano N (2020) Medicinal importance of garlic and onions on autonomic nervous system. Clin Pharmacol Biopharm 9:2

Ali M, Thomson M, Afzal M (2000) Garlic and onions: their effect on eicosanoid metabolism and its clinical relevance. Prostaglandins Leukot Ess Fatty Acids 62(2):55–73

Alzandi AA, Naguib DM, Abas ASM (2022) Onion extract encapsulated on nano chitosan: a promising anticancer agent. J Gastrointest Cancer 53:211–216

Appel LJ, Frohlich ED, Hall JE, Pearson TA, Sacco RL, Seals DR et al (2011) The importance of population-wide sodium reduction as a means to prevent cardiovascular disease and stroke. Circulation 123:1138e43

Arshad MS, Sohaib M, Nadeem M, Saeed F, Imran A, Javed A, Amjad Z, Batool SM (2017) Status and trends of nutraceuticals from onion and onion by-products: a critical review. Cogent Food Agric 3:1280254

Asemani Y, Zamani N, Bayat M, Amirghofran Z (2019) *Allium* vegetables for possible future of cancer treatment. Phytother Res 33:3019–3039

Bakhru HK (1993) Herbs that heal. Orient Paperbacks, Delhi, India, pp 132–136

Batiha GES, Beshbishy AM, Ikram M et al (2020) The pharmacological activity, biochemical properties, and pharmacokinetics of the major natural polyphenolic flavonoid: quercetin. Food 9(3):374

Bhaskar P, Tailor AK, Sharma HP, Singh RK, Gupta PK (2018) Medicinal, nutraceutical values and consumption pattern of onion (*Allium cepa*) in India: an overview. Int J Curr Microbiol Appl Sci 6:2629–2638

Bhil MMS, Bhamare MMB, Jadhav MPT, Borse MJC, Chaudhari MVA (2020) Formulation and evaluation of hair setting gel by using onion oil, Baheda. Int J Res Writ 3(1):91–99

Bibbins-Domingo K, Chertow GM, Coxson PG, Moran A, Lightwood JM, Pletcher MJ et al (2010) Projected effect of dietary salt reductions on future cardiovascular disease. N Engl J Med 362:590e9

Bilyk A, Cooper PL, Sapers GM (1984) Varietal differences in distribution of quercetin and kaempferol in onion (*Allium cepa* L.) tissue. J Agric Food Chem 32:274–276

Block E (1992) The organosulfur chemistry of the genus *Allium*. Implications for organic sulfur chemistry. Angew Chem Int Ed Engl 31:1135–1178

Brooks D (1986) An onion in your ear. J Laryngol Otol 100(9):1043–1046

Calucci L, Pinzino C, Zandomeneghi M, Capocchi A (2003) Effects of gamma-irradiation on the free radical and antioxidant contents in nine aromatic herbs and spices. J Agric Food Chem 51:927–993

Campos FM, Ribeiro SMR, Della LCM, Pinheiro-Sant'Ana HM, Stringheta PC (2009) Optimization of methodology to analyze ascorbic and dehydroascorbic acid in vegetables. Quim Nova 32:87–91

Carr AC, Rowe S (2020) The emerging role of vitamin C in the prevention and treatment of COVID-19. Nutrients 12:3286

Carter JH, Tourtellotte WG (2007) Early growth response transcriptional regulators are dispensable for macrophage differentiation. J Immunol 178(5):3038

Cazzola R, Camerotto C, Cestaro B (2011) Anti-oxidant, anti-glycant, and inhibitory activity against α-amylase and α-glucosidase of selected spices and culinary herbs. Intern J Food Sci Nutr 62:175–184

Challier B, Pernau J, Viel J (1998) Garlic, onion and cereal fibre as protective for breast cancer: a French case study. Eur J Epidemiol 14:739–747

Cheraghipour K, Marzban A, Ezatpour B, Moradpour K, Nazarabad VH (2019) The role of onion (Allium cepa) in controlling parasitic diseases: a mini review. Herb Med J 175–180

Choucair N, Laporte V, Levy R, Tranchant C, Gies J-P, Poindron P et al (2006) The role of calcium and magnesium ions in uptake of b-amyloid peptides by microglial cells. Int J Immunopathol Pharmacol 19:683

Cook NR, Obarzanek E, Cutler JA et al (2009) Joint effects of sodium and potassium intake on subsequent cardiovascular disease: the trials of hypertension prevention follow-up study. Arch Intern Med 169:32–40

Crozier A, Lean MEJ, McDonald MS, Black C (1997) Quantitative analysis of the flavonoid content of commercial tomatoes, onions, lettuce, and celery. J Agric Food Chem 45:590–595

Dahlawi SM, Nazir W, Iqbal R, Asghar W, Khalid N (2020) Formulation and characterization of oil-in-water nanoemulsions stabilized by crude saponins isolated from onion skin waste. RSC Adv 10:39700–39707

Desai G, Schelske-Santos M, Nazario CM, Rosario-Rosado RV, Mansilla-Rivera I, Ramirez-Marrero F et al (2020) Onion and garlic intake and breast cancer, a case-control study in Puerto Rico. Nutr Cancer Int J 72:791–800

Dorant EVDB, van den Brandt PA, Goldbohm RA, Sturmans FERD (1996) Consumption of onions and a reduced risk of stomach carcinoma. Gastroenterology 110:12–20

Dweck AC (1997) Indian plants. Cosmet Toilet 112:37–51

El-Hashim AZ, Khajah MA, Orabi KY, Balakrishnan S, Sary HG, Abdelali AA (2020) Onion bulb extract downregulates EGFR/ERK1/2/AKT signaling pathway and synergizes with steroids to inhibit allergic inflammation. Front Pharmacol 11:551683

Elhassaneen YA, Sanad MI (2009) Phenolics, selenium, vitamin C, amino acids and pungency levels and antioxidant activities of two Egyptian onion varieties. Am J Food Technol 4:241–254

Ge Z, Zhang J, Chen X et al (2016) Are 24 h urinary sodium excretion and sodium:potassium independently associated with obesity in Chinese adults? Public Health Nutr 19:1074–1080

Ghorani V, Marefati N, Shakeri F, Rezaee R, Boskabady M, Boskabady MH (2018) The effects of Allium cepa extract on tracheal responsiveness, lung inflammatory cells and phospholipase A2 level in asthmatic rats. Iran J Allergy Asthma Immunol 17:221–231

Griffiths G, Trueman L, Crowther T, Thomas B, Smith B (2002) Onions—a global benefit to health. Phytother Res 16:603–615

Guercio V, Turati F, La Vecchia C, Galeone C, Tavani A (2016) *Allium* vegetables and upper aerodigestive tract cancers: a meta-analysis of observational studies. Mol Nutr Food Res 60:212–222

Gulsen G, Ayaz E (2010) Antimicrobial effect of onion (*Allium cepa*) and traditional medicine. J Anim Vet Adv 9:1680–1693

Gupta PK, Bhaskar P (2020) Medicinal values: onion and garlic. 23rd Bulletin, published by National Horticultural Research and Development Foundation, New Delhi

Iqbal K, Khan A, Khattak MAK (2004) Biological significance of ascorbic acid (vitamin C) in human health-a review. Pak J Nutr 3:5–13

Jafarpour-Sadegh F, Montazeri V, Adili A, Esfehani A, Rashidi MR, Pirouzpanah S (2017) Consumption of fresh yellow onion ameliorates hyperglycemia and insulin resistance in breast cancer patients during doxorubicin-based chemotherapy: a randomized controlled clinical trial. Integr Cancer Ther 16:276–289

Jain N, Minhajuddin AT, Neeland IJ et al (2014) Association of urinary sodium-to-potassium ratio with obesity in a multiethnic cohort. Am J Clin Nutr 99:992–998

Jayedi A, Ghomashi F, Zargar MS, Shab-Bidar S (2019) Dietary sodium, sodium-to-potassium ratio, and risk of stroke: a systematic review and nonlinear dose-response meta-analysis. Clin Nutr 38:1092–1100

Jiang F, Li WP, Kwiecien J, Turnbull J (2006) A study of the purine derivative AIT-082 in G93A SOD1 transgenic mice. Int J Immunopathol Pharmacol 19:489

Kameshwari MS (2013) Chemical constituents of wild onion Urginea indica Kunth Liliaceae. Int J Pharm Life Sci 4:2414–2420

Kang HJ, Pichiah BT, Abinaya RV, Sohn HS, Cha YS (2016) Hypocholesterolemic effect of quercetin-rich onion peel extract in C57BL/6J mice fed with high cholesterol diet. Food Sci Biotechnol 25:855–860

Kapoor LD (2018) CRC handbook of Ayurvedic medicinal plants. CRC Press

Kendler BS (1987) Garlic (*Allium sativum*) and onion (*Allium cepa*): a review of their relationship to cardiovascular disease. Prev Med 16:670–685

Khalsa KPS, Tierra M (2010) The way of ayurvedic herbs. Motilal Banarsidass Publishers, Delhi, India, pp 60–62

Khan N, Ahmed MJ, Shah SZA (2019) Comparative analysis of mineral content and proximate composition from chilli pepper (*Capsicum annuum* L.) germplasm. Pure Appl Biol 8:1338–1347

Khar A, Zimik M, Verma P, Singh H, Mangal M, Singh MC, Gupta AJ (2022) Molecular marker-based characterization of cytoplasm and restorer of male sterility (*Ms*) locus in commercially grown onions in India. Mol Biol Rep 49(6):5535–5545

Khar A, Singh H (2020) Rapid methods for onion breeding. In: Accelerated plant breeding, vol 2. Springer, Cham, pp 77–99

Kim JH (1997) Anti-bacterial action of onion (*Allium cepa* L.) extracts against oral pathogenic bacteria. J Nihon Uni Sch Dent 39:136–141

Kleijnen J, Knipschild P, ter Riet GT (1989) Garlic, onions and cardiovascular risk factors. A review of the evidence from human experiments with emphasis on commercially available preparations. Br J Clin Pharmacol 28:535–544

Kolekar YS, Tamboli FA, More HN, Mulani SA, Mali NP (2021) Medicinal plants used in cosmetics for skin and hair care. Int J Pharm Chem Anal 8:36–40

Krishnamurthi RV, Moran AE, Feigin VL, Barker-Collo S, Norrving B, Mensah GA et al (2015) Stroke prevalence, mortality and disability-adjusted life years in adults aged 20–64 years in 1990–2013: data from the global burden of disease 2013 study. Neuroepidemiology 45:190e202
Kumari P, Dembra S, Dembra P, Bhawna F, Gul A, Ali B, Sohail H, Kumar B, Memon MK, Rizwan A (2020) The role of vitamin C as adjuvant therapy in COVID-19. Cure 12:e11779
Lanzotti V, Romano A, Lanzuise S, Bonanomi G, Scala F (2012) Antifungal saponins from bulbs of white onion, *Allium cepa* L. Phytochemistry 74:133–139
Lee SG, Parks JS, Kang HW (2017) Quercetin, a functional compound of onion peel, remodels white adipocytes to brown-like adipocytes. J Nutr Biochem 42:62–71
Li X, Guo B, Jin D, Wang Y, Jiang Y, Zhu B, Chen Y, Ma L, Zhou H, Xie G (2018) Association of dietary sodium: potassium ratio with the metabolic syndrome in Chinese adults. Br J Nutr 120:612–618
Ma YL, Zhu DY, Thakur K, Wang CH, Wang H, Ren YF et al (2018) Antioxidant and antibacterial evaluation of polysaccharides sequentially extracted from onion (*Allium cepa* L.). Int J Biol Macromol 111:92–101
McCabe RD, Bakarich MA, Srivastava K, Young DB (1994) Potassium inhibits free radical formation. Hypertension 24:77e82
Memarzia A, Amin F, Saadat S, Jalali M, Ghasemi Z, Boskabady MH (2019) The contribution of beta-2 adrenergic, muscarinic and histamine (H-1) receptors, calcium and potassium channels and cyclooxygenase pathway in the relaxant effect of *Allium cepa* L. on the tracheal smooth muscle. J Ethnopharmacol 241:112012
Mendis S, Puska P, Norrving B (2011) Global atlas on cardiovascular disease prevention and control. World Health Organization, Geneva, Switzerland
Metrani R, Singh J, Acharya P, Jayaprakasha K, Patil SB (2020) Comparative metabolomics profiling of polyphenols, nutrients and antioxidant activities of two red onion (*Allium cepa* L.) cultivars. Plants 9(9):e1077
Mitra J, Shrivastava SÁ, Rao PS (2012) Onion dehydration: a review. J Food Sci Technol 49:267–277
Moreno-Rojas JM, Moreno-Ortega A, Ordonez JL, Moreno-Rojas R, Perez-Aparicio J, Pereira-Caro G (2018) Development and validation of UHPLC-HRMS methodology for the determination of flavonoids, amino acids and organosulfur compounds in black onion, a novel derived product from fresh shallot onions (*Allium cepa* var. *aggregatum*). LWT-Food Sci Technol 97:376–383
Nabavi SM, Suntar I, Barreca D, Khan H (2019) Phytonutrients in food: from traditional to rational usage. Woodhead Publishing
Nadkarni KN (1954) *Allium cepa* Linn and Allium sativum Linn. In: Puranik MV, Bhatkal GR (eds) The Indian Materia Medico, 3rd edn. (Part 1). Popular Book Depot, Bombay, p 63
Nadkarni KM (2002) Indian Materia medica, vol 1. Popular Prakashan, Mumbai, India, pp 63–64
Nemeth K, Piskula MK (2007) Food content, processing, absorption and metabolism of onion flavonoids. Crit Rev Food Sci Nutr 47:397–409
Nibodhi (2010) Annapurna's Prashad. Mata Amritanandamayo Mission Trust, Amritapuri, India, p 105
Nile SH, Park SW (2013) Total phenolics, antioxidant and xanthine oxidase inhibitory activity of three colored onions (*Allium cepa* L.). Front Life Sci 7:224–228
Nile A, Gansukh E, Park GS, Kim DH, Nile SH (2021) Novel insights on the multi-functional properties of flavonol glucosides from red onion (*Allium cepa* L.) solid waste—*in vitro* and in silico approach. Food Chem 335:127650
Nohara T, Fujiwara Y (2017) Antitumor sulfur compounds from *Allium* species (onion, welsh onion, and garlic). Nat Prod Commun 12:1235–1236
Okayama A, Okuda N, Miura K et al (2016) Dietary sodiumto-potassium ratio as a risk factor for stroke, cardiovascular disease and all-cause mortality in Japan: the NIPPON DATA80 cohort study. BMJ Open 6:e011632
Park J, Kwock CK, Yang YJ (2016) The effect of the sodium to potassium ratio on hypertension prevalence: a propensity score matching approach. Nutrients 8:482

Patil BS, Pike LM, Hamilton BK (1995) Changes in quercetin concentration in onion (*Allium cepa* L.) owing to location, growth stage and soil type. New Phytol 130:349–355

Ravanbakhshian R, Behbahani M (2018) Evaluation of anticancer activity of lacto- and natural fermented onion cultivars. Iran J Sci Technol Trans Sci 42:1735–1742

Ren FY, Reilly K, Kerry JP, Gaffney M, Hossain M, Rai DK (2017) Higher antioxidant activity, total flavonols, and specific quercetin glucosides in two different onion (*Allium cepa* L.) varieties grown under organic production: results from a 6-year field study. J Agric Food Chem 65:5122–5132

Roger VL, Go AS, Lloyd-Jones DM, Benjamin EJ, Berry JD, Borden WB et al (2012) Heart disease and stroke statistics—2012 update. Circulation 125:e2e220

Scalbert A, Williamson G (2000) Dietary intake and bioavailability of polyphenols. J Nutr 8:2073–2085

Sellappan S, Akoh CC (2002) Flavonoids and antioxidant capacity of Georgia-grown Vidalia onions. J Agric Food Chem 50:5338–5342

Singh AK (2017) Early history of crop introductions into India: I. Allium (L.) Spp. Asian Agri-History 21(3)

Singh H, Khar A (2021) Perspectives of onion hybrid breeding in India: an overview. Indian J Agric Sci 91(10):1426–1432

Singh H, Khar A, Verma P (2021a) Induced mutagenesis for genetic improvement of Allium genetic resources: a comprehensive review. Genet Res Crop Evol 68:2669–2690

Singh H, Verma P, Lal S K, Khar A (2021b) Optimization of EMS mutagen dose for short day Indian onion. Indian J Hort 78(1):35–40. https://doi.org/10.5958/0974-0112.2021.00005.0

Singh H, Verma P, Kumar A, Khar A (2022) Screening of forty-five Indian short-day onion cultivars for Vitamin C content to ensure nutritional security. Indian J Hort 79:160–167

Singh H, Lombardo M, Goyal A, Khar A (2023a) Genotypic variation in Na, K and their ratio in 45 commercial cultivars of Indian tropical onion: a pressing need to reduce hypertension among the population. Front Nutr 10:1098320. https://doi.org/10.3389/fnut.2023.1098320

Singh H, Sekhon BS, Kumar P, Dhall RK, Devi R, Dhillon TS, Sharma S, Khar A, Yadav RK, Tomar BS, Ntanasi T, Sabatino L, Ntatsi G (2023b) Genetic mechanisms for hybrid breeding in vegetable crops. Plant 12:2294

Stajner D, Varga IS (2003) An evaluation of the antioxidant abilities of *Allium* species. Acta Biologica Szeged 47:103–106

Suleria HAR, Butt MS, Anjum FM, Saeed F, Khalid N (2013) Onion: nature protection against physiological threats. Crit Rev Food Sci Nutr 1–17

Turati F, Pelucchi C, Guercio V, Vecchia CL, Galeone C (2015) *Allium* vegetable intake and gastric cancer: a case-control study and meta-analysis. Mol Nutr Food Res 59:171–179

Verotta L, Macchi MP, Venkatasubramanian P (2015) Connecting Indian wisdom and western science: plant usage for nutrition and health, vol 15. CRC Press

Viera VB, Piovesan N, Rodrigues JB, Mello RD, Prestes RC, dos Santos RCV et al (2017) Extraction of phenolic compounds and evaluation of the antioxidant and antimicrobial capacity of red onion skin (*Allium cepa* L.). Int Food Res J 24:990–999

WHO (2002) The world health report 2002: reducing risks, promoting healthy life. World Health Organization, Geneva, Switzerland

WHO (2010) Global status report on noncommunicable diseases. Geneva, World Health Organization. http://whqlibdoc.who.int/publications/2011/9789240686458_eng.pdf

WHO (2013) World Health Organization: a global brief on hypertension. http://apps.who.int/iris/bitstream/handle/10665/79059/WHO_DCO_WHD_2013.2_eng.pdf?sequence=1

Wu X, Shi J, Fang WX, Guo XY, Zhang LY, Liu YP et al (2019) Allium vegetables are associated with reduced risk of colorectal cancer: a hospital-based matched case-control study in China. Asia Pacific J Clin Oncol 15:e132–e141

Yang Q, Liu T, Kuklina EV et al (2011) Sodium and potassium intake and mortality among US adults: prospective data from the Third National Health and Nutrition Examination Survey. Arch Intern Med 171:1183–1191

Yang C, Li LH, Yang LG, Lu H, Wang SK, Sun GJ (2018) Anti-obesity and hypolipidemic effects of garlic oil and onion oil in rats fed a high-fat diet. Nutr Metab 15:43

Yang WS, Kim JC, Lee JY, Kim CH, Hwang CW (2019) Antihyperlipidemic and antioxidative potentials of onion (Allium cepa L.) extract fermented with a novel Lactobacillus casei HD-010. Evid Based Complement Altern Med 2019:3269047

Yasmin T, Ali MT, Haque S, Hossain M (2017) Interaction of quercetin of onion with axon guidance protein receptor, NRP-1 plays important role in cancer treatment: an in silico approach. Interdiscip Sci Comput Life Sci 9:184–191

Zaki SM (2019) Evaluation of antioxidant and anti-lipid peroxidation potentials of Nigella sativa and onion extract on nicotine-induced lung damage. Folia Morphol 78:554–563

Zamri N, Abd Hamid H (2019) Comparative study of onion (Allium cepa) and leek (Allium ampeloprasum): identification of organosulphur compounds by UPLC-QTOF/MS and anticancer effect on MCF-7 cells. Plant Foods Hum Nutr 74:525–530

Zhang Z, Cogswell ME, Gillespie C et al (2013) Association between usual sodium and potassium intake and blood pressure and hypertension among U.S. adults: NHANES 2005–2010. PLoS ONE 8:1002–1004

Zhao YL, Fan DM, Zheng ZP, Li ETS, Chen F, Cheng KW et al (2017) 8-C-(E-phenylethenyl) quercetin from onion/beef soup induces autophagic cell death in colon cancer cells through ERK activation. Mol Nutr Food Res 61:1600437

Zhao X-X, Lin F-J, Li H, Li H-B, Wu D-T, Geng F, Ma W, Wang Y, Miao B-H, Gan R-Y (2021) Recent advances in bioactive compounds, health functions, and safety concerns of onion (*Allium cepa* L.). Front Nutr 8:669805

Nutritional Care for Cancer with Sustainable Diets: A Practical Guide

Bushra Shaida, Mayuri Rastogi, and Aditi Rikhari

1 Introduction

The word “cancer” is derived from the Latin (originally Greek) word for “crab” due to the fact that cancer sticks to any part that it seizes upon in a persistent manner, much like the crab. Cancer is a complicated disease that has emerged as a result of numerous genetic alterations that cause unchecked cell growth with the propensity to metastasize (Saha 2022). Deoxyribonucleic acid (DNA), the genetic component of cells, undergoes alterations that are associated with cancer. Each DNA gene codes for a particular enzyme or protein (Nenclares and Harrington 2020). Protooncogenes, which are involved in healthy cell growth, and tumor suppressor genes, which make proteins that regulate cell growth, are two key genes that are crucial for cell proliferation. Apoptosis, also known as programmed cell death, is the process by which extra or damaged cells are also eliminated from the body, keeping the body in balance. These genes’ mutations encourage unchecked cell proliferation (D’arcy 2019). The most recent figures on the cancer burden worldwide were issued by the International Agency for Research on Cancer (IARC). In 2020, there was 19.3 million new cases of cancer and 10.0 million cancer-related deaths. (IARC 2020). According to the most recent data from the World Health Organization (WHO)-International Agency for Research on Cancer (IARC)-GLOBOCAN, 2020, India has cancer mortality rates of 784,821 and incidence rates of 1,157,294 per 100,000 people (Fig. 1). Before the age of 75, the risk of acquiring cancer was 9.6%, and the risk of dying from it was 6.8%.

More than 60% of newly diagnosed cancer cases and more than 70% of cancer-related fatalities are caused by the 10 most prevalent cancer forms. With 11.7% of all new cases, female breast cancer is the most frequent cancer in the world, followed by lung cancer (11.4%), colorectal cancer (10.0%), prostate cancer (7.3%), and stomach

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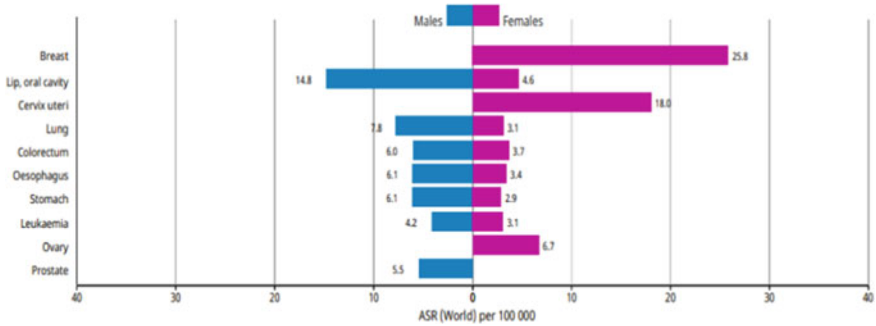


Fig. 1 Age-standardized (world) incidence rates per sex, top 10 cancers (*Source* GLOBOCAN 2020)

cancer (5.6%). The most common type of cancer that results in death (representing 18.0% of all cancer deaths) is lung cancer, which is then followed by colorectal cancer (9.4%), liver cancer (8.3%), stomach cancer (7.7%), and female breast cancer (6.9%) (GLOBOCAN 2020).

Nutrition and diet are essential for the birth, management, and prevention of cancer. Dietary management for cancer aims to meet the increased calorie and protein needs to prevent loss of weight, muscle mass, and fat mass; improve the immune system; and meet the nutrient requirements because cancer patients unintentionally lose weight and exhibit some degree of malnutrition. Thus in the current chapter dietary management of cancer and its development will be discussed.

2 Development of Cancer

The cancer development is a process involving initiation, promotion and progression. When a carcinogen enters a cell as a result of exposure to it, the process is said to have begun. After then, the cellular DNA (deoxyribo nucleic acid) is modified by this carcinogen. Promotion occurs when cancer development is accelerated and cells start to multiply uncontrollably. The third phase of tumor formation is referred to as progression. It could spread to different organs or tissues. Thus, metastasis refers to the expelled of cells that spread to other places of the body. Cancer development is not just an event, it is a multistage process (Wodarz and Näthke 2007).

Chemical or physical events can start a chain reaction. The chemical reaction could happen if a carcinogen enters the cell and modifies the genetic code. When radiation bombards the cell and changes happen in genetic content, the physical event might take place. Whatever the cause, the cell's system for producing proteins alters, causing the DNA to make an unusual structural protein. The cells then start to grow uncontrollably and form a tumor (Fig. 2). Excessive cellular multiplication, invasiveness, and autonomy are key features of cancer. Metastasis refers to the active

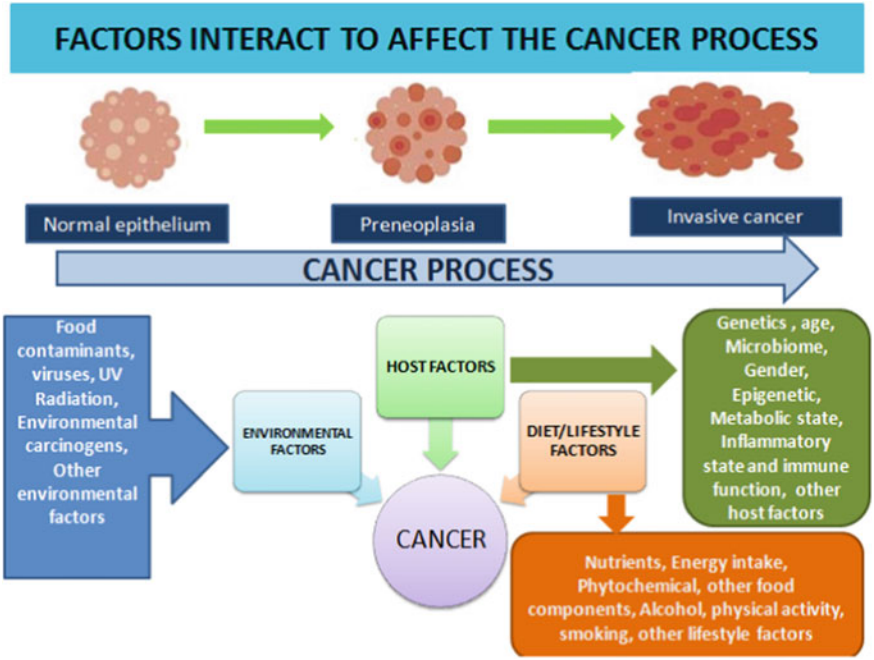


Fig. 2 Development of cancer

invasion process. Specific surface receptors, enzymes, protein synthesis, and energy consumption are needed for metastasis (Baba and Câtoi 2007).

2.1 Properties of Cancer Cells

The body's normal cells and cancer cells are very different from one another. When a series of mutations (changes) causes the cells to continue to proliferate and divide uncontrollably, normal cells turn into malignant ones. Cancer cells can invade neighboring tissues and move to distant areas of the body, unlike normal cells that stay in the area where they first appeared (Fig. 3). When DNA-based genes undergo specific alterations (mutations) that lead the cells to act improperly, cancer cells begin to emerge. These alterations could result from genetics or environmental factors like smoking or UV exposure. Additionally, mutations may occur at random. Normal cells frequently go through stages in which their appearance gets progressively more aberrant as they develop into cancer. Before cancer, these stages may include hyperplasia (enlarged) and dysplasia (growing incorrectly) (Szlasa et al. 2020).

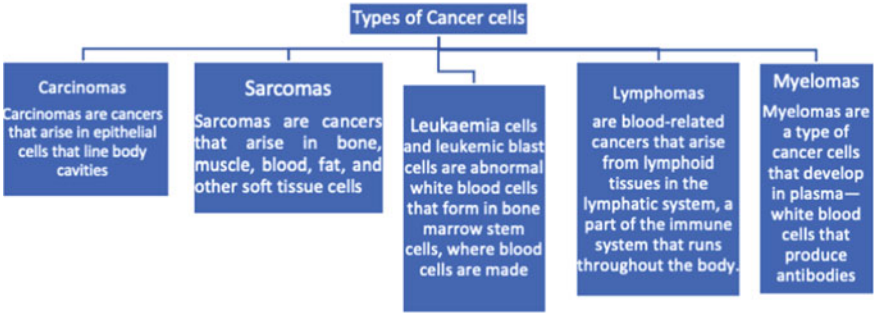


Fig. 3 Types of cancer cells

3 Risk and Etiological Factors in Cancer

Sedentary lifestyles and diets rich in fat and sugar but low in fruits, vegetables, legumes, and whole grains are contributing to an increase in cancer risks. The risk is increasing in developing countries as a result of the urban poor's fast urbanization of rural areas. It is well recognized that migration causes a loss of traditional agricultural practices and nutritional practices, as well as an increase in the use of manufactured foods and beverages. Another significant contributor to the rising cancer hazard is obesity.

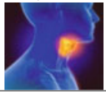
Numerous danger factors are continually present in human life. First and foremost, must keep in mind that different types of cancer will have different etiological or risk factors (Table 1).

The fundamental cause of malignancies is typically the lack of control over cellular reproduction as it normally occurs. This loss of cell control is caused by a number of causes. They include stress factors as well as genetic factors, environmental variables, nutritional factors, carcinogens, radiation, and oncogenic viruses (Friedenreich et al. 2021). Let us find out more about these cancer etiological risk factors.

3.1 Genetics

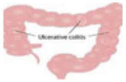
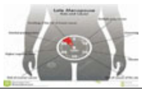
Genes can direct the development of some malignancies. One or more regulatory genes in the cell nucleus cause gene mutations. Although it could be inherited, environmental variables also affect how it manifests. A person's risk of having cancer is higher than it would be in the absence of a genetic predisposing factor such as a family history of the disease (Hemminki et al. 2021).

Table 1 Dietary and non-dietary risk factors in development of different types of cancers

S. No.	Type of cancer	Dietary factors	Non-dietary factors	Risk factors
1	Mouth and pharynx cancer	Alcohol 	Smoking and tobacco 	Vegetables and fruits lack in the diet (vitamin C)
2	Nasopharynx cancer 	Salted fish 	Tobacco smoking and virus infection 	
3	Larynx cancer 	Alcohol 	Tobacco smoking 	Vegetables and fruits lack in the diet (vitamin C and B-carotene)
4	Oesophagus cancer 	Alcohol, very hot drinks, nitrosomes 	Tobacco smoking 	Vegetables and fruits lack in the diet (vitamin C and B-carotene)
5	Stomach cancer 	Grilled meats and nitrosomes 	Bacterial infection *H. Pylori* 	Vegetables and fruits lack in the diet (vitamin C and B-carotene) green tea, garlic, selenium
6	Pancreas cancer 	High energy intake, cholesterol, meat, smoked meat, and fish 	Tobacco smoking 	Vegetables and fruits lack in the diet (vitamin C fiber)

(continued)

Table 1 (continued)

S. No.	Type of cancer	Dietary factors	Non-dietary factors	Risk factors
7	Gall bladder cancer 	High energy and fat intake 	–	–
8	Liver cancer 	Alcohol, aflatoxins, iron 	Viruses: hepatitis B and C 	Vegetables and fruits lack in the diet (selenium)
9	Colon and rectum cancer 	Red meat, alcohol high fat and sugar, eggs, and iron 	Genetic, smoking, ulcerative colitis 	Vegetables and fruits lack in the diet (vitamin C, B-carotene, fibre)
10	Lung cancer 	Alcohol, saturated fat, animal fat, and cholesterol 	Smoking tobacco, asbestos, nickel, and chromium 	Vegetables and fruits lack in the diet (fibre and vitamin C) vitamin E, selenium
11	Breast cancer 	Excess energy, alcohol, saturated fat 	Late menopause and pregnancy 	Vegetables and fruits lack in the diet and fruits, fibre, vitamin C and carotene
12	Ovary cancer 	Total fat, eggs and saturated fat 	–	Vegetables and fruits lack in the diet (vitamin C and carotene)

(continued)

Table 1 (continued)

S. No.	Type of cancer	Dietary factors	Non-dietary factors	Risk factors
13	Prostate cancer 	Total fat, saturated animal fat 	–	Vegetables and fruits lack in the diet (vitamin C and b-carotene)
14	Kidney cancer 	Excess energy, meat, and dairy 	Smoking or drug abuse 	Vegetables and fruits lack in the diet

3.2 Environmental Factors

Cancer is known to be brought on by a number of environmental causes, including smoking, sun exposure, and water and air pollution.

3.3 Dietary Factors: Carcinogenic

Food ingredients may also cause cancer. However, it is unknown to what extent nutrition has a role in the development of cancer. In regions of the world where people consume large amounts of foods that have been highly smoked, pickled, or salt-cured, which contain carcinogenic nitrosamines, there is a high prevalence of cancers, particularly stomach cancers. A high incidence of various malignancies, particularly those of the mouth and throat, has also been linked to alcohol. Alcoholic beverages like beer and scotch may also contain harmful nitrosamines. The carcinogen urethane, which is created during fermentation, may be present in other alcoholic beverages including wine and brandy (Bryan et al. 2012). Cancer's genesis has been linked to nitrosamines. A wide range of substances known as nitrosamines are created when substituted amides, urea's, and guanidine are nitridated. Since nitrosamines are direct-acting carcinogens, their activation happens by spontaneous hydrolysis rather than an enzymatic process.

The relationship between dietary factors and the etiology of various malignancies has been demonstrated in a number of laboratory and epidemiological investigations. The majority of tumor forms have been demonstrated to be inhibited by severe caloric restriction in animals. However, cutting calories will not stop tumors from growing. Numerous epidemiological studies have demonstrated a link between high calorie intake in people and a higher risk of endometrial and gall bladder cancer (Tahergorabi et al. 2016). According to certain epidemiological research, consuming a lot of protein may increase your risk of developing cancer. For instance, colon and breast cancers are more common in developed countries. High intakes of total protein or animal protein have been linked by some researchers to an increased risk of these particular malignancies (Craig 2010).

It is thought that animal tumor formation is influenced by both the kind and quantity of fat.

Humans who consume a lot of fat may be more likely to develop colon and breast cancer. High fat intake, increased intestine anaerobic bacteria, and biliary steroid release have all been proposed as potential mechanisms (Long et al. 2017). These anaerobic bacteria have the ability to make estrogens. In mammary tissues, estrogens are thought to have the potential to cause cancer. Additionally, intestinal bacteria convert bile acids into secondary bile acids like deoxycholate and lithocholate. These might cause cancer in the colon. Another hypothesis holds that cis fatty acids are less cancer-causing than trans fatty acids (Virsangbhai et al. 2020).

3.4 Non-dietary Factors: Carcinogenic

There are number of agents that can cause genetic damage and induce neoplastic transformation of cells. They fall into the following categories.

- Oncogenic viruses
- Chemical carcinogens
- Radiant energy.

3.4.1 Oncogenic Viruses

There are specific viruses known to disrupt the operations of the regulatory genes. Oncogenic viruses are those that cause cancer. These viruses are thought to be the second most significant risk factor, according to several studies. Numerous DNA and RNA viruses have been shown to cause cancer in animals.

- **DNA viruses**: There are three types of DNA virus which can cause human cancers i.e. EBV, HBV and HPV.
- **Epstein-Barr virus (EBV)**: This virus belongs to herpes family and can lead to Burkitt's lymphoma which is a B-lymphocyte tumour. The tumour cannot be caused by the EBV virus alone. EBV consistently promotes the growth of beta cells in patients with immunological dysregulation. It has been discovered that EBV and nasopharyngeal cancer are tightly related.
- **Hepatitis B Virus (HBV)**: Hepatitis B virus infection is found to be closely associated with formation of liver cancer.
- **The human papilloma virus (HPV)** is a benign squamous papilloma that causes many warts. The warts can become cancerous in some cases. Cervical squamous cell cancer has been linked to HPV, according to research.

3.5 Chemical Carcinogens

It has been established that certain chemicals cause cancer. Some are naturally occurring elements of microorganisms and plants. Some of them are industrially produced synthetic goods. Based on a substance's capacity to bind to DNA, chemical carcinogens can be divided into two broad types.

Genotoxic substances are those that bind to DNA, whereas epigenetic substances are those that are carcinogenic but show no sign of binding to DNA. Alkylating agents, acylating agents, and aromatic amines are a few of the main chemical carcinogens. Some other chemical carcinogens include aflatoxin B1, betel nuts, nitrosamines and amides, vinyl chloride, nickel, and chromium insecticide and fungicide. Cancer is also known to be caused by tobacco, smoking, and drug misuse.

3.6 Radiant Energy

Radiant energy, whether it takes the form of UV light from the sun or ionizing electromagnetic and particle radiation, has the ability to alter all cell types in vitro and cause neoplasia in vivo in both humans and lab animals.

- **Ultraviolet rays**: Epidemiological studies have found plenty of proof that exposure to the sun's ultraviolet rays increases the risk of developing squamous cell carcinoma, basal cell carcinoma, and melanocarcinoma of the skin (Braun-Falco et al. 2012)
- **Ionizing radiation**: Ionization radiation causes cancer in the same way as electromagnetic (X, gamma) and particulate (protons, neutrons, and particles) radiations do. It has been proven that radiation, even when used therapeutically, causes cancer.

3.7 Stress Factors

It is not novel to think that emotions may contribute to cancer. But evaluating these relationships is incredibly challenging. The surprising reality is that greater correlations between cancer and quantifiable stressors are being observed. Clinicians and academics have noted that emotional trauma and cancer appear to be strongly correlated. This correlation has two significant physiological factors, it is certain. One is harm done to the immune system and thymus gland. The neuroendocrine effects, which are mediated by the hypothalamus, pituitary, and adrenal cortex, come in second (Moreno-Smith et al. 2010). To confirm the link between stress factors and cancer, specific studies in this area must be conducted.

4 Metabolic Alterations and the Cancer-Related Nutritional Problems

In several studies it has been demonstrated that malignancy development (cancer) is responsible for a variety of metabolic abnormalities that are connected with changes in the patient's body composition and nutritional status. These alterations can be seen as a variety of clinical consequences, which are often classified under the umbrella term Cancer Cachexia (Shyh-Chang 2017).

4.1 Cancer-Related Metabolic Changes

Patients with advanced cancer, as previously studied, have deep anorexia, early satiety, changes in the function of organs/glands/body parts, many deficiencies related to nutrition, and losses in weight. Further the source of the symptoms is unknown, this have been proven to be connected with the patient's metabolic condition. There are changes in energy expenditure, carbohydrate, and protein consumption. Protein and fat metabolism, acid–base balance, enzyme activity, and endocrine functions are all examples of metabolic processes. There is a general rise in metabolic rate. For example, it may be 10% more than the normal level. However, there are differences among patients with gastrointestinal malignancies. Some people may be hyper metabolic, but patients with colon and rectal cancer may not. As a result, it is understandable that there may be differences amongst patients. Glucose intolerance has been observed in cancer patients. This is attributed to increased insulin resistance as well as decreased insulin secretion. There are also numerous reports indicating an increased rate of endogenous glucose generation in cancer patients. Weight loss is connected with higher production paired with other carbohydrate modifications. Cancer patients have been found to have a higher rate of Cori cycling (Bobrovnikova-Marjon and Hurov 2014).

4.2 Cori Cycle

Glucose produced by the tissues in periphery metabolized as lactate in this cycle, it is then re synthesized as glucose in the liver. In this procedure energy consumed because it requires 6 ATP to synthesize only 2 ATP. As a result, if all tumour cells more lactate is released, more energy will be squandered for glucose re-synthesis. As a result, this is believed that Cori Cycling could be one of the important variables in the development of weight reduction. According to many research findings, the majority of weight loss in cancer patients is attributable to depletion in fat deposits. It includes higher lipolytic (fat breakdown) rates driven by decreased food intake, suppression of lipolysis due to the stress response to disease, and tumour-produced lipolytic agents (Lelbach et al. 2007).

Elevated lipid levels are not significant in cancer patients, but they may occur in conjunction with specific tumours. In cancer patients who had lost a large amount of weight, the rate of fat oxidation was shown to be greater than the rate of carbohydrate oxidation.

The following modifications in protein metabolism have been found.

- Whole-body turnover rates increase by 0.1.
- As the condition progresses, catabolic (breakdown) rates of muscle protein increase, resulting in weight loss.
- Lower plasma branched-chain amino acids.
- Skeletal muscle mass is diminished.

- Albumin is the liver's main secretory protein. Hypoalbuminemia is caused by its depletion, which is prevalent in cancer.
- Negative nitrogen balance occurs despite adequate ingestion.

Severe metabolic alterations can result in progressive weight loss, protein energy deficiency anaemia, and other protein, fat, and carbohydrate metabolism problems. Cancer cachexia is the name given to this syndrome. Aside from metabolic alterations, there are other changes that are thought to be endogenous host responses. Advanced cancer patients have fluid and electrolyte abnormalities. Severe vomiting/diarrhoea, as well as alterations in the enzyme system, can cause a variety of symptoms.

The host's immune functions may be compromised, resulting in increasing malnutrition. These are ascribed to the production of mediators originating from immune system cells, which are known as cytokines. Cytokines are polypeptides that regulate cell proliferation, differentiation, metabolism, and activation. These regulatory polypeptides have a specific relationship with three areas of cancer. One is the inhibition of cytokines by activated oncogenes, the loss of tumour suppressor genes, the growth of drug resistance, and the loss of intimate cell-to-cell contact. Secondly, these regulators' have roles in tumour growth and the development of numerous cancer metabolic disorders. Third, certain cytokines are being used in anti-tumour therapy (Waldmann 2018). Many cancer patients have loss of taste and appetite. The factors that influence taste and scent are highly complex. There have been few studies that show there is no aberration in taste perception. Despite the fact that these variations occur in the research. One should not dismiss the loss of taste and appetite in cancer patients based on these findings.

These are also contributing causes to their weight loss. One of the most prevalent metabolic consequences is hypercalcemia. Nausea, muscle weakness, extra urination, and high blood pressure are common symptoms. Anorexia, lethargy, bewilderment, and stupor lead to coma (Hariyanto and Kurniawan 2021). Certain types of tumours, on the other hand, lower calcitriol concentration in conjunction with hypophosphatemia, resulting in oncogenic Osteomalacia. Muscle weakness of different severity and back pain have been common complaints.

5 Cancer-Related Clinical Manifestations and Nutritional Issues

Cancer causes changes in the metabolism of carbohydrates, protein, fat, fluids, and various micronutrients. Changes in metabolism, as well as changed structural/functional capability, result in cancer cachexia, increased morbidity, and death. Main medical signs and symptoms connected with a cancer patient's nutritional status include:

- Anorexia accompanied by increasing weight loss and malnutrition.

- Changes in taste can result in decreased or altered meal intake. Changes in protein, carbohydrate, and lipid metabolism.
- Increased energy consumption despite losing weight.
- Reduced food intake and malnutrition as a result of mechanical bowel obstruction at any level, gastrointestinal dysmotility caused by various malignant tumours.
- Malabsorption caused by a lack of or inactivation of pancreatic enzymes, bile salts, or a failure of food to mix with digestive enzymes; fistulous bypass of the small bowel; and malignant cell infiltration of the small intestinal wall, lymphatics, and mesentery.
- Enteropathy with protein loss.
- Tumour-induced metabolic disorders.
- Chronic blood loss anaemia with bone marrow suppression.
- Electrolyte and fluid difficulties linked with chronic vomiting caused by intestinal blockage or intracranial tumours, intestinal fluid losses via fistulas or diarrhoea.

6 Nutritional Assessment and Screening

Nutritional screening and assessment techniques can be helpful in detecting malnutrition in cancer patients at an early stage. Nutritional screening must be the first step of cancer therapy and should be done as early as possible like at the time of diagnosis or hospital admission. The screening should be done regular intervals with the aim to detect vulnerable patients who are at risk of malnutrition. A good screening test for malnutrition should be quick and simple to use, affordable, extremely sensitive, and must have excellent precision. Thus, selection of an appropriate assessment tool should be the first approach for any effective intervention and nutritional therapy for cancer patients. Although, various screening and assessment tools as been used till now, however, the most commonly used tools are MUST (Malnutrition Understanding Screening Tool), MNA (Mini Nutritional Assessment) and NRS (Nutritional Risk Screening) for screening malnutrition. These tools consist of series of questionnaire associated with malnutrition and anthropometric measurements (Castillo-Martínez et al. 2018).

When the risk of malnutrition is present, more precise, and comprehensive assessment tool are administered to determine the course intervention therapy. Nutritional Assessment tools include, clinical observations, nutritional intake, psychological conditions, biochemical measurements, and functional status of patients. The most reliable and widely used assessment for cancer patients are SGA (Subjective Global Assessment) and PG-SGA (Patient Generated-Subjective Global Assessment). The assessment should be done in accurate intervals to obtain body changes during the course of treatment. Nutritional assessment tools include the questionnaire and screening of following aspects:

- **Physical Examination**: This includes, functional status, body strength, and skeleton mass, respiratory strength, immune function and grip strength.

- **Biochemical Assessment**: This includes, measurement of blood parameters, Albumin levels, and haematological parameters.
- **Anthropometric measurement**: This includes, body mass index, mid upper arm circumference, body composition, fat mass, lean body mass, and weight change over a period of time.

6.1 Dietary and Medical History

Includes, nutrient intake, food and fluid intake, gap between the intake and recommendations, socio-economic status, food availability and accessibility, History of prior illness and high risk possibility (Fig. 4).

7 Nutritional Intervention and Counselling

The method of nutrition therapy to be adopted is chiefly depends on the location of cancer in addition to gastrointestinal functionality, ability of oral intake and stages of cancer. A complex outcome of cancer-related, nutrition- and/or metabolic-factors leads to nutritional decline. The adverse symptoms can be reduced by proper eating,

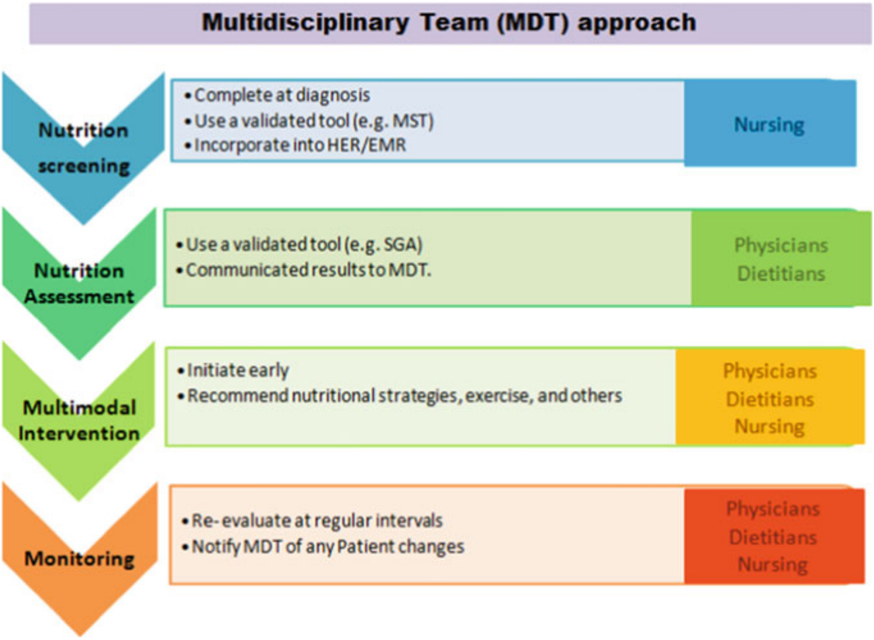


Fig. 4 Multidisciplinary approach for nutrition intervention

that enhance overall health, assist cancer survivorship and an outcome of effective cancer therapy. While adopting nutrition intervention, oral route should always be adopted first. If the oral intake is insufficient or not possible due to surgery or cancer invasion, artificial nutritional therapy must be adopted. Enteral Nutrition (EN) should be adopted to maintain gut integrity, if intestinal functions are maintained. Depending on the digestibility and tolerance, polymeric or elemental feeding should be administered in regular intervals. Enteral nutrition, can also be adopted along with oral diet, if oral intake alone is not as per recommendations. In case of thoracic cancer, Head or neck cancer, PEG or Jejunostomy feed should be adopted. In some cancer cases like, short bowel syndrome, intestinal obstruction, intestinal haemorrhage, where, enteral nutrition is not possible or not enough to provide micro and macro nutrients as per requirements, Parenteral Nutrition (PN) must be adopted as early as possible to prevent muscle catabolism and further malnourishment. PN can also be administer as supplemental route of Nutrient Administration (SRNA). SRNA, provide the benefits of optimum energy intake, muscle mass maintenance, prevent tissue depletion during cancer therapy and reduces morbidities.

Nutritional counselling, also plays an important role in providing optimum nutrition. An effective nutrition counselling should be done based on dietary pattern, psychological status, presence of food allergy or/and intolerances, dietary intake, present weight, and clinical parameters. Nutritional counselling acts as an intervention, for adequate diet intake, improved mental conditions and feeling of wellbeing in the patients (Valentini et al. 2012). Furthermore, it also allows decline in recovery time after cancer therapy.

8 Nutrient Requirements

8.1 Energy

The energy demands during cancer are higher due to hypercatabolic state, preserve tissues and encourage weight gain. It might not be possible to promote an intake above 2000 kcal per day due to some of the restrictive factors connected with food consumption (cancer cachexia). Malnourished patients can, however, be encouraged to ingest about 35–40 kcal/kg body weight per day (3000–4000 kcal/day) with the aid of appetite stimulants and/or nutrition support systems (enteral tube feeding). The negative effects of chemotherapy and cancer cachexia can also be reduced with a high energy diet (Young 1977; Table 2).

Table 2 Tips for better nutrition for cancer patients

Add liquid foods e.g., nutritious soup, broth or pre-made liquid meal	**Snack more** Go for snacks that are easy to prepare and eat like sandwiches or crackers
Soften foods Add milk, cream, or butter to soften the texture, or cook porridge instead of rice	**Include protein-rich food** e.g., lean meat, poultry, fish and seafood, eggs, beans, lentils, and soy products
Try frozen foods e.g., frozen yogurt, and ice cream-high in calories and do not require chewing	**Add calories to drink** e.g., opt for fresh fruit juice instead of drinking water

8.2 Protein

Cancer patients recommended to take high protein (1.5–1.8 g/kg/day) to prevent negative nitrogen balance and muscle wasting. However, due to adverse physiological effects of chemotherapy or radiotherapy, most of the patients are not able to meet their healthy individual (0.8–1 g/kg/day) requirements. In case of reduced oral intake, or deprived gut function, parenteral nutrition therapy must be adopted to provide essential amino acids and albumin. While oral intake, emphasis should be given on inclusion of high biological value proteins like, eggs, dairy, meats and poultry. Renal and liver parameters should be monitored closely while planning high proteins.

8.3 Fat Requirement

Due to enhanced mobilization of free fatty acids from adipose tissues, and making diet palatable and calorie dense, 18–20% calories should be planned from fats sources. Emphasis should be given on medium chain triglycerides and essential fatty acids. Hard to digest fats like animal fats and hydrogenated fats should be restricted. However, cream, butter, coconut oil can be incorporated to improve texture and palatability of diet. Eicosapentaenoic acid (EPA) showed a positive impact on reducing inflammation, and improved body composition.

8.4 Carbohydrate

An adequate amount of carbohydrate (55–60%) is required to prevent protein utilization for energy production. To make the foods energy dense, and easy digestible, simple carbohydrate should be adopted with small interval meal pattern. If the gastrointestinal function is impaired, low fibre diet should be planned to prevent digestive disturbances. In case of hyperglycaemia, soluble fibre rich food like legumes, and cereals must be planned.

8.5 Micronutrients

Due to the poor dietary intake and adverse physiological cancer therapy European Society for Clinical Nutrition and Metabolism (ESPEN) recommends supplementation dosage for both chemotherapy and radiotherapy (Muscaritoli et al. 2021). Vitamin and mineral supplementation in high doses, can be avoided in case of absence of particular deficiency. Vitamin B complex are essential for energy production and tissue recovery. Vitamin C, E and A are potential antioxidants, required for scavenging free radicals, and promote tissue integrity and cell differentiation. Zinc and selenium are two minerals that are extremely important, and supplementation should be used to significantly boost their intake. Inclusion of phytochemicals rich food sources like fruits, carrots, soybeans and Indian spices also have significant symptomatic relieve.

8.6 Fluids

To prevent gastrointestinal disturbances or infections, optimum fluid intake are recommended to dispose of metabolic by products of cancer therapy. To prevent the development of cystitis, 2–3 L water is required. In case of swallowing difficulty, thick shakes and beverages should be planned to meet daily's nutrient requirements.

9 Conclusion

Results from observational studies showed that meal pattern and food choices may influence cancer progression, risk of recurrence, and overall survival in people who have been treated for cancer.

- In order to ensure proper food intake, meal schedules are essential. Cancer patients frequently regret their ability to eat less as the day goes on. This could be due to delayed gastric emptying, decreased gastric secretions, and mucosal atrophy. In such cases, small frequent meals are recommended.
- Use of flavours and seasoning can be used to enhances taste sensation and enhanced food intake.
- Chemotherapy may cause meat dislikes in some patients. Since lean meats (chicken, seafood, etc.) have a milder flavour than red meats (lamb, hog, buffalo, etc.), lean meats can taken over red meat.
- In case of dysphagia, mouth ulcers, lesions in oesophagus due to chemotherapy, easily digestible full liquid diet should be given.
- To improve calorie dense foods, Milk shakes, custards, puddings, cheese, cream soups, dextrose should be encouraged to consume in small intervals.

- The enteral or parenteral nutrition can be adopted if oral intake alone is not fulfilling nutritional needs. Amino acids and glucose based PN formulas provide 30–35 kcal/kg/day and 2–2.5 gm protein as supplementary. For enteral nutrition, milk or soy based commercial feeds can be adopted.
- Supplements can be considered for supportive and fast recovery in case of nutrient biochemical deficiencies.
- The bioactive components must be added in the diet of the patients so that body will have the immunity to fight the disease.

References

Baba AI, Câtoi C (2007) Tumor cell morphology. In: Comparative oncology. The Publishing House of the Romanian Academy

Bobrovnikova-Marjon E, Hurov JB (2014) Targeting metabolic changes in cancer: novel therapeutic approaches. Annu Rev Med 65:157–170

Braun-Falco O, Schwarze HP, Horstmann A, Freitag M (2012) Skin cancer and UV radiation. Springer Science & Business Media

Bryan NS, Alexander DD, Coughlin JR, Milkowski AL, Boffetta P (2012) Ingested nitrate and nitrite and stomach cancer risk: an updated review. Food Chem Toxicol 50(10):3646–3665

Castillo-Martínez L, Castro-Eguiluz D, Copca-Mendoza ET, Pérez-Camargo DA, Reyes-Torres CA, Ávila EAD, López-Córdova G, Fuentes-Hernández MR, Cetina-Pérez L, del Pilar M-G (2018) Nutritional assessment tools for the identification of malnutrition and nutritional risk associated with cancer treatment. Revista de Inves Clinica 70(3):121–125

Craig WJ (2010) Nutrition concerns and health effects of vegetarian diets. Nutr Clin Prac 25(6):613–620

D'arcy MS (2019) Cell death: a review of the major forms of apoptosis, necrosis and autophagy. Cell Biol Intern 43(6):582–592

Friedenreich CM, Ryder-Burbidge C, McNeil J (2021) Physical activity, obesity and sedentary behaviour in cancer etiology: epidemiologic evidence and biologic mechanisms. Molecul Oncol 15(3):790–800

GLOBOCAN (2020) Fact sheets of India. https://gco.iarc.fr/today/data/factsheets/populations/356-india-fact-sheets.pdf

Hariyanto TI, Kurniawan A (2021) Appetite problem in cancer patients: pathophysiology, diagnosis, and treatment. Cancer Treat Res Comm 27:100336

Hemminki K, Sundquist K, Sundquist J, Försti A, Hemminki A, Li X (2021) Familial risks and proportions describing population landscape of familial cancer. Cancers 13(17):4385

IARC (2020). International Agency for Research on Cancer. Latest global cancer data: cancer burden rises to 19.3 million new cases and 10.0 million cancer deaths in 2020. https://www.iarc.who.int/wp-content/uploads/2020/12/pr292_E.pdf

Lelbach A, Muzes G, Feher J (2007) Current perspectives of catabolic mediators of cancer cachexia. Med Sci Monitor: Intern Med J Experi Clin Res 13(9):RA168–173

Long SL, Gahan CG, Joyce SA (2017) Interactions between gut bacteria and bile in health and disease. Mol Asp Med 56:54–65

Moreno-Smith M, Lutgendorf SK, Sood AK (2010) Impact of stress on cancer metastasis. Future Oncol 6(12):1863–1881

Muscaritoli M, Arends J, Bachmann P, Baracos V, Barthelemy N, Bertz H, Bozzetti F, Hütterer E, Isenring E, Kaasa S, Krznaric Z (2021) ESPEN practical guideline: clinical nutrition in cancer. Clinic Nutr 40(5):2898–2913

Nenclares P, Harrington KJ (2020) The biology of cancer. Medicine 48(2):67–72
Saha M (2022) Medical oncology in cancer treatment. In: Cancer diagnostics and therapeutics: current trends, challenges, and future perspectives. Springer Singapore, Singapore, pp 271–285
Shyh-Chang N (2017) Metabolic changes during cancer cachexia pathogenesis. Translational research in breast cancer: biomarker diagnosis, targeted therapies and approaches to precision medicine, pp 233–249
Szlasa W, Zendran I, Zalesińska A, Tarek M, Kulbacka J (2020) Lipid composition of the cancer cell membrane. J Bioenerg Biomemb 52:321–342
Tahergorabi Z, Khazaei M, Moodi M, Chamani E (2016) From obesity to cancer: a review on proposed mechanisms. Cell Biochem Funct 34(8):533–545
Valentini V, Marazzi F, Bossola M, Miccichè F, Nardone L, Balducci M, Dinapoli N, Bonomo P, Autorino R, Silipigni S, Giuliani F (2012) Nutritional counselling and oral nutritional supplements in head and neck cancer patients undergoing chemoradiotherapy. J Human Nutr Diet 25(3):201–208
Virsangbhai CK, Goyal A, Tanwar B, Sihag MK (2020) Potential health benefits of conjugated linoleic acid: an important functional dairy ingredient. Eur J Nutr Food Safety 11(4):200–213
Waldmann TA (2018) Cytokines in cancer immunotherapy. Cold Spring Harbor Pers Biol 10(12):028472
Wodarz A, Näthke I (2007) Cell polarity in development and cancer. Nat Cell Biol 9(9):1016–1024
Young VR (1977) Energy metabolism and requirements in the cancer patient. Cancer Res 37(7):2336–2347

Microorganisms as Potential Source for Food Sustainability

Aarti Yadav, Rekha Mehrotra, and Preeti Verma

1 Microbes Role in Food

Microbes have been an integral part of the human diet from production to consumption from thousands of years. The fermentation process carried out by microbes has been utilized globally in different ways. There are several traditional cuisines including various form of breads, cheese, wine, fermented fish, vegetables and meat etc. exhibiting the key role of microbes in food. However, with increasing population demands the problem to maintain the nutritional and proteins demands have pushed the current food system to a crisis. The existing food structure is highly pressurized and unable to keep the pace with our rising population and meet its demands for nutrition and protein (Graham and Ledesma- Amaro 2023; Rockstrom et al. 2020). Furthermore, the existing issues of climate changes, land quality degradation, intoxication of water bodies and lands to be used for agriculture, aqua culture and animal husbandry has shown an additive effect on scarcity for availability of nutritive food (Change et al. 2019; Sun et al. 2022).

Agriculture, aquaculture and animal husbandry facing consequences with the limitations of land, increased diseases and parasitic infections, abnormal use of chemicals and insecticides, compromised nutritional availability and climate change are leading to critical set back to the food industry. The fact that micro-organisms have the ability to complement, assist, advance and replace the current conventional food options such as agricultural produce, meat etc, making them the best suited alternative for sustainable microbial food revolution (Choi et al. 2022). Microbes are resilient to environmental conditions and have potential to be in their native state as well

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as genetically engineered to recycle leftover inexpensive noncompetitive nutritional sources such as agricultural waste and feedstocks for their own growth thus reducing several issues of waste management, stubble burning (Javourez et al. 2021; Gao et al. 2020). Additionally, they have an excellent nutritional profile helping in escalating the issues with malnourished diets (Linder 2019). Heading towards sustainable food system is the need of the hour. Microorganism having beneficial outcomes can play a role in sustainable food production and agriculture. Although microbes have been a part of the food production from ages, the health benefits of microbes and ecological savings have been revealed lately taking into consideration the importance and potential to enhance, improve or even replace the currently available alternatives and be a part of sustainable food system.

Microbes from generation to generation have been used to improve the quality, texture, taste of our various food items such as cheese, alcoholic beverages, curd, yogurt, kanji, sauerkraut, pickles, kombucha, butter, buttermilk etc (Tamang et al. 2016; Marullo and Dubourdiew 2022). These food items have been extensively studied and has not only shown to be associated with alleviating various life style disorders such as irritable bowel syndrome, crohn's disease, cardiovascular issues etc but also nutritive for aquaculture (Sharif et al. 2021; Marco et al. 2017). Thus, not only improving the quality of life but also saving other associated expenditures (Sharif et al. 2021; Marco et al. 2017). Using this traditional knowledge with the recent advances various value-added products have been synthesized (Fig. 1) as nutritional food sources such as single cell proteins, probiotic drinks, vegan meat (Jones et al. 2020; Banks et al. 2022; Yuan et al. 2019; Wang et al. 2021). Nonetheless, these advancements despite having numerous benefits face some challenges such as ecological and economic stability, scalability, advancements in the existing strains for better production (Sen et al. 2019). Metabolic engineering, high throughput methods, omics approaches for characterization and genetic engineering may ameliorate some these set backs to a great extent (Pan and Barrangou 2020; Helmy et al. 2022). Thus, advancement in microbial food revolution can ignite its application and usage.

2 Microbial Food Product:

Microbes have gained significant attention as a sustainable alternative to traditional animal and plant-based food sources due to their potential to address global food challenges. Some of the key aspects of microbes as sustainable food are microbial food product are primary source of protein that plays key role in health supplements. Currently microalgae are being used in the form of capsule, supplements or liquid form. Certain microbes, such as bacteria, fungi, and algae, can be rich in proteins, vitamins, minerals, and other essential nutrients. They have the advantage of efficient resource utilization which requires fewer resources, including water, land, and energy, compared to traditional livestock and crop production (Sousa et al. 2008). This makes them more sustainable and less environmentally impactful. Further cultivation of microbes can be performed using diverse feedstocks, including agricultural

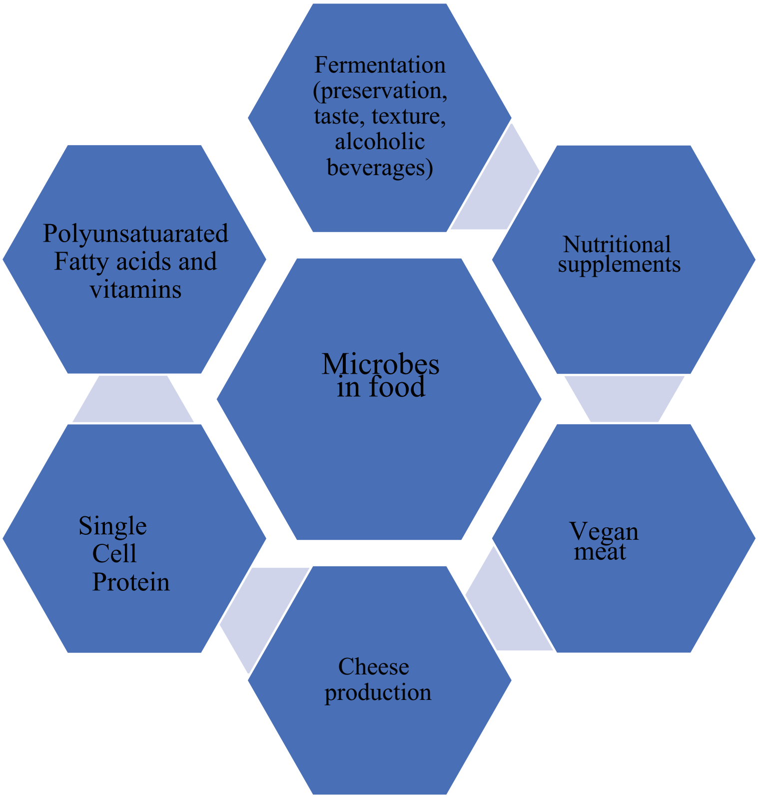

Fig. 1 Schematic showing the roles microbes play in different sectors

waste/biomass, organic byproducts, and even non-arable land. Food out of thin air is the new concept towards sustainable food production where in minimal requirements one can obtain significant produce to overcome the futuristic needs (Ercili-Cura et al. 2020). This versatility reduces the competition for resources with traditional agriculture and expands the potential for sustainable food production. Having short life cycles microbes can reproduce quickly that can be grown in controlled environments, such as bioreactors or fermentation tanks, with minimal space requirements. This fast growth rate allows for higher yields in a shorter time compared to traditional agriculture. Moreover, microbes can be genetically modified or selectively bred to enhance specific traits, such as protein content, nutritional composition, and flavour profile. This customization allows for the production of tailored food products to meet specific consumer needs and preferences.

3 Microbes as Source of Food for Human

3.1 Single Cell Protein and Microbe Powder:

Single-cell protein (SCP) refers to protein-rich biomass/ microbe powder also known as microbial biomass refers to the dried and powdered form of microbial cells such as bacteria, fungi, yeast, or algae Fig. 2 (Choi et al 2022) which can serve as a valuable source of dietary protein, is a potential ingredient for human food production.

It is a rich source of essential nutrients, including proteins, amino acids, vitamins, minerals, and fatty acids (Ciani et al. 2021). Some SCP are used as whole cell preparations, while in others the cell wall may be broken down to make the protein more accessible (Ritala et al. 2017). The single cell protein spirulina has gained importance as superfood for leading a healthy life. A range of commercially available spirula tablet, capsule and powder can be observed showing one aspect towards use of SCP as substitute towards traditional nutritional requirements (Fig. 3). Depending on the type of microbes used, the nutritional composition can vary. For instance, certain microbial species may have a higher protein content, making them a valuable source of plant-based protein. Microbe powder can possess functional properties that make it suitable for various food applications (ERDOĞAN et al. 2022). For instance, it can act as a thickener, emulsifier, or stabilizer in food formulations. The composition and characteristics of the microbial biomass determine its functional potential.

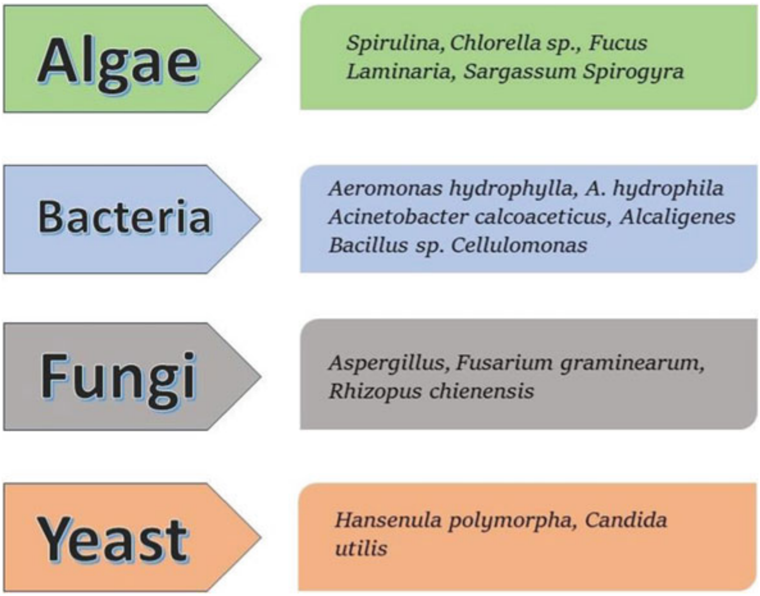

Fig. 2 Sustainable food product (SCP) obtained from various microbial sources

Fig. 3 Commercially produced spirulina as powder and tablet forms

3.2 Fungi- Mushrooms as Vegan Meet

Fungi, particularly mushrooms, have gained popularity as a vegan alternative to meat due to their unique texture, umami flavor, and nutritional benefits. Mushrooms have a meaty texture and a rich, umami flavor, making them a suitable substitute for meat in various dishes. Their fibrous texture allows them to mimic the chewiness of certain meats, providing a satisfying eating experience. Mushrooms offer several nutritional benefits. They are low in calories, fat, and cholesterol and contain essential nutrients such as protein, fiber, vitamins (B-complex vitamins, vitamin D), minerals (iron, selenium, potassium), and antioxidants. While not as protein- dense as meat, certain mushroom varieties, like shiitake and oyster mushrooms, contain notable amounts of protein. Mushrooms can be incorporated into recipes that traditionally use meat, providing a plant-based alternative. For instance, portobello mushrooms can be grilled and used as a burger patty, while minced mushrooms can be used as a substitute for ground meat in dishes like tacos, Bolognese sauce, or meatballs. Mushroom cultivation generally requires fewer resources compared to traditional livestock farming. They can be grown on agricultural waste products like sawdust, straw, or wood chips, reducing the demand for land, water, and feed resources. Additionally, mushroom cultivation has a lower carbon footprint and generates less greenhouse gas emissions compared to animal agriculture. Studies suggest that mycoprotein is associated with a reduction in LDL cholesterol levels (Turnbull et al. 1990). Quorn™ a well-known company produces a range of meat substitutes using mycoprotein—a type of protein derived from filamentous fungi. Mycoprotein is produced through a fermentation process using a fungus called *Fusarium venenatum.*

4 Industrial Production of Microbial Foods

There are several companies that are actively involved in microbial food production. Some of the notable firms are:

Quorn: Quorn is a well-known company that specializes in producing meat substitutes made from mycoprotein, a type of filamentous fungi. They offer a variety of products, including burgers, sausages, nuggets, and deli slices.

Perfect Day: Perfect Day is a company that utilizes microbial fermentation to produce animal- free dairy products. They create dairy proteins, such as whey and casein, by fermenting genetically modified yeast, offering a sustainable and vegan alternative to traditional dairy.

Clara Foods: Clara Foods is focused on producing animal-free egg proteins using microbial fermentation. They aim to create sustainable and cruelty-free egg products, including liquid eggs and egg whites, by fermenting yeast with the desired protein characteristics.

Geltor: Geltor is a company that specializes in producing animal-free collagen and gelatin using microbial fermentation. Their technology allows them to create sustainable, cruelty-free collagen and gelatin for various applications, including food, cosmetics, and pharmaceuticals.

Solar Foods: Solar Foods is developing a novel approach to produce food using microbes and renewable energy. They use a type of bacteria called hydrogen-oxidizing bacteria to convert hydrogen and carbon dioxide into a protein-rich powder called Solein, which can be used as a food ingredient.

Biomilq: Biomilq is focused on producing cultured breast milk using microbial fermentation. They aim to provide a sustainable and ethical alternative to traditional dairy-based infant formula by culturing human mammary cells and producing milk without the need for animal farming.

MycoTechnology: MycoTechnology is a company that utilizes fungi-based fermentation to address taste and nutritional challenges in the food industry. They have developed technology to reduce bitterness and enhance flavor profiles in food and beverages, utilizing fungi as a natural alternative to traditional additives.

Air Protein: Air Protein is a company focused on using microbial fermentation to convert carbon dioxide into a protein-rich food source. They utilize a type of microbe called hydrogenotrophs to create protein. This approach has the potential to produce food without the need for arable land or conventional agriculture.

Algama: Algama is a company that utilizes microalgae to create sustainable food products. They have developed products like plant-based mayonnaise and other sauces using microalgae as a key ingredient.

Motif Ingredients: Motif Ingredients is a food technology company focused on developing animal-free and sustainable food products using fermentation and microbial processes. They work on creating proteins, fats, and other food components that can replace traditional animal-based ingredients.

These companies represent a growing sector of microbial food production, demonstrating the potential for sustainable and innovative alternatives to conventional food sources.

5 Sustainable Approach

The development of novel processing and storage techniques such as lyophilization, preservatives etc have provided us with new sustainable nutritive food prepared with micro-organisms imparting numerous health benefits. Due to resilient and microscopic nature of these microbes they can be cultivated from a small scale to a bioreactor level without being impacted by climatic changes. The composition can vary greatly depending on the microflora and the settings used for the cultivation. It is critical to choose the species carefully keeping the safety concerns. Moreover, microbes have sufficient levels of necessary amino acids that cannot be synthesized by humans and must be obtained through diet (Jach et al. 2022; Yamada et al. 2005). Dietary fibres are essential keeping the balance of gut microflora (Wastyk et al. 2021). Algae are known rich source of cellulose, polysaccharides and other dietary fibres which can be used by human gut flora (Moreira et al. 2022). Further, yeast and fungi are rich in mannans and glucans promoting the growth of gut flora and immune system (McFarlin et al. 2013; Cuskin et al. 2015).

6 Future Prospects and Conclusions

Microorganisms are now frequently consumed in diet more research needs to be undertaken on their nutritional profile, digestibility of all the components, as high ribonucleic acid concentration have been associated with kidney stones. Food developed with microbes could transform the present food structure with sustained ethical and sustainable innovation. The future solutions for food safety and scarcity heavily rely on the success of microbial revolution of food.

References

Bajpai P, Bajpai P (2017) Microorganisms used for single-cell protein production. In: Single cell protein production from lignocellulosic biomass, pp 21–30

Banks M, Johnson R, Giver L, Bryant G, Guo M (2022) Industrial production of microbial protein products. Curr Opin Biotechnol 75:102707
Change IC (2019) Land: An IPCC Special Report on Climate Change. Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems 1– 864 (IPCC)
Choi KR, Yu HE, Lee SY (2022) Microbial food: microorganisms repurposed for our food. Micro Biotechnol 15:18–25
Ciani M, Lippolis A, Fava F, Rodolfi L, Niccolai A, Tredici MR (2021) Microbes: food for the future. Food 10(5):971
Cuskin F, Lowe EC, Temple MJ, Zhu Y, Cameron E, Pudlo NA, Porter NT, Urs K, Thompson AJ, Cartmell A, Rogowski A, Hamilton BS, Chen R, Tolbert TJ, Piens K, Bracke D, Vervecken W, Hakki Z, Speciale G, Munōz-Munōz JL, Day A, Peña MJ, McLean R, Suits MD, Boraston AB, Atherly T, Ziemer CJ, Williams SJ, Davies GJ, Abbott DW, Martens EC, Gilbert HJ (2015) Human gut Bacteroidetes can utilize yeast mannan through a selfish mechanism. Nat 517:165–169
Ercili-Cura D, Hakamies A, Sinisalo L, Vainikka P, Pitkanen J (2020) Food out of thin air. Food Sci Technol 34(2):44–48
Erdoğan E, Orhan KA, Derin E, Hava Bazlı EBCİMBÇ (2022) Proteinin Alternatif Bir Protein Kaynağı Olarak Kullanım Olanaklarının İncelenmesi. Intern J Life Sci Biotechnol 15(3):643–668
Gao R, Li Z, Zhou X, Bao W, Chemg S, Zheng L (2020) Enhanced lipid production by *Yarrowia lipolytica* cultured with synthetic and waste-derived high-content volatile fatty acids under alkaline conditions. Biotechnol Biofuels 13:1–16. https://doi.org/10.1186/s13068-019-1645-y
Graham AE, Ledesma-Amaro R (2023) The microbial food revolution. Nat Commun 14(2231):1–10
Helmy M, Elhalis H, Yan L, Chow Y, Selvarajoo K (2022) Perspective: multi-omics and machine learning help unleash the alternative food potential of microalgae. Adv Nutr 14:1–11
Jach ME, Serefko A, Ziaja M, Kieliszek M (2022) Yeast protein as an easily accessible food source. Metabol 12:63
Javourez U, O'Donohue M, Hamelin L (2021) Waste-to-nutrition: a review of current and emerging conversion pathways. Biotechnol Adv 53:107857
Jones SW, Karpol A, Friedman S, Maru BT, Tracy BP (2020) Recent advances in single cell protein use as a feed ingredient in aquaculture. Curr Opin Biotechnol 61:189–197
Linder T (2019) Making the case for edible microorganisms as an integral part of a more sustainable and resilient food production system. Food Secur 11:265–278
Marco ML, Heeney D, Binda S, Cifelli CJ, Cotter PD, Foligné B, Gänzle M, Kort R, Pasin G, Pihlanto A, Smid EJ, Hutkins R (2017) Health benefits of fermented foods: microbiota and beyond. Curr Opinion Biotechnol 44:94–102. https://doi.org/10.1016/j.copbio.2016.11.010
Marullo P, Dubourdieu D (2022) Yeast selection for wine flavor modulation. in Managing Wine Quality (ed. Reynolds, A. G.) Elsevier, pp 371–426
McFarlin BK, Carpenter KC, Davidson T, McFarlin MA (2013) Baker's yeast beta glucan supplementation increases salivary iga and decreases cold/flu symptomatic days after intense exercise. J Diet 10:171–183
Moreira JB, Vaz BdS, Cardias BB, Cruz CG, ACAd, Almeida, Costa JAV, MGd, Morais (2022) Microalgae polysaccharides: an alternative source for food production and sustainable agriculture. Polysacc 3(2):441–457
Pan M, Barrangou R (2020) Combining omics technologies with CRISPR-based genome editing to study food microbes. Curr Opin Biotechnol 61:198–208
Ritala A, Häkkinen ST, Toivari M, Wiebe MG (2017) Single cell protein—state-of-the-art, industrial landscape and patents 2001–2016. Front Microbiol 13:8–2009
Rockström J, Edenhofer O, Gaertner J, DeClerck F (2020) Planet-proofing the global food system. Nat Food 1:3–5
Sen T, Barrow CJ, Deshmukh SK (2019) Microbial pigments in the food industry—challenges and the way forward. Front Nutr 6:7

Sharif M, Hammad Zafar M, Islam Aqib A, Saeed M, Farag MR, Alagawany M (2021) Single cell protein: sources, mechanism of production, nutritional value and its uses in aquaculture nutrition. Aquacult 531:735885

Sousa I, Gouveia L, Batista AP, Raymundo A, Bandarra NM (2008) Microalgae in novel food products. Food Chem Res Develop 75–112

Sun Z, Sun Z, Scherer L, Tukker A, Spawn-Lee S, Brukner M, Gibbs HK (2022) Dietary change in high-income nations alone can lead to substantial double climate dividend. Nat Food 3:29–37

Tamang JP, Shin DH, Jung SJ, Chae SW (2016) Functional properties of microorganisms in fermented foods. Front Microbiol 7:578

Turnbull WH, Leeds AR, Edwards GD (1990) Effect of mycoprotein on blood lipids. Am J Clin Nutr 52(4):646–650

Wang Y, Liu L, Jin Z, Zhang D (2021) Microbial cell factories for green production of vitamins. Front Bioeng Biotechnol 9:473

Wastyk HC, Fragiadakis GK, Perelman D, Dahan D, Merrill BD, Yu FB, Topf M, Gonzalez CG, Van Treuren W, Han S, Robinson JL, Elias JE, Sonnenburg ED, Gardner CD, Sonnenburg JL (2021) Gut-microbiota-targeted diets modulate human immune status. Cell 184:4137–4153

Yamada EA, Sgarbieri VC (2005) Yeast (*Saccharomyces cerevisiae*) protein concentrate: preparation, chemical composition, and nutritional and functional properties. J Agric Food Chem 53:3931–3936

Yuan SFF, Alper HS (2019) Metabolic engineering of microbial cell factories for production of nutraceuticals. Micro Cell Fact 18:1–11

A Holistic Approach: Exploring Pre, Pro, Syn, Post and Paraprobiotics in Sustainable Diets

Ragini Surolia, Muskan Tyagi, and Anuradha Singh

1 Introduction

Sustainable diets support food security, encourage a healthy lifestyle for both the present and future generations, and have little detrimental impact on the environment. Diets that are sustainable safeguard biodiversity and ecosystems, are accessible to all people, equitable in terms of economic opportunity and affordability, provide appropriate nutrition, are safe and functioning properly, and make the best use of human and natural resources (Burlingame 2012). A sustainable diet focuses on protecting and preserving biodiversity while promoting and achieving overall population well-being in terms of physical, mental, and social aspects. (Vassilakou et al. 2022). Our health and the quality of the food we eat are both directly impacted by pollution and environmental decline (Iribarne-Duran et al. 2022). Since many environmental pollutants accumulate in breast milk, there is growing evidence that we are exposed to them at high levels from birth (Zhao et al. 2019). Additionally, environmental contamination is linked to the emergence of new diseases, including those with autoimmune roots (Di Nisio et al. 2019).

Sustainable diets are an approach to eating that considers the long-term health of both individuals and the planet. They aim to minimize the negative environmental and social consequences associated with food production and consumption, while also meeting nutritional requirements. Sustainable diets ensure access to sufficient, safe, and nutritious food for all individuals. Food is essential to many parts of our life, and the production, distribution, use, and waste of food has in fact had a considerable

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detrimental influence on the environment, public health, and climate change (Fanzo et al. 2018; Lindgren et al. 2018; Ritchie and Roser 2020).

A sustainable diet focuses on promoting both human health and the health of the planet. It entails making food decisions that support food and nutrition security, minimize adverse effects on the environment, and advance a healthy lifestyle for both the present and the coming generations. To achieve these goals, sustainable diets often incorporate the use of various components such as prebiotics, probiotics, synbiotics, postbiotics and paraprobiotics. Prebiotics are indigestible fibers that promote the growth of beneficial bacteria in the gut, while probiotics are live microorganisms that confer health benefits when consumed. A sustainable diet that incorporates synbiotics, the combination of prebiotics and probiotics, can synergistically enhance gut health (Thakur 2016). Moreover, the metabolic byproducts produced by beneficial microorganisms, known as postbiotics, further contribute to these improvements. By integrating these elements into their diets, individuals have the potential to enhance gut health, minimize food waste, optimize nutrient utilization, and promote a food system that is both environmentally sustainable and socially equitable.

2 Prebiotic

Prebiotics, which are indigestible fibers that promote the growth of beneficial bacteria in the gut, can be a valuable component of a sustainable diet (You et al. 2022). Prebiotics are a type of dietary fiber that provide nourishment to beneficial bacteria in the gut. They play a crucial role in supporting gut health and promoting a balanced and diverse gut microbiome. A healthy gut microbiome helps regulate immune responses, promoting a well-functioning immune system. By including prebiotic-rich foods in a diet, such as fruits, vegetables, whole grains, and legumes, individuals can promote their overall health and well-being.

Prebiotics can help reduce food waste by increasing the utilization of edible parts of plants that may otherwise be discarded (Surolia and Singh 2022a, b). For example, parts like peels, stems, and leaves of fruits and vegetables often contain high amounts of prebiotic fibers. These parts can be used to extract the valuable bioactive compound that can be used as a prebiotic.

Many prebiotic-rich foods are derived from plants, such as chicory root, Jerusalem artichoke, garlic, onions, and bananas. Growing and consuming these plant-based foods supports sustainable agriculture practices. Plant-based diets generally have a lower environmental impact compared to diets heavy in animal products. Numerous underutilized fruits and vegetables possess or have the potential to contain significant amounts of pectin, a complex polysaccharide. Pectin exhibits remarkable structural diversity, which makes it highly versatile and applicable in various contexts. Its wide-ranging properties and characteristics enable pectin to be utilized in a diverse array of applications (Surolia and Singh 2022a, b). A diverse diet that includes a variety of prebiotic-rich foods supports biodiversity and ecosystem health. Encouraging the consumption of different fruits, vegetables, whole grains, and legumes helps maintain genetic diversity within crop species and supports the preservation of traditional and heirloom varieties. Additionally, sustainable farming practices that prioritize the use of prebiotic-rich crops can enhance soil health and biodiversity on farmlands.

Prebiotics contribute to the efficient utilization of resources in the food system. Since they are indigestible by humans, they pass through the digestive system relatively intact. However, they provide nourishment for beneficial gut bacteria, promoting their growth and activity. By supporting the proliferation of these microbes, prebiotics optimize the use of nutrients and energy, improving overall resource efficiency (Dai et al. 2022).

2.1 Sources of Prebiotic

Prebiotics, which are indigestible fibers that promotes the growth of healthy microbes in the gut, can be an important part of a sustainable diet. A healthy gut microbiome has been linked to a number of positive benefits on nutritional absorption, immune system performance, and digestion. By including prebiotic-rich foods in a diet, such as fruits, vegetables, whole grains, and legumes, individuals can promote their overall health and well-being. They naturally exist in different dietary food products (Fig. 1), including garlic, sugar beet, asparagus, chicory, onion, Jerusalem artichoke, banana, barley, honey, tomato, rye, chia seeds, soybean, human's and cow's milk, peas, wheat, beans, etc., and recently, microalgae and seaweeds. They are produced on an industrial basis due to their low concentration in foods. The basic materials lactose, sucrose, and starch are also used to make some prebiotics.

Incorporating prebiotic-rich foods into a diet can support both individual health and the sustainability of the food system. It's important to choose a diverse range of prebiotic sources, prioritize organic or regenerative farmed options, and consider the overall ecological footprint of the food choices made to maximize the sustainability benefits.

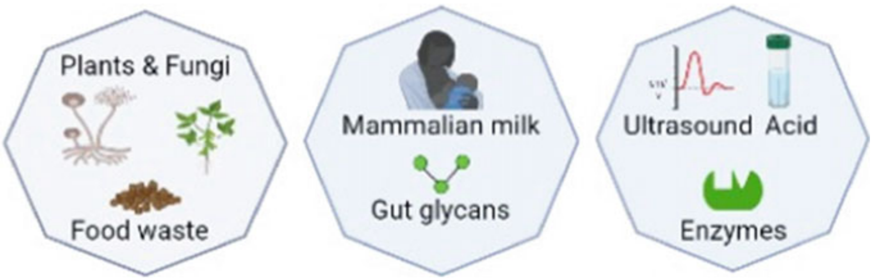

Fig. 1 Sources of prebiotic

3 Probiotic

Probiotics are live microbes, such as bacteria or yeasts, that have been shown to provide health advantages when taken in sufficient quantities (You et al. 2022), can be associated with a sustainable diet in several ways as Probiotics promote a healthy gut microbiome by restoring or maintaining a balance of beneficial bacteria in the digestive system. A healthy gut microbiome is essential for proper digestion, nutrient absorption, and overall gastrointestinal health (Vera-Santander et al. 2023). By supporting gut health, probiotics contribute to overall well-being and can reduce the need for medical interventions or medications, aligning with the principles of sustainability.

The use of probiotics can potentially help reduce the need for antibiotics (Anee et al. 2021). Probiotics have been shown to help prevent or alleviate certain gastrointestinal infections and may enhance the immune response. The addition of probiotics to antibiotic therapies seems to help preserve alpha diversity and lessen the effects of antibiotic use on the makeup of the gut microbial community (Fernandez-Alonso et al. 2022). Probiotics can be derived from sustainable sources, such as fermented foods or cultured strains. Fermentation processes used to produce probiotic-rich foods can contribute to reducing food waste by preserving perishable ingredients (Marco et al. 2021). Additionally, incorporating fermented foods into a diet promotes traditional food preservation techniques, supporting local food economies and traditional food practices.

3.1 Sources of Probiotic

Sources of the probiotic-rich foods (Fig. 2) are yogurt, buttermilk, fermented pickles, sourdough bread, miso soup, kimchi, cottage cheese, tempeh, kefir, etc. Although beneficial bacteria are typically linked to our stomach, especially the large intestines, our body contains a variety of additional locations where they might be located. Including mouth, skin, vagina, gut, urogenital tract, and lungs.

Probiotics can be beneficial for the health and well-being of livestock animals (Anee et al. 2021). They are used in animal agriculture to promote gut health, reduce stress, and enhance nutrient absorption in animals (Al-Shawi et al. 2020). By improving animal welfare through probiotic supplementation, sustainable diets can support more ethical and humane practices in livestock production. Sustainable diets often prioritize plant-based foods and reduce reliance on resource-intensive animal products. Incorporating probiotic-rich fermented plant-based foods, such as kimchi or sauerkraut, can provide beneficial bacteria (Leeuwendaal et al. 2022) while reducing the environmental footprint associated with intensive animal agriculture.

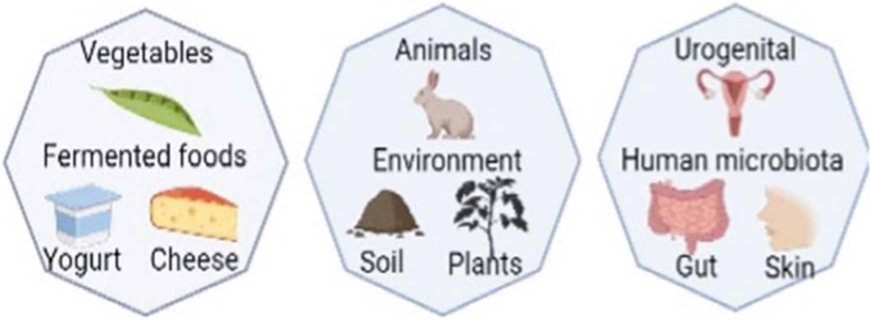

Fig. 2 Sources of probiotic

It's important to note that while probiotics have potential benefits in promoting a sustainable diet, other factors such as sourcing of ingredients, packaging materials, and the overall ecological footprint of the production process should also be considered to maximize sustainability.

4 Synbiotic

A mixture of living microorganisms and substrate(s) specifically used by host microorganisms that benefits the host's health" is now the updated definition of synbiotic (Swanson et al. 2020a, b). Synbiotics refer to the combination of probiotics and prebiotics in a single product or dietary approach (Yadav et al 2022). While synbiotics themselves are not inherently a sustainable diet, they can be part of a sustainable dietary pattern. Synbiotics when the substrate is suggested to be utilised by the co-administered microorganisms preferentially are consider as Synergistic synbiotics and Synbiotics made up of a probiotic and a prebiotic and designed to target the body's own bacteria are categorized as Complementary synbiotics (Swanson 2020). Table 1 lists the several synbiotic combinations and their results.

Synbiotics promote a healthy gut microbiome by providing a combination of beneficial bacteria and the necessary fibers to support their growth. A healthy gut microbiome has been linked to various health benefits, including improved digestion, enhanced immune function, and potential reductions in the risk of certain diseases. By supporting gut health, synbiotics can contribute to overall well-being, which is a key component of a sustainable lifestyle (Surolia et al. 2022).

The use of synbiotics can potentially help reduce the need for antibiotic use. Probiotics can aid in the restoration of the balance of good bacteria in the gut, which can be upset by antibiotic treatments. By promoting a healthy gut microbiome, synbiotics may help strengthen the immune system and reduce the risk of infections, potentially minimizing the need for antibiotics (Pela 2022). This aligns with the goal of

Table 1 Synbiotic combinations and their outcomes

Prebiotic fibre	Probiotic strain	Outcome	Reference
Turmeric powder	*Lactobacillus rhamnosus* GG	Effective in response to allergic asthma	Ghiamati Yazdi (2020)
Acacia gum	*Lactobacillus plantarum* M BTU-HK1	Reduction in tumor necrosis factor alpha and prevention of colon cancer	Chundakkattumalayil et al. (2019)
Mannan-oligosaccharides	*Bacillus subtilis*	Reduce *Salmonella* colonization in chicken	Girgis (2022)
Dietary fibres(soluble) obtained from *Lentinula edodes*	*Lactobacillus plantarum* LP90	Alleviated colitis	Xue et al. (2023)
Fructo-oligosaccharides (FOS)	*Enterococcus faecium*, *Lactobacillus plantarum*, *Streptococcus*	Clinical activity in patients with inflammatory bowel disease has improved	Kamarlı Altun et al. (2019)
Fructo-oligosaccharides	*Lactobacillus casei*, *L. acidophilus*, *L. rhamnosus*, *L.bulgaricus*, *Bifidobacterium breve, longum*, *Streptococcus thermophiles*	Mitigated symptoms in patients with UC (Ulcerative colitis)	Amiriani et al. (2020)
Fructo-oligosaccharides	*L. plantarum*, *S. thermophilus*, *B. bifidum*	Significantly decreased fasting blood glucose, body weight and BMI was not reduced in obese people	Anggeraini (2021)
Cinnamon powder	*L. acidophilus*	Increase of antioxidant enzymes	Mirmiranpour et al. (2020)
FOS, inulin	*L. acidophilus, L. plantarum, L. reuteri*	decreased waist circumference, Improvement in visceral adiposity, Total cholestrol, TCA, HDL, TNF-α, decrease metabolic syndrome prevalence and mean arterial pressure	Cicero (2021)
FOS	*Lactobacillus acidophilus, L. rhamnosus, Bacillus coagulans*	Reduced insulin level, HOMA-IR CRP, and HOMA-β levels in T2DM	Velayati et al. (2021)

reducing the environmental impact of antibiotic use in both human health and livestock farming. The production of synbiotics can be aligned with sustainable agricultural practices. For instance, probiotics can be derived from sustainable sources such as fermented foods or cultured strains. Prebiotics can be sourced from plant-based ingredients, preferably from organic or regeneratively farmed crops. Emphasizing the use of sustainable and locally sourced ingredients in synbiotics supports the principles of sustainable food production and reduces the carbon footprint associated with long-distance transportation.

Synbiotic products can be formulated to have a longer shelf life, reducing the risk of spoilage and minimizing food waste (Seyedzade Hashemi et al. 2022). By extending the shelf life, synbiotic products can help prevent unnecessary food losses and reduce the environmental impact of food waste. This contributes to the efficient use of resources and supports the goal of a sustainable food system. It's important to note that while synbiotics can be part of a sustainable diet, the use of synbiotics can further enhance their alignment with sustainable principles.

5 Concept of Postbiotic

Postbiotic is a relatively new and emerging concept in the field of nutrition and health. They refer to the metabolic byproducts produced by beneficial bacteria during fermentation or growth. These byproducts include short-chain fatty acids, enzymes, peptides, vitamins, organic acids, and other bioactive compounds. A sustainable diet focuses on promoting both human health and the health of the planet. It typically involves consuming foods that are nutritious, environmentally friendly, and ethically produced. Postbiotics can play a role in promoting a sustainable diet.

The concept of postbiotics highlights the importance of secretory components produced by probiotic *Lactobacillus* strains in promoting beneficial effects in the host. The term "postbiotics," specifically refer to the secreted substances that contribute to these positive effects. These components include proteins, peptides, organic acids, and other small molecules, indicating the diverse nature of the substances involved. Furthermore, by noting that they can be released by live bacteria or as a result of bacterial lysis, these components become available to exert their physiological benefits in the different ways (Teame et al. 2020).

Postbiotics have been shown to support a healthy gut microbiome, which is essential for overall health and well-being. A diverse and balanced gut microbiota can improve digestion, enhance nutrient absorption, and strengthen the immune system (Wegh et al. 2019). By consuming foods rich in postbiotics or taking postbiotic supplements, individuals can promote gut health, which is an important aspect of a sustainable diet. Postbiotics, such as organic acids and antimicrobial peptides, have natural preservative properties (Thorakkattu et al 2022). They can inhibit the proliferation and activity of harmful bacteria and extend the shelf life of foods. This can reduce food waste and contribute to sustainable food production and consumption.

Postbiotics offer an alternative approach to promoting health and preventing diseases without relying solely on antibiotics.

Many postbiotics are produced during the fermentation of foods, such as yogurt, sauerkraut, kimchi, and kefir. These fermented foods are not only rich in beneficial bacteria but also provide a natural source of postbiotics (Vera-Santander et al. 2023). Including fermented foods in a sustainable diet can offer health benefits while reducing the environmental footprint associated with intensive agricultural practices. Postbiotics can enhance the bioavailability of certain nutrients in food. For example, they can improve the absorption of minerals like calcium, iron, and magnesium (Zolkiewicz et al. 2020). By optimizing nutrient utilization, postbiotics can contribute to a more sustainable food system by reducing the need for excessive food production.

It is important to emphasize that the field of postbiotics is still in its early stages, and more research is needed to fully understand their impact on human health and sustainability. However, the initial findings suggest that postbiotics can play a role in promoting a sustainable diet by supporting gut health, reducing food waste, and optimizing nutrient utilization several advantages, sources and applications of postbiotics was shown in Fig. 3.

6 Concept of Paraprobiotics

Paraprobiotics, which are defined as "inactivated microbial cells (non-viable microbial cell either intact or broken) that confer a health benefit to the human or animal consumer," have the power to control both the adaptive and innate immune systems. They also have anti-inflammatory, antioxidant and, antiproliferative properties, and they have an antagonistic effect on pathogens.

Studies have demonstrated that the cell surface components of *Lactobacilli*, which are categorized as paraprobiotics, have significant implications in their interactions with host cells. The initial interaction between these components and the host cells is of great importance, as it sets the stage for subsequent physiological responses, as they play a crucial role as effector molecules during the initial interaction with host cells. These components, collectively referred to as paraprobiotics, encompass various elements such as peptidoglycan, teichoic acid, cell-wall polysaccharides, cell surface-associated proteins, and proteinaceous filaments. It has been reported that these components are responsible for facilitating beneficial effects on the host (Teame et al. 2020).

More studies are required to completely comprehend the mechanisms of action and possible health advantages of paraprobiotics, which are currently in the early stages of research. Their advantage includes having a longer shelf life and a lower risk of probiotic sepsis and antibiotic resistance because as the probiotic organisms they don't need to be kept in a cold chain to stay alive. (Shripada et al. 2020). Various characteristics, advantages and sources of Paraprobiotic was shown in Fig. 4.

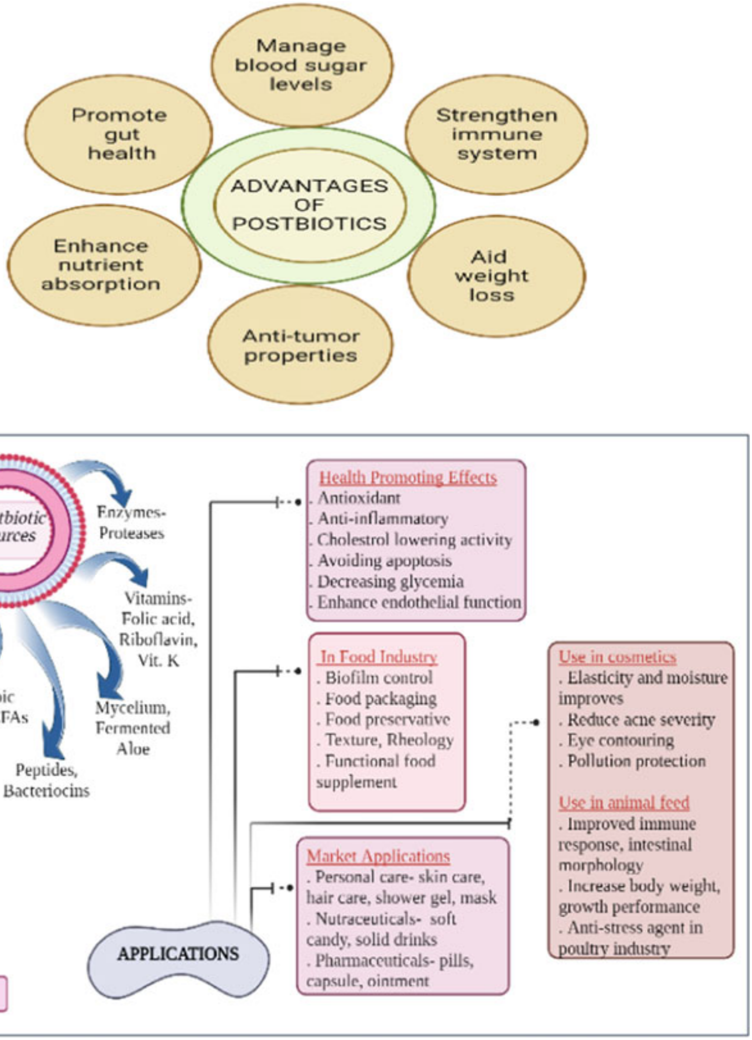

Fig. 3 Postbiotic: advantages and sources and applications

7 Difference in the Concept of Postbiotic and Para Probiotic

It is crucial to distinguish between the ideas of postbiotics and paraprobiotics by limiting their definition. The terms "postbiotic" and "paraprobiotic" are related to different aspects of probiotics but have distinct meanings as shown in Fig. 5. Postbiotics are the beneficial substances or metabolic byproducts that probiotic microbes make while growing and metabolizing. Short-chain fatty acids, enzymes, organic

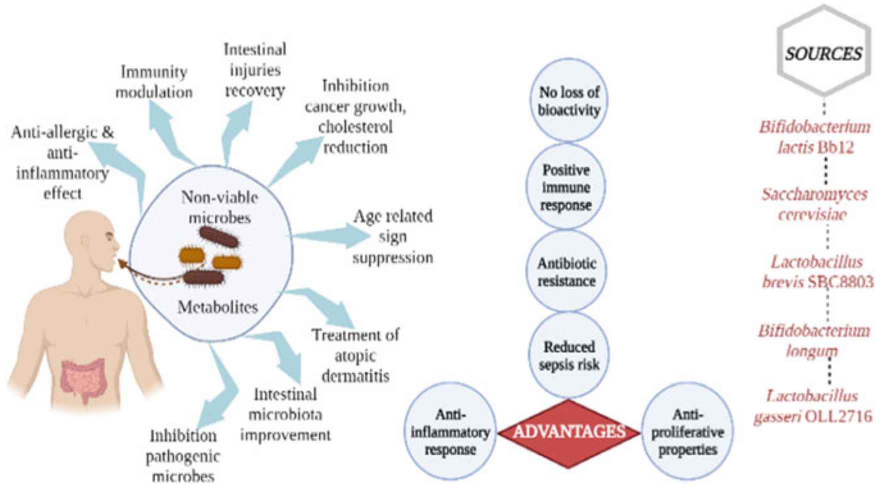

Fig. 4 Paraprobiotics: Properties, advantages and sources

acids, bacteriocins, peptides, polysaccharides, and cell wall constituents are only a few examples of the various chemicals that can be included in these molecules. Postbiotics can be obtained from live probiotic bacteria or through the fermentation process, where the bacteria release these substances into the surrounding environment (Aguilar-Toala et al. 2018). They have been demonstrated to have qualities that improve health, such as immunological modulation, anti-inflammatory actions, and improved gut barrier performance. Postbiotics are bioactive substances that can be employed alone or as parts of therapeutic therapies.

Paraprobiotics, also known as non-viable probiotics or ghost probiotics, refer to inactivated or non-viable microbial cells or their components that still retain some beneficial properties (Barros et al 2020). Paraprobiotics can be pure cell surface components such as peptidoglycan, teichoic acid, polysaccharides, or proteins or they can be heat-killed bacteria, cell wall fragments, secreted metabolites, or cell wall-killed bacteria. Despite not having the capacity to replicate or metabolize, some substances can nonetheless interact with host cells and cause-specific physiological reactions. Paraprobiotics are believed to modulate the host immune system, exert anti-inflammatory effects, and enhance gut barrier function. They are typically more stable and have a longer shelf life compared to live probiotics, making them suitable for various applications in food, supplements, and therapeutic products (Cuevas-Gonzalez et al. 2020).

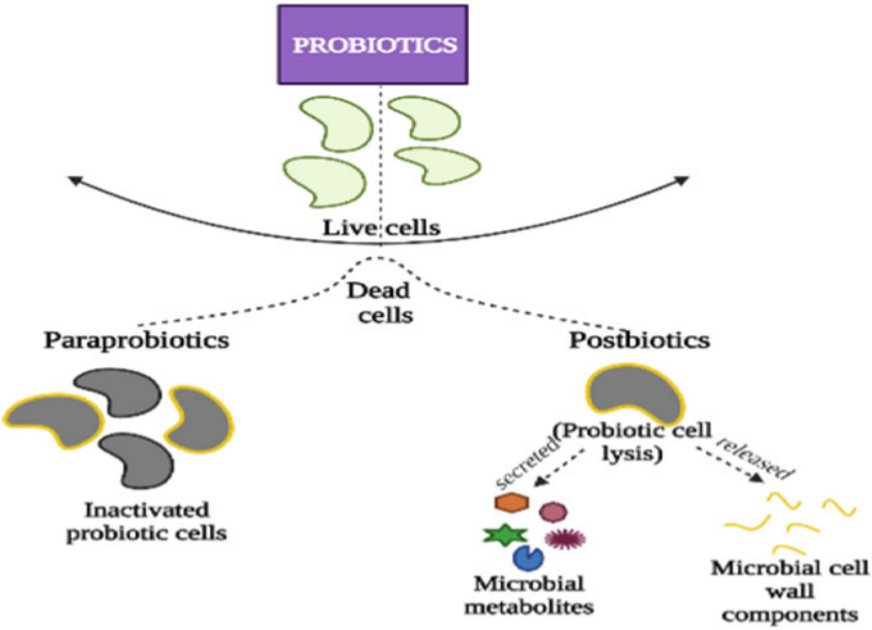

Fig. 5 Differentiation between paraprobiotics and postbiotics

8 Conclusion

The integration of prebiotics, probiotics, synbiotics, postbiotics and para probiotic in sustainable diets offers a holistic approach to address both human health and environmental sustainability. By promoting beneficial gut bacteria, these components enhance nutrient absorption, immune function, and reduce the risk of chronic diseases. Moreover, the adoption of sustainable diets that incorporate these elements contributes to minimizing food waste, improving resource efficiency, and reducing the environmental impact of food production. However, further studies are required to support the positive effects of paraprobiotics and postbiotics. Postbiotics refer to the beneficial substances produced by live probiotic bacteria or through their fermentation process, whereas paraprobiotics encompass the inactivated microbial cells or their components that still retain beneficial properties. Both postbiotics and paraprobiotics offer potential therapeutic benefits, but their mode of action and applications may differ. Collectively, prebiotics, probiotics, synbiotics, postbiotics, and paraprobiotics have diverse health effects that contribute to overall well-being and potentially aid in preventing or managing certain conditions. In conclusion, the various biotics, including prebiotics, probiotics, synbiotics, postbiotics, and paraprobiotics, have distinct mechanisms of action and health effects. When used individually or in combination, they have the potential to support gut health, modulate immune function, reduce inflammation, enhance metabolic processes, and contribute to overall well-being. To completely comprehend the unique mechanisms and ideal uses of each biotic group for focused health advantages, more research is required. We can build a future where people and the earth are healthier by adopting these holistic strategy.

References

Aguilar-Toala JE, Garcia-Varela R, Garcia HS, Mata-Haro V, Gonzalez-Cordova AF, Vallejo-Cordoba B, Hernandez-Mendoza A (2018) Postbiotics: An evolving term within the functional foods field. Trends Food Sci Technol 75:105–114

Al-Shawi SG, Dang DS, Yousif AY, Al-Younis ZK, Najm TA, Matarneh SK (2020) The potential use of probiotics to improve animal health, efficiency, and meat quality: a review. Agricult 10(10):452

Amiriani T, Rajabli N, Faghani M, Besharat S, Roshandel G, Akhavan Tabib A, Joshaghani H (2020) Effect of lactocare® synbiotic on disease severity in ulcerative colitis: a randomized Placebo-Controlled Double-Blind clinical trial. Middle East J Dig Dis 12:27–33

Anee IJ, Alam S, Begum RA, Sahjahan RM, Khandkar AM (2021) The role of probiotics on animal health and nutrition. JoBAZ 82:52

Anggeraini AS, Massi MN, Hamid F, Ahmad A, As'ad S, Bukhari A (2021) Effects of synbiotic supplement on body weight and fasting blood glucose levels in obesity: A randomized placebo-controlled trial. Ann Med Surg 9(68):102548

Barros CP, Guimaraes JT, Esmerino EA, Duarte MCKH, Silva MC, Silva R, Cruz AG (2020) Paraprobiotics and postbiotics: concepts and potential applications in dairy products. Curr Opinion Food Sci 32:1–8

Burlingame B (2012) Sustainable diets and biodiversity—Directions and solutions for policy research and action. In: Proceedings of the International Scientific Symposium Biodiversity and Sustainable Diets United Against Hunger. Rome: FAO

Chundakkattumalayil HC, Kumar S, Narayanan R, and Raghavan KT (2019) Role of L. plantarum KX519413 as Probiotic and Acacia Gum as Prebiotic in Gastrointestinal Tract Strengthening. Microorg 7(12): 659

Cicero AFG, Fogacci F, Bove M, Giovannini M, Borghi C. (2021) Impact of a short-term synbiotic supplementation on metabolic syndrome and systemic inflammation in elderly patients: A randomized placebo-controlled clinical trial. Eur. J. Nutr

Cuevas-Gonzalez PF, Liceaga AM, Aguilar-Toala JE (2020) Postbiotics and paraprobiotics: From concepts to applications. Food Res Intern 136:109502

Dai L, Gu Y, Xu J, Guo J, Jiang K, Zhou X et al (2022) Toward green production of xylooligosaccharides and glucose from sorghum straw biowaste by sequential acidic and enzymatic hydrolysis. Ind Crops Prod 179:114662. https://doi.org/10.1016/j.indcrop.2022.114662

Di Nisio A, Foresta C (2019) Water and soil pollution as determinant of water and food quality/contamination and its impact on male fertility. Reprod Biol Endocrinol 17:4. https://doi.org/10.1186/s12958-018-0449-4

Fanzo J, Davis C, McLaren R, Choufani J (2018) The effect of climate change across food systems: Implications for nutrition outcomes. Glob Food Secur 18:12–19

Fernandez-Alonso M, Aguirre Camorlinga A, Messiah SE, Marroquin E (2022) Effect of adding probiotics to an antibiotic intervention on the human gut microbial diversity and composition: a systematic review. J Med Microbiol 71(11)

Ghiamati Yazdi F, Zakeri A et al (2020) Crude turmeric extract improves the suppressive effects of lactobacillus rhamnosus GG on allergic inflammation in a murine model of house Dust Mite-Induced Asthma. Front Immunol 11:1092

Girgis G, McBride H, Boyle B, Araba M, Bodle BC, Lohrmann T (2022) Effects of a synbiotic combination of Bacillus subtilis and yeast cell wall-derived glucomannan on cecal colonization of Salmonella Enteritidis in layer chickens. J Appl Poultry Res 31(2):100240

Iribarne-Duran LM, Peinado FM, Freire C, Castillero-Rosales I, Artacho-Cordon F, Olea N (2022) Concentrations of bisphenols, parabens, and benzophenones in human breast milk: A systematic review and meta-analysis. Plt Sci Total Environ 806:150437. https://doi.org/10.1016/j.scitotenv.2021.150437

Kamarlı Altun H, Akal Yıldız E, Akın M (2019) Effects of synbiotic therapy in mild-to-moderately active ulcerative colitis: A randomized placebo-controlled study. Turk J Gastroenterol 30:313–320

Leeuwendaal NK, Stanton C, O'Toole PW, Beresford TP (2022) Fermented Foods. Health and the Gut Microbiome. Nutr 14(7):1527. https://doi.org/10.3390/nu14071527.PMID:35406140;PMCID:PMC9003261

Lindgren E, Harris F, Dangour AD, Gasparatos A, Hiramatsu M, Javadi F, Loken B, Murakami T, Scheelbeek P, Haines A (2018) Sustainable food systems—A health perspective. Sustain Sci. 13:1505–1517

Marco ML, Sanders ME, Ganzle M et al (2021) The International Scientific Association for Probiotics and Prebiotics (ISAPP) consensus statement on fermented foods. Nat Rev Gastroenterol Hepatol 18:196–208

Mirmiranpour H, Huseini HF, Derakhshanian H, Khodaii Z, Tavakoli-Far B (2020) Effects of probiotic, cinnamon, and synbiotic supplementation on glycemic control and antioxidant status in people with type 2 diabetes; a randomized, Double-Blind, Placebo-Controlled Study. J Diabetes Metab Disord

Pelá F. (2022) The domino effects of synbiotic: From feed to health [Internet]. Prebiotics and Probiotics—From food to health. IntechOpen; Available from: https://doi.org/10.5772/intechopen.99733.

Ritchie H, Roser M (2020) Environmental impacts of food production. One World Data. Available: https://ourworldindata.org/environmental-impacts-of-food

Seyedzade Hashemi S, Khorshidian N, Mohammadi M (2022) An insight to potential application of synbiotic edible films and coatings in food products. Front Nutr Jul 27;9:875368. doi: https://doi.org/10.3389/fnut.2022.875368. PMID: 35967779; PMCID: PMC9363822

Surolia R, Ali S, Singh A (2022) Synbiotics: A promising approach for improving human health. J Pharm Negat Results, 13(7): 766–777. https://doi.org/10.47750/pnr.2022.13.S07.100

Surolia R, Singh A (2022a) Study on physicochemical properties, structural morphology, and prebiotic potential of extracted pectin from a novel source: Bael pulp (Aegle marmelos) residue. J Biotech Res 13:247–259

Surolia R, Singh A (2022b) Underutilized sources of pectin as edible coating. Lett Appl Nano Bio Sci 12(3):83

Swanson KS, Gibson GR, Hutkins R, Reimer RA, Reid G, Verbeke K, Scott KP, Holscher HD, Azad MB, Delzenne NM et al (2020a) The international scientific association for probiotics and prebiotics (ISAPP) consensus statement on the definition and scope of synbiotics. Nat Rev Gastroenterol Hepatol 17:687–701

Teame T, Wang A, Xie M, Zhang Z, Yang Y, Ding Q, Gao C, Olsen RE, Ran C, Zhou Z (2020) Paraprobiotics and postbiotics of probiotic lactobacilli, their positive effects on the host and action mechanisms: a review. Front Nutr 22(7):570344

Thakur M (2016) Significance of prebiotics, probiotics and synbiotics as health potentiators. Food Sci Res J 7(2):327–334

Thorakkattu P, Khanashyam AC, Shah K, Babu KS, Mundanat AS, Deliephan A, Deokar GS, Santivarangkna C, Nirmal NP (2022) Postbiotics: Current trends in food and pharmaceutical industry. Food 11(19):3094. https://doi.org/10.3390/foods11193094.PMID:36230169;PMCID:PMC9564201

Vassilakou T, Grammatikopoulou MG., Gkiouras K, Lampropoulou MA, Pepa A, Katsaridis S., Alexandropoulou I., Bobora D., Bati Z., Vamvakis A., et al. (2022) Practical sustainable nutrition guide for young people: shifting our dietary habits from animal, to plant-based foods. WWF World Wild Fund; Athens, Greece

Velayati A, Kareem I, Sedaghat M, Sohrab G, Nikpayam O, Hedayati M, Abhari K, Hejazi E (2021) Does symbiotic supplementation which contains Bacillus Coagulans Lactobacillus rhamnosus, Lactobacillus acidophilus and fructooligosaccharide has favourite effects in patients with type-2 diabetes? A randomised, double-blind, placebo-controlled trial. Arch Physiol Biochem 2(1):8

Vera-Santander VE, Hernández-Figueroa RH, Jiménez-Munguía MT, Mani-López E, López-Malo A (2023) Health benefits of consuming foods with bacterial probiotics, postbiotics, and their metabolites: a review. Molecul 28(3):1230

Wegh CAM, Geerlings SY, Knol J, Roeselers G, Belzer C (2019) Postbiotics and Their Potential Applications in Early Life Nutrition and Beyond. Int J Mol Sci. Sep 20; 20(19):4673. https://doi.org/10.3390/ijms20194673. PMID: 31547172; PMCID: PMC6801921

Xue Z, Li R, Liu J, Zhou J, Zhang X, Zhang T, Zhang M, Yang Y, Chen H (2023) Preventive and synbiotic effects of the soluble dietary fiber obtained from Lentinula edodes byproducts and Lactobacillus plantarum LP90 against dextran sulfate sodium-induced colitis in mice. J Sci Food Agric 103(2):616–626

Yadav MK, Kumari I, Singh B et al (2022) Probiotics, prebiotics and synbiotics: Safe options for next-generation therapeutics. Appl Microbiol Biotechnol 106:505–521

You S, Ma Y, Yan B, Pei W, Wu Q, Ding C, Huang C (2022) The promotion mechanism of prebiotics for probiotics: A review. Front Nutr. Oct 5; 9:1000517. https://doi.org/10.3389/fnut.2022.1000517. PMID: 36276830; PMCID: PMC9581195

Zhao CN, Xu Z, Wu GC, Mao YM, Liu LN, Dan YL, Tao SS, Zhang Q, Sam NB, Fan YG et al (2019) Emerging role of air pollution in autoimmune diseases. Autoimmun Rev 18:607–614. https://doi.org/10.1016/j.autrev.2018.12.010

Zolkiewicz J, Marzec A, Ruszczyński M, Feleszko W (2020) Postbiotics-A step beyond pre- and Probiotics. Nutrients. Jul 23;12(8):2189. https://doi.org/10.3390/nu12082189. PMID: 32717965; PMCID: PMC7468815

Functional Properties and Health Benefits of Underutilized Crops and Plants in Northern India

Kirti Gautam and Renu Khedkar

1 Introduction

With the growing populace and rapid depletion of natural resources, it has become essential to discover the opportunities of the usage of more native indigenous plant resources. In today's scenario, agriculture is one of the foremost assets of renewable wealth. There are many plant species nonetheless mendacity unexplored and underexploited. Therefore, there was targeted interest via way of means of the researchers on exploiting opportunity or underutilized plant species for multifarious use. "Underutilized (UU) Plants" are plant species that are used historically for food, fiber, fodder, oil, or medicinal properties, however have not begun to be followed via way of means of large-scale agriculturalists. Underutilized food can be defined as "food that is less readily available, less commonly used, or not used frequently, or reserved for an area" (William and Haq 2002). Unused or neglected Plants species are often old native plant species still in use at the local, national, or even international level, but potentially additionally contributing to range of food sources relative to the present (Thakur 2014; Thakur et al. 2018).

UU plants are those that, in most of the cases, may and have historically been utilized for food and different other large-scale purposes (Mayes et al. 2011). Global Facilitation Unit (GFU) for underutilized species explains "Underutilized plant species have potential to contribute to food security and health including nutrition, income generation and environmental services." These little used Plants are also referred to as "little children", "orphans", "promising" and "little used" (Thakur 2014). In terms of marketing and research, underutilized Plants are plant species that are less well-known, but are well-adapted to marginal and stress environments.

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People are aware of their indigenous potential and ethno botanical data, but they are unaware of their commercial significance and market value. Insufficiently substructured policies, laws, and programmes, as well as a lack of attractive traits, inadequate marketing, and a lack of understanding about their wide range of uses, result in underutilized Plants, which generate minimal income. Research on their genetic variety assessment and plant breeding is limited or nonexistent. As a result, they are vulnerable to displacement by other species, resulting in their disappearance or low occurrence as well as the loss of traditional knowledge about them (Gugal and Kotiyal 2022). These Plants are grown, exchanged, and eaten in the local community. Depending on the type of Plants and the area, the popularity of various horticulture Plants varies, but it can be boosted through exposure. A vital source of vitamins, the mountain horticultural plant has long gone overlooked by metropolitan people. Nowadays, people are becoming more aware of the potential of these species and variations to improve food and nutrition security for people living in poor areas of the world (Gajanana et al. 2010; Gugal and Kotiyal 2022). In the case of mountainous locations, this is related to the identified dietary features of the Plants, the biodiversity, and the richness in know-how guiding of the food. Because they are easier to grow and tougher in nature, they will produce a harvest even under adverse soil and climate conditions. Most of them are a great source of vitamins, minerals, and other nutrients such as carbs, proteins, and lipids. Since this under-utilized Plants has been consumed for a long time, locals are aware of its culinary and therapeutic benefits. Aside from that, they are inexpensive and easily accessible. As the demand for food changes (rediscovery of nutritional and culinary value, therapeutic value—full ethno-biology), Underutilized plants and crops can overcome the restrictions on the wider production and use of the poor. Underutilized plant species have different past, present or potential use value, but their current uses are limited relative to their economic potential (Gruère et al. 2006). In developing countries, despite the potential to diversify diets and provide micronutrients such as vitamins and minerals, they still receive little attention in research and development, export through develop new resources.

Underutilized crops and plants are capable to play a variety of roles in improving India's food security, including (Mayes et al. 2011);

- Part of a focused effort to help the poor maintain livelihoods and incomes,
- A way of reducing the risk of over-reliance on a very limited number of key staple foods,
- A way to increase the sustainability of agriculture by reducing inputs,
- Increasing the quality of food;
- A way of preserving and celebrating cultural and nutritional diversity.

To address the increased demand for food, a method of exploiting marginal and unoccupied land for agricultural purposes has been developed. Therefore, due to their untapped potential, these Underutilized plants and crops will be investigated to combat food security.

2 Unveiling the Underutilized Plants of India

As we continue to unearth the hidden treasures of the North West Himalayas, let us now explore some of the underutilized Plants in India that combine nutrition with tremendous market potential (Fig. 1; Table 1). Few underutilized Plants are identified and their details such as physiochemical, phytochemical properties, traditional uses, pharmacological properties, and their market potential have been discussed as follows.

Fig. 1 Underutilized plants and crops in Northern India

Table 1 Some of the underutilized plants in Northern India and their uses

S. No.	Plants	Family	Common name	Uses	References
1	Buckwheat	Polygonaceae	Kuttu	Variety of food products such as bread, pancakes, noodles, and pastas. Its flour is also used as a gluten-free alternative in baking; used as a grain substitute in pilafs, salads, and porridge; provides valuable nutrition for livestock, particularly for poultry and pigs; utilized as a cover plants and beneficial in organic farming systems; used in honey production; production of biodegradable plastics, biofuels, and as a source of functional compounds for pharmaceutical and nutraceutical industries	Yilmaz et al. (2020), Singh et al. (2015), Sood et al. (2017), Kala (2015), Dhyani et al. (2010)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
2	Horse gram	Fabaceae (Leguminosae)	Kulith	Often used in soups, stews, curries, and dal (lentil) recipes; used to make dishes like rasam (a spicy soup), dosa (a fermented pancake), and sundal (a stir-fried snack); consumed as a nutritious addition to salads, sandwiches, and wraps; used as animal feed, particularly for horses and cattle, good feed option for cattles; used as medicines for aiding digestion, promoting weight loss, and managing diabetes; used as a green manure plants to improve soil health; grown as a cover plants in areas prone to erosion, protecting the soil from wind and water erosion; applications in the food, pharmaceutical, and nutraceutical industries	Bhartiya et al. (2015), Pushpamma et al. (1990), Sreeramulu et al. (2012), Thakur and Sharma (2022)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
3	*Hippophae rhamnoides*	Elaeagnaceae	Sea buckthorn	Used as a nutritional supplement to support overall health and well-being; seed in culinary applications. They are used to make juices, jams, jellies, sauces, and syrups; utilized in a multitude of cosmetic products like creams, lotions, serums, and oils; use in traditional medicine systems, including Tibetan and Ayurvedic medicine.; used in ecological restoration projects due to its ability to tolerate harsh environmental conditions and its nitrogen-fixing properties, helps restore degraded ecosystems and improve soil fertility	Yang and Kallio (2002), Geetha and Asheesh (2011), Suryakumar and Gupta (2011), Wang et al. (2011)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
4	*Girardinia diversifolia*	Urticaceae	Himalayan nettle	Nettle fiber is used for making traditional textiles, ropes, bags, and handicrafts; into various textiles, including shawls, scarves, rugs, and traditional clothing; used to treat conditions such as arthritis, rheumatism, fever, and urinary problems; nettle fiber production and weaving provide income generation opportunities, preserve traditional skills, and contribute to sustainable rural development; promote biodiversity conservation and sustainable land management practices	Pandey et al. (2020), Kumar Rana et al. (2015), Kala (2015)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
5	Millets (*Eleusine coracana, Paspalum scrobiculatum, Panicum sumatrense, Brachiaria ramose*)	Poaceae	Finger millet/kauni/ragi, kodo millet, little millet, browntop millet	Used to make a variety of dishes such as porridge, bread, couscous, pilaf, and as a rice substitute. Millet grains are gluten-free and have a mildly nutty flavor; provides a good source of energy and can contribute to a balanced diet; used in gluten-free baking to make bread, cookies, cakes, and other baked goods; provide a source of nutrition and energy for animal; fermented to make traditional beers and spirits; fast growth and extensive root system help prevent soil erosion, improve soil structure, and contribute to nutrient cycling; popular as bird feed, especially for pet birds like parakeets, canaries, and finches	Ravi (2004), Gruère et al. (2009), Ravi et al. (2010), Thapliyal and Singh (2014, 2015), Thakur and Modi (2020)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
6	*Buchanania lanzan*	Anacardiaceae	Chironji/Chirali	Used in making traditional Indian sweets like kheer (rice pudding), barfi, halwa, and laddu; seeds contain oil, which can be extracted and used for culinary purposes; used in traditional Ayurvedic medicine for its therapeutic properties; used in herbal formulations and remedies for treating ailments like diarrhea, cough, and skin disorders; used in creams, lotions, soaps, and hair care products to promote skin and hair health; believed to have cooling properties and are used in preparations to balance Pitta dosha (one of the three Ayurvedic constitutional types)	Neeraj and Purwar (2020), Gopalan et al. (1982), Sharma (2012), Singh (2007), Srivastava et al. (2017)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
7	*Rhododendron arboreum*	Ericaceae	Buransh	Used in traditional medicine by local communities; grown as an ornamental plant; used local festivals and rituals, symbolizing purity, beauty, and protection; used as valuable nectar source for honeybees; wood used for various purposes, including construction, furniture-making, and fuelwood	Rawat et al. (2018), Negi et al. (2013), Singh et al. (2015), Phondani et al. (2010)
8	Sichuan pepper	Rutaceae	Timur	Widely used in Chinese cuisine to add a unique and numbing flavor to dishes; used as traditional Chinese medicine; considered to have anti-inflammatory and analgesic properties; used to preserve food and as a natural ingredient in disinfectant formulations; used in various Asian dishes as a flavouring agent, adding a unique taste to soups, stews, and marinades	Chen et al. (2021), Moza et al. (2008), McGee (2004), Xiang et al. (2016)

(continued)

Table 1 (continued)

S. No.	Plants	Family	Common name	Uses	References
9	*Citrus sinensis*	Rutaceae	Malta orange	Used for fresh consumption and juice extraction; used in beverages, and processed into various products like concentrates, canned juices, and flavoured drinks; zest is used as a natural flavouring agent in cooking, baking, and confectionery; peel is used for the extraction of *C. sinensis* essential oil	Etebu and Nwauzoma (2014), Lahlou (2013)
10	*Cleome viscosa*	Cleomaceae	Jakhya	Used to treat ailments such as fever, skin diseases, respiratory disorders, and digestive issues; consumed as a part of traditional dishes, providing a source of vitamins and minerals; useful for pest control and as a natural insect repellent; used as fodder for livestock due to its availability and palatability; cultivated as an ornamental plant for its attractive flowers	Mali et al. (2007), Singh et al. (2015), Upadhyay (2015)

2.1 Rhododendron arboreum *(Buransh)*

Rhododendron is a popular plant that is grown for its beauty, medicinal properties, and cultural significance (Verma et al. 2020; Sharma et al. 2022). The genus *Rhododendron* contains over 1,000 species, and many of them are native to Asia. The *R. arboreum* is an evergreen small tree that is found in the Himalayas. It has pink to purple flowers that are edible. The flowers are often eaten raw or processed into juices or squash. *Rhododendrons* are also used in traditional medicine. The leaves and flowers of some species have been used to treat a variety of ailments, including fever, diarrhoea, and dysentery. The bark of some species is used to make a tea that is said to be beneficial for the heart.

Rhododendrons are beautiful and versatile plants that can be grown in a variety of climates. *Rhododendrons* are also a valuable source of food and medicine for many people around the world.

Here are some additional facts about *Rhododendron arboreum*:

- It is the state tree of Uttarakhand, India.
- It is the national flower of Nepal.
- It is a popular ornamental plant in many parts of the world.
- The flowers are edible and can be eaten raw or processed into juices or squash.
- The leaves and flowers have medicinal properties and have been used to treat a variety of ailments.
- The bark of some species can be used to make a tea that is said to be beneficial for the heart.

The taxonomic classification of the *R. arboreum* is as follows (Rawat et al. 2018);
Kingdom: Plantae
Phylum: Magnoliophyta
Class: Angiospermae
Order: Ericales
Family: Ericaceae
Genus: *Rhododendron*
Species: *Rhododendron arboreum*
Sub species (Bhattacharyya 2011):

- *R. arboreum* spp. *arboreum* (red or rose red flowers) found in Western Himalayas.
- *R. arboreum* spp. cinnamomeum (white, pink, or red flowers) found in Central Himalayas.
- *R. arboreum* spp. *delavayii* (red flowers) found in Eastern Himalayas.
- *R. arboreum* spp. *nilagiricum* (red flowers) found in Nilgiri.

R. arboreum, depicted (Figs. 2 and 3) is a tree with branching, reaching heights of up to 10 m. The leaves are evergreen, smooth on the upper surface, and display silvery scales on the lower surface. They are approximately 8.5 cm long, oblong-lanceolate, leathery, and cluster at the end of the branches. The flowers grow in corymb with a terminal inflorescence. The calyx consists of 5–8 lobes, and the

Fig. 2 *Rhododendron arboreum* tree

corolla is campanulate, tubular, with 5–8 lobes. Stamens are inserted at the corolla's base. The ovary is positioned superiorly and is multilocular, leading to a cylindrical capsule with scales and numerous winged seeds. The bark is pale brown and tends to flake. The tree typically flowers from March to May, while fruiting occurs between April and November (Madhvi et al. 2019). Propagation is achieved using cuttings and seeds. For optimal growth, *R. arboreum* prefers moist loam without lime, but it can also thrive in rocky soil conditions if sufficient soil-moisture and humus are present.

2.1.1 Physiochemical Properties

Rhododendron possesses a variety of minerals, including manganese, iron, zinc, copper, sodium, chromium, cobalt, cadmium, molybdenum, nickel, lead, and arsenic. These minerals are essential for maintaining various physicochemical processes vital for life (Kumar et al. 2019). Notably, manganese, copper, selenium, zinc, iron, and molybdenum serve as crucial cofactors within the structure of specific enzymes, playing indispensable roles in numerous biochemical pathways (Table 2). Additionally, sodium plays a vital role in preserving the osmotic balance between cells and interstitial fluid. A Research presents valuable insights into the physical characteristics, proximate composition, and mineral content of *Rhododendron* flowers collected from various regions in northern part of India (Devi and Vats 2017). The average petal length was measured at 4.92 ± 0.50 cm, with slight variations among the flowers from the different regions. Similarly, the average weight of the flowers was found to be 24.45 ± 5.02 g per flower, showing variations in various regions. The fatty acid compositions of stem wood, the major constituents are butanoic acid, 4-heptanoic

Fig. 3 *R. arboreum* flower

acid, and pentanoic acid. Flowers contain approximately sixteen different amino acids (Shrestha 2009). The details are as follows.

These studies emphasize the nutritional value and potential of *Rhododendron* flowers as a valuable food resource, with variations in their composition attributed to diverse agro-climatic conditions in the regions of northern India.

2.1.2 Phytochemical Properties

Various phytochemicals have been successfully identified and isolated from different parts of *R. arboreum* through various research studies. Painuli et al. (2012) reported a total of 34 compounds, with major compounds like beta-amyrin, heptadecane, 22-stigmasten-3-one, tetradecane, methyl ester, linoleic acid, linoleyl alcohol, beta-citronellol, dodecane, L-ascorbic acid, 2,6-dihexadecanoate, alpha-amyrin, and dibutyl phthalate. These compounds were detected using GC–MS analysis of the methanolic leaf extract. In another study of the ethanolic leaf extract, 13 compounds were identified (Table 3), with major compounds including geraniol formate, 1-hexadecene, 1,2,3-propanetriyl ester, 1-octadecanol, and docosanoic acid. Gautam et al. (2014) reported 26, 24, and 17 compounds in the chloroform, ethyl acetate, and hexane fractions, respectively. Notably, two flavonoids, namely 3-Hydroxy-4-(5-hydroxy-7-methoxy-4-oxo-4H-chromen-2-yl) phenyl β-D-glucopyranoside and (8S)-8,9-Dihydro-13,16-dimethoxy-10H-8,11-epoxy-4,7-etheno-1,3-benzodioxacyclododecin-10-one, along with two flavonoid glycosides,

Table 2 Physiochemical properties of *R. arboretum* (Madhvi et al. 2019)

Wood (stem)		Leaves	
Physicochemical parameters	Value (%)	Parameters	Value (%)
Ash content	0.75	Moisture content	0.78
Extractives	4.39	Total ash	1.6
Hollocelluloses	69.82	Acid insoluble ash	0.32
Hemicelluloses	22.00	Sulphated ash	0.0214
Alpha-celluloses	47.98	Water soluble extractives	12.00
Pentosans	16.84	Alcohol soluble extractives	9.65
Lignins	24.88		

Flower			
Physicochemical parameters	Value (%)	Minerals	Value (ppm)
Moisture	79.40 ± 0.10	Mn	50.2
Ash	2.30 ± 0.05	Fe	405
Crude fat	1.52 ± 0.08	Zn	32
Crude fiber	2.90 ± 0.05	Cu	26
Total nitrogen	0.58 ± 0.07	Na	385
Total protein	1.68 ± 0.05	Cr	08
Carbohydrate	12.20 ± 0.12	Co	<0.5
Organic matter	97.70 ± 0.20	Cd	<1
Insoluble ash	1.29 ± 0.05	Mo	<0.5
Soluble ash	1.15 ± 0.08	Ni	2
		Pb	3
		As	<0.5

Rutin and Pectolinaroside (=5-Hydroxy-6-methoxy-2-(4-methoxyphenyl)-4-oxo-4H-chromen-7-yl 6-O-(α-L-rhamnopyranosyl)-β-D-glucopyranoside, and a phenol derivative, terephthalic acid dimethyl ester, were reported in the leaves.

Harborne and Williams (1971) employed two-dimensional chromatography to isolate phenolic compounds from alcoholic leaf extracts. They successfully identified several compounds, including gossypetin, kempferol, azaleatin, caryatin, quercetin, and leucoanthocyanidins. Additionally, HPTLC confirmed the presence of compounds like quercetin, rutin, and coumaric acid in the methanolic flower extract, gallic acid in the leaves, and three triterpenoids (ursolic acid, β-sitosterol, and lupeol) in both the flowers and leaves. Moreover, RP-HPTLC analysis revealed phenolic compounds such as quercitrin, syringic acid, epicatechin, and quercetin-3-O-galactoside in the methanolic leaf extract.

Table 3 Phytochemistry of *Rhododendron*

Compound names	Plant part
Flavonoids	
Quercetin-3-O-galactoside ($C_{21}H_{20}O_{12}$)	Flower, leaves
Quercetin ($C_{15}H_{10}O_7$)	Flower, leaves
Sterol	
β-sitosterol ($C_{29}H_{50}O$)	Leaves
Flavonol glycoside	
Rutin ($C_{27}H_{30}O_{16}$)	Leaves
Quercitrin ($C_{21}H_{20}O_{11}$)	Flower
Triterpenoid	
3-O-acetylbetulinic acid ($C_{32}H_{50}O_4$)	Bark
β-sitosterol-3-O-beta-d-glucosidose ($C_{32}H_{50}O_4$)	Bark
3-β-acetoxyurs-11-en-13β,28-olide ($C_{32}H_{48}O_4$)	Bark
Betulin ($C_{30}H_{50}O_2$)	Bark
Lupeol ($C_{30}H_{50}O$)	Bark
3-O-acetylursolic acid ($C_{32}H_{50}O_4$)	Bark
Betulinic acid ($C_{30}H_{48}O_3$)	Bark
Taraxerol ($C_{30}H_{50}O$)	Bark
Epifriedelinol ($C_{30}H_{52}O$)	Leaves
3,10-epoxyglutinane ($C_{30}H_{50}O$)	Leaves
Pentacyclic triterpenoid	
Ursolic acid ($C_{30}H_{48}O_3$)	Flower, bark, leaves

(continued)

Table 3 (continued)

Compound names	Plant part
α-amyrin ($C_{30}H_{50}O$)	Leaves
β-amyrin ($C_{30}H_{50}O$)	Leaves
Friedelin ($C_{30}H_{50}O$)	Leaves
15-oxoursolic acid ($C_{30}H_{46}O_4$)	Bark
Other	
Leuco-pelargonidin ($C_{15}H_{14}O_6$)	Bark
4,4,6a,6b,11,12,14b-heptamethyl-16oxo-1,2,3,4,4a,5,6,6a,6b,7,8,9,10,11,12,12a,14a, 14b-octadecahydro-12b,8a(epoxymethano)picen-3-yl acetate ($C_{32}H_{48}O_8$)	Bark

Source Madhvi et al. (2019)

2.1.3 Traditional Uses

The stem wood of *Rhododendron arboreum* serves as a valuable source of fuel. Additionally, it is utilized in the production of various wooden products such as handles, packsaddles, and gift boxes (Table 4). These items demonstrate the versatility and usefulness of the wood derived from this tree. The striking and beautiful flowers of *R. arboreum* find applications in house decorations (Ranjitkar et al. 2014; Chettri and Sharma 2009; Kumar and Sharma 2009). Their vibrant colours and attractive appearance make them a popular choice for adding aesthetic value to homes and various settings. Apart from their visual appeal, the flowers of *Rhododendron arboreum* possess a sweet–sour taste. They can be consumed raw or processed into chutneys or juice. The juice derived from the flowers is known to have refreshing properties. Additionally, it is believed to provide relief in cases of headache, stomach-ache, fever, nosebleeds, diabetes, and rheumatism (Semwal et al. 2010; Sharma and Samant 2014; Krishna et al. 2014). The dried flowers of *Rhododendron arboreum* can be ground into a powder, which is utilized as a medicinal remedy to treat bloody dysentery (Sharma et al. 2010). The bark of the tree is also used for its healing properties, specifically in aiding the recovery of cuts and wounds (Rana et al. 2015; Bhattacharyya 2011). The multi-faceted uses of *Rhododendron arboreum*, ranging from its wood as a fuel source and for various wooden products, to the aesthetic and medicinal uses of its flowers, highlight the significance of this plant in the local communities of the North West Himalayas region (Madhvi et al. 2019). It serves as a valuable resource that contributes to livelihoods, cultural practices, and traditional healthcare systems.

2.1.4 Pharmacological Uses

Various compounds extracted from *Rhododendron arboreum* leaves exhibit remarkable pharmacological properties. The medicinal properties of *R. arboreum* have been extensively documented in various studies (Madhvi et al. 2019).

a. Adaptogenic activity

The methanolic extract contains a significant quantity of quercetin and gallic acid, as revealed by HPTLC analysis, contributing to potent anti-stress activity. These compounds are likely responsible for this activity when compared to hydroethanol and aqueous extracts (Roy et al. 2014). Karki et al. (2023) studied the adaptogenic activity of *R. arboretum* flower extract on mice and rats using anoxia stress and swimming endurance stress-induced models. The ethanolic extract at doses of 200 and 400 mg/kg showed significant adaptogenic activity in the animals.

b. Antidiarrheal activity

The ethyl acetate fraction of the flower shows a dose-dependent reduction in the number of diarrheal faeces (24.55–73.65%) in magnesium sulfate-induced diarrhea (Verma et al. 2011). It also decreases gastrointestinal transit of Charcoal Meal (91.36–66.03%), inhibits intestinal contents (2.64 ± 0.37 to 1.43 ± 0.29), and reduces the

Table 4 Traditional uses of *R. arboretum*

Part of *R. arboreum*	Form	Ailment/Use	Locality (state/ country)
Flower	Flower bud	Vegetable	Uttarakhand
	Drink containing honey	To cure blurry vision and asthma	Southern China/ China Myanmar
	Aqueous extract	Food colouring agent	Himachal Pradesh/ India
	Raw flower	Sauce and jam making	J&K/India
	Dried flower fried in ghee	To stop blood dysentery	Tamil Nadu/India
	Crushed flower	Used to stop nasal bleeding	Himachal Pradesh/ India
	Flower juice	To cure menstrual disorder	
		Sold as health tonic	Uttarakhand/India
		To cure heart related issues, stomach disorder, fever	
		Used when fish bone stucks in the throat	Sikkim/India
	Juices and squash	Cure diabetes	Uttarakhand/India
Leaves	Young leaves	To cure headache by applying on forehead	
	Dried leaves	To get rid of external parasites	
	Dried leaf tincture	To cure rheumatism and gout	Homeopathy
Bark	Bark and leaves	To cure the roughness of skin	Manoor Valley/ Pakistan
	Bark juice	To cure liver disorders, cough cold, piles	Alai Valley/Pakistan
Stem wood	Wood	To make gift boxes, pots, gunstocks etc.	Arunachal Pradesh/ India
		As fuel	
Root	Decoction of root	To cure early stage of cancer	Nagaland/India

Source Madhvi et al. (2019)

weight of intestinal contents (3.87 ± 0.45 to 2.21 ± 0.67) in castor oil-induced enter pooling. The fraction significantly inhibits the number of diarrheal faeces (24.48–71.07%) in castor oil-induced diarrhoea at the above concentrations (Verma et al. 2011).

c. Anti-inflammatory and Antinociceptive activity

Flower extracts of *R. arboreum* exhibit significant anti-inflammatory activity against phlogistic agents induced hind paw edema in rats, with the aqueous extract showing the highest activity compared to the 50% ethanol and methanol extracts (Agarwal and Kalpana 1988). The acetone extract of *R. arboreum* leaves at 3000 ug/ml demonstrates 50.56% erythrocyte membrane stabilizing activity, attributed to tannins, saponins, and flavonoids, including hyperin (Nisar et al. 2016).

d. Antioxidant and Antimutagenic activity

The hexane, chloroform, and ethyl acetate fractions of *R. arboreum* leaf extract reduce the production of nitric oxide radicals, prevent deoxyribose degradation, and inhibit lipid peroxidation. The presence of phytochemicals, vitamin E, and 3,7,11,15-tetramethyl-2-hexadecen-1-ol likely contributes to the antioxidant activity (Prakash et al. 2007; Acharya et al. 2011). Additionally, the ethyl acetate fraction exhibits high antimutagenic activity in the pre-incubation mode, showing 83.48% inhibition against the TA-98 strain and 76.869% inhibition against the TA-100 strain of Salmonella typhimurium (Gautam et al. 2018).

e. Anticancer activity

The ethanolic extract of the leaves displays significant dose-dependent activity against Agrobacterium tumefaciens-induced tumors in potato discs. The leaf extract exhibits substantial activity compared to TAM, while the flower extract shows no significant effect on the MCF-7 tumor cell line. Quercetin and rutin, isolated from the ethanol extract, are potential candidates responsible for the antitumor activity (Sonar et al. 2012a, b). Moreover, the isolated compound, 15-oxoursolic acid, demonstrates varying IC50 values (ranging from 2.3 ± 0.04 μM to 32.8 ± 1.54 μM) against different cell lines, including A498, NCI-H226, H157, Hep G2, and MDR 2780AD. The presence of an OH group at carbon 3 and a carbonyl group at carbon 17 likely contributes to its cytotoxic properties (Ali et al. 2017). Furthermore, the aqueous leaf extract, up to a concentration of 5000 μg/ml, is non-cytotoxic against *S. cerevisiae* strain BY4741 (Painuli et al. 2012). However, the extract exhibits a considerable inhibition of cell proliferation (ranging from 25.41 to 75.30%) in Vero cells and (ranging from 60.12 to 87.66%) in HELA cells. Additionally, the expression of HIF-1α is reduced to 0.332 fold, and VEGE expression is lowered to 0.24 fold by the extract.

f. Antidiabetic activity

The ethyl acetate-soluble fraction of *R. arboreum* exhibits higher α-glucosidase inhibitory activity than the water-soluble fraction (Bhandary and Kawabata 2008).

Hyperin, an isolated compound, demonstrates dose-dependent inhibition of α-glucosidase, with an IC50 of 0.76 mM for maltase and 1.66 mM for sucrose. Hyperin significantly reduces blood glucose levels in streptozotocin-induced diabetic rats and leads to a reduction in triglycerides, VLDL, LDL, and total cholesterol levels compared to diabetic control rats. The compound also shows a dose-dependent decrease in the activity of enzymes glycogen phosphorylase, glucose-6-phosphatase, and glycosylated haemoglobin, while increasing glycogen synthase and hexokinase activity. Furthermore, the compound-treated rat's exhibit improved histological features of the pancreas. In the case of the isolated compounds from the methanolic bark extract, they show less than 13% inhibition against β-glycosidase. However, 3-O-acetylursolic acid demonstrates potent inhibition of α-glycosidase (IC50 = 3.3 ± 0.1 μM) compared to the standard inhibitor Acarbose (IC50 = 545 ± 7.9 μM). Another compound, 3-β-acetoxyurs-11-en-13β, 28-olide, shows significant inhibition (76.3 ± 6%) of glycation. In another study, a significant decrease in blood glucose levels is observed in rats treated with a 200 mg/kg dose of the aqueous extract compared to metformin-treated rats (10 mg/kg). The ethyl acetate fraction significantly reduces the maximum blood glucose level in streptozotocin-induced diabetic rats, particularly 5 h after treatment. The active fraction also decreases serum urea, creatinine, hemoglobin A1C, and blood glucose levels in diabetic rats while increasing insulin levels, like glybenclamide-treated rats. The dose of 400 mg/kg of the active fraction significantly reduces LDL (42.3 ± 9.4 mg/dL), VLDL (10.3 ± 6.9 mg/dL), total cholesterol (64.5 ± 6.5 mg/dL), TGs, and significantly increases HDL compared to untreated diabetic rats.

g. Cardioprotective activity

The ethanolic extract of the whole plant of *R. arboreum* demonstrates dose-dependent reductions in ALT, AST, and LDH enzyme activity, as well as decreased levels of MDA in serum and heart tissue. Additionally, it increases the activity of SOD, catalase, GPx, and GSH in isoproterenol-treated rats. The extract-treated groups show marked improvements in vacuolation, myocardial degeneration, and inflammatory cell infiltration (Mudagal and Goli 2011; Parcha et al. 2017).

h. Antibacterial activity

The methanolic crude extracts derived from the flower, leaf, stem, and roots of *R. arboreum* exhibit potent to significant activity against *B. subtilis*, *Salmonella typhi*, and *S. aureus* (Nisar et al. 2013). The ethanol extract, methanol extract, and isolated quercetin demonstrate the lowest effective concentrations of 12.5 mg/ml, 50 mg/ml, and 25 mg/ml, respectively, against *E. coli* and *S. aureus* (Sonar et al. 2012a, b). In another study, the ethanolic flower extract (50 mg/ml) displays zone of inhibition values of 20 ± 1 mm, 19 ± 1 mm, and 17 ± 1 mm against *E. coli*, *S. epidermidis*, and *S. aureus*, respectively. The methanolic leaf extract exhibits greater effectiveness against gram-positive bacteria compared to the acetone extract. The growth inhibition of *S. aureus* is 60–40% with the methanolic leaf extract and 50–50% with the methanolic flower extract, with the leaf extract being more effective than the flower extract (Prakash et al. 2016; Chauhan et al. 2016; Saranya and Ravi 2016; Sharma 2013).

2.1.5 Market Potential

Rhododendron arboreum, commonly known as Burans or the Indian *Rhododendron*, has several market potential opportunities. According to Negi et al. (2013), some general areas where *R. arboreum* can be commercially utilized are;

a. ***Herbal and Medicinal Products***: *R. arboreum* has been used in traditional medicine systems, including Ayurveda, for its potential health benefits (Swamidasan et al. 2018). The tree's bark, flowers, and leaves are believed to possess medicinal properties. Extracts, teas, supplements, or herbal formulations derived from *R. arboreum* may find a market in the herbal and natural medicine sectors.
b. ***Cosmetics and Skincare***: *R. arboreum* extracts or essential oils can be incorporated into cosmetic and skincare products due to their potential antioxidant and anti-inflammatory properties. These natural ingredients may be used in creams, lotions, serums, or facial oils targeting specific skin concerns (Ghimeray et al. 2015).
c. ***Nutraceuticals and Functional Foods***: *R. arboreum* contains bioactive compounds that can be utilized in the production of nutraceuticals or functional foods. Products such as health supplements, fortified beverages, or functional food additives might be developed to cater to consumers interested in natural and functional ingredients (Bhatt et al. 2017a, b).
d. ***Floral and Perfume Industry***: *R. arboreum*'s vibrant and attractive flowers can have value in the floral industry. They may be used in floral arrangements, decorations, or as cut flowers (Buchbauer 2000). Additionally, the floral extracts or oils of *R. arboreum* can be utilized by the perfume and fragrance industry for their unique scent profiles.
e. ***Landscaping and Horticulture***: The ornamental beauty of *Rhododendron arboreum* makes it suitable for landscaping purposes (Sharma et al. 2022). The tree can be planted in gardens, parks, or public spaces to enhance their visual appeal. Nurseries and horticulture businesses may find a market for selling *R. arboreum* saplings or plants.

2.2 Sichuan Pepper (Timur)

Sichuan pepper, also known as prickly ash or Szechuan pepper is considered an underutilized Plants in India. While it is not native to the country, it has been introduced and cultivated in some regions, particularly in the northern and northeastern regions of India where the climate and terrain are conducive to its growth. Despite its potential as a unique and flavorful spice, Sichuan pepper is not widely cultivated or incorporated into mainstream Indian cuisine.

The taxonomic classification of the Sichuan pepper is as follows (Petruzzello 2022).

Kingdom: Plantae
Phylum: Angiosperms

Class: Eudicots
Order: Sapindales
Family: Rutaceae
Genus: *Zanthoxylum*
Species: *Zanthoxylum simulans* (or *Zanthoxylum bungeanum*, depending on the specific species used as Sichuan pepper).

Another species of Sichuan pepper *Zanthoxylum bungeanum*, referred to as Da Hongpao Hua jiao, belongs to the *Zanthoxylum* genus of the Rutaceae family and can be found widely distributed in China (Hebei, Shanxi, Sichuan, Gansu, and Shandong provinces) as well as some countries in Southern Asia. Like other species within this genus, *Z. bungeanum* possesses a distinctive tingling sensation when consumed (Yang 2008). The dried fruits, renowned for their fresh aroma and taste, are commonly used as a spice in local cuisines, either ground or whole. These fruits can stimulate saliva production and enhance appetite. Hua jiao, a combination of salt and Sichuan pepper (*Z. bungeanum*), is frequently employed as a condiment in barbecue dishes such as chicken tikka or roast duck (Zhang et al. 2017).

Sichuan pepper plants, including both the red and Chinese pepper varieties, share a similar appearance. They are deciduous shrubs or small trees with multiple trunks. In cool climates, these plants can grow up to 7 m (23 feet) in height, while the green Sichuan pepper plant is generally smaller. To facilitate harvesting, cultivated plants are often pruned and kept short. The leathery leaves are pinnately compound, typically consisting of 5–15 oval serrated leaflets, and they are armed with prickles (Figs. 4 and 5). These plants are mostly dioecious, meaning male and female flowers are usually borne on separate individuals. However, there are instances where male plants produce a few peppercorns, and some female plants can form bisexual flowers and self-pollinate. Certain varieties and cultivars do not require a male plant for a satisfactory harvest. The small flowers grow in upright clusters, which eventually become pendulous as the fruits develop. The fruit husks of the red Sichuan pepper and Chinese pepper are red in color, while those of the green Sichuan pepper are green. Sichuan pepper species demonstrate a notable resistance to pests and plant diseases.

In addition to its culinary uses, *Z. bungeanum* possesses various medicinal properties across its different parts. In various traditional medicines, the pericarp is employed for the treatment of gastralgia and dyspepsia, while the seed is recognized for its anti-inflammatory and diuretic effects. The leaves are known for their carminative, stimulant, and sudorific properties, and the root is utilized to alleviate epigastric pains and aid in the healing of bruises, eczema, and snake bites (Deng et al. 2019). Recent experimental studies have unveiled further benefits of *Z. bungeanum*, such as its cardiovascular activity exhibited by the pericarp, its inclusion in cosmetic products, the anti-inflammatory properties of methanol extracts, and the remarkable antioxidant and antimicrobial activities (Yang 2008; Gong et al. 2021) found in the essential oil derived from the seed and fruit.

The leaves of *Z. bungeanum* are not only edible but also possess a slightly pungent and harmless taste (Ji et al. 2019). In certain rural regions, residents consume the young leaves as a vegetable during the spring season. Furthermore,

Fig. 4 Sichuan pepper tree

Fig. 5 Sichuan pepper

they are commonly used as condiments in Chinese cuisine and added to beverages to enhance flavor. Despite its long history of consumption, there has been limited research conducted on the chemical composition of this substance. However, Wei et al. (2011) have explored the ultrasonic-assisted extraction of total flavonoids from *Z. bungeanum* leaves, while Yang (2008) have identified 13 polyphenolics in leaves grown in Hebei, China, using HPLC/MS. Major constituents identified include chlorogenic acid, hyperoside, and quercitrin. Nevertheless, there are still certain areas of uncertainty regarding the phytochemical profiles and physiological effects of this edible material for consumers.

Alkylamides such as sanshools and hydroxyl sanshools (McGee 2004), which belong to the same family as piperine and capsaicin, are widely found in Sichuan Pepper. We can feel them in our mouth when we eat Sichuan pepper-flavored foods or food products. Unlike capsaicin, piperine, or isothiocyanates, this sensation is unique. As opposed to activating TRPA1 or TRPV1, it is caused by modifying potassium channels with two-pores (Albin and Simons 2010). To a considerable extent, Sichuan pepper extract's anti-inflammatory and antioxidant properties are due to its polyphenol concentration. There are over 20 polyphenols in *Zanthoxylum*, including flavonoids, lignans, and their glycosides. This makes Sichuan pepper a viable ingredient in food and cosmetics as well as pharmaceutical and agricultural industries. It has been proven to have antibacterial and antiviral properties as well as skin lifting, herbicide safener, and medicine transdermal penetration enhancement capabilities.

In addition to its utilization in fragrance and culinary fields, Sichuan pepper extract exhibits a diverse range of beneficial properties. These include antimicrobial, antiviral, skin lifting, herbicide safener, drug transdermal penetration enhancing, and lipid lowering capabilities. Due to these impressive attributes, Sichuan pepper holds immense promise as a valuable ingredient across various industries such as food, cosmetics, pharmaceuticals, and agriculture (Zhu et al. 2011; Oh and Chung 2014; Hisatomi et al. 2000; Artaria et al. 2011; Lan et al. 2014; Tang et al. 2014; Li et al. 2015; Zeng et al. 2018).

2.2.1 Physiochemical Properties

Volatile components

A growing number of people are interested in figuring out the volatile components that give Sichuan pepper its characteristic aroma because of its high value as a flavour and fragrance enhancer. When extracting fragrance components from *Z. piperitum*, headspace extraction utilising mulberry paper bags (HS-MPB—SPE) with solid phase micro extraction (SPME) (Cardeal et al. 2006; Yoon and Lee 2009; Jiang and Kubota 2004). A total of 13 compounds were discovered using the HS-MPB-SPE method, with limonene, eucalyptol, and ocimene as the primary components.

Sichuan pepper possesses a robust and delightful fragrance. More than two hundred volatile compounds have been identified, responsible for its citrus, woody, and spicy notes. The pleasant scent of Sichuan pepper extract has been utilized in the creation of fine fragrances, adding an accentuating touch. In Chinese cuisine, Sichuan pepper is widely used as a spice, providing a distinctive flavour accompanied by a tingling and numbing sensation. It is often combined with chili pepper to create the renowned Mala flavour, which translates to "numbing and spicy." Non-volatile compounds, such as alkylamides and polyphenols, have been identified in Sichuan pepper. In certain *Zanthoxylum* species, like *Z. pipertum*, the total amide content can reach as high as 3% (Ravindran et al. 2012).

Sichuan pepper contains sanshools and hydroxyl sanshools, alkylamides from the same family as piperine and capsaicin. These compounds are responsible for the numbing, tingling, and buzzing sensation experienced when consuming Sichuan pepper-infused dishes or food products. This unique sensation differs from the pungency caused by capsaicin, piperine, or isothiocyanates, as it modulates two-pore potassium channels rather than activating TRPA1 or TRPV1 channels (Albin and Simons 2010). The antioxidant and anti-inflammatory properties of Sichuan pepper extract are mainly attributed to its polyphenol content. More than twenty polyphenols, including flavonoids, lignans, and their glycosides, have been identified in the *Zanthoxylum* genus (Koo et al. 2007).

Non-volatile components

Alkylamides are abundant components in Sichuan pepper, with hydroxy α-sanshool being the most prevalent in both *Z. bungeanum* oil and *Z. schinifolium* oil. These alkylamides contribute significantly to the pungency experienced when consuming Sichuan pepper. Differentiating between *Z. bungeanum* and *Z. schinifolium* is suggested based on their alkylamide composition, particularly considering hydroxyl γ-sanshool and bungeanool (Zhao et al. 2013).

In a study by Mizutani et al. (1988), new alkylamides, namely hydroxyl γ-isosanshool, bungeanool, and isobungeanool, were identified in addition to hydroxyl α, β, and γ sanshool in *Z. bungeanum.* The researchers extracted pericarps using chloroform, fractionated the extract with silica gel column chromatography, and further purified it with HPLC. The structures of these newly identified alkylamides were determined using NMR.

Jang et al. (1978) identified 2′,3′-dihydroxy α-sanshool and 2′,3′-dihydroxy α-sanshool in seeds of *Z. piperitum.* The plant material was extracted with methanol and dichloromethane, and the extract was separated using reversed-phase vacuum flash chromatography and HPLC. Among the five fatty acid amides isolated, they found—hydroxyl sanshool and two newly identified sanshools. NMR was employed to determine the structures of these compounds. Huang et al. (2012) discovered two new alkylamides, namely (2E,7E,9E)-N-(2-hydroxy-2-methylpropyl)-6,11-dioxo-2,7,9-dodecatrienamide and (2E,6E,8E)-N-(2-hydroxy-2-methylpropyl)-10-oxo-2,6,8-decatrienamide, in *Z. bungeanum.* The pericarps were extracted using methanol (MEOH) and fractionated the extract with a silica gel column. HR-ESI-MS analysis was employed to determine the molecular formula of each fraction, and NMR was used to elucidate the structures of the unknown compounds.

Polyphenols

Various analytical techniques have been employed to analyze the non-volatile fraction of Sichuan pepper. One such method is Ultra Performance Liquid Chromatography-Diode Array Detection-Electrospray Ionization-Quadrupole Time-of-Flight Mass Spectrometry (UPLC-DAD-ESI-QTOF-MS/MS), which has proven to be a rapid and effective approach for quantifying specific compounds in *Zanthoxylum armatum* species. Asarinin, sesamin, fargesin, kobusin, and armatamide were successfully quantified using this method. Additionally, this technique was utilized to identify 12 compounds, including flavonoids, lignans, coumarin, and amides, present in *Z.*

armatum leaves. Another species, *Zanthoxylum bungeanum*, is known for its abundance of ten flavonoid glycosides in its leaves. These compounds include isovitexin, vitexin, hyperoside, isoquercitrin, rutin, foeniculin, trifolin, quercitrin, astragalin, and afzelin. With the presence of these flavonoid glycosides, the leaves of *Z. bungeanum* serve as a valuable natural antioxidant source (Zhong et al. 2014).

2.2.2 Phytochemical Properties

Zanthoxylum species offer a diverse array of significant compounds, as follows:

a. ***Zanthoxylum rhetsa*** (found in India) consists of sabinene, limonene, pinene, para-cymene, terpinene, 4-terpineol, and alpha-terpineol
b. ***Zanthoxylum fagara*** (found in Central and Southern Africa, South America) contains alkaloids and coumarin, according to a study published in Phytochemistry in 1988.
c. ***Zanthoxylum simulans*** (found in Taiwan) primarily contains beta-myrcene, limonene, 1,8-cineol, and Z-beta-ocimene, as reported in the Journal of Agricultural and Food Chemistry in 1996.
d. ***Zanthoxylum armatum*** (found in Nepal) is rich in linalool (50%), along with limonene, methyl cinnamate, and cineole.
e. ***Zanthoxylum piperitum*** (found in Japan [leaf]) contains citronellal, citronellol, and Z-3-hexenal, according to Bioscience, Biotechnology, and Biochemistry in 1997.
f. ***Zanthoxylum acanthopodium*** (found in Indonesia) contains citronellal and limonene.

Sichuan pepper is renowned for its distinctive flavor, accompanied by a numbing and tingling sensation that can alter the perception of other flavors. Bader et al. (2014) conducted a successful study that established a correlation between the tingling and numbing sensations and specific taste compounds extracted from Sichuan pepper. They determined the thresholds at which these sensations are perceived. Notably, hydroxy-α-sanshool, hydroxy-γ-sanshool, bungeanool, isobungeanool, hydroxy-ε-sanshool, and hydroxy-ζ-sanshool were identified as responsible for the tingling and paresthetic sensation. Meanwhile, hydroxy-β-sanshool and hydroxy-γ-isosanshool were found to induce a numbing and anesthetic sensation. It is worth mentioning that the molecules responsible for the tingling sensation lack a cis-double bond, as previous structure–activity relationship findings have revealed (Ji et al. 2019). Furthermore, several studies have observed that hydroxy-α-sanshool increases salivation in human subjects. This finding is significant because taste compounds must first dissolve in saliva to reach the taste receptors. Additionally, the presence of these tingling and numbing components can induce changes in the protein components of saliva, potentially affecting the perception of other tastes (Galopin et al. 2004).

2.2.3 Traditional Uses

Culinary

In Asian cuisine, Sichuan pepper is commonly utilized. Spice is one of the five spices that make up Five-Spice Powder, along with star anise, Sichuan pepper, cassia, and clove (Ji et al. 2019). It is possible to add ginger, galangal, and black cardamom to the recipe as an optional ingredient to marinate meat and flavour fried vegetables and meat with flour batter, five-spice powder is widely used in Chinese cooking. There is more Sichuan pepper flavoured packaged food products on the market today as unusual and daring cuisine trends emerge among consumers, especially the millennial generation. Examples include Ramen noodles, spicy chicken ramen, crispy fried chicken, and beef jerky (to name a few). Also, chefs are utilizing Sichuan peppercorns to flavor savory dishes as well as desserts such as ice cream and tartetartin (Deng et al. 2019).

Flavour modulation

As well as selected cooling agents and an isothiocyanate compound which offers a warming, tingling feeling to provide an elevated sensation of pungency (Moza et al. 2008), Sichuan pepper's chemistries were proposed to be used in the liquid cooling sensate formulation. This composition in flavour and scent products to provide a unique and engaging sensory experience. It is also utilized as a flavour enhancer in fruit juice containing food products, together with selected cooling agents and refreshing agents, in order to promote flavour acceptability during normal or warm extended storage conditions (Shimizu et al. 2007).

2.2.4 Pharmacological Properties

Antibacterial activity

Sanshool amide, a component of Sichuan pepper, inhibited the development of heter-cyclicamines (HAs) in beef grilling. HAs PhIP, IQx, MeIQx, and 4,8-DiMelQx were studied since they are classified by the International Agency for Research on Cancer as possible human carcinogens (IARC). Researchers tested the inhibitory effects of ground Sichuan pepper powder as well as hydroxyl—sanshool solution at three dilution levels, both substances can successfully suppress HA levels by up to 80% (Zeng et al. 2018). Water distillation of *Z. bungeanum* fruit yields essential oils that inhibit the growth of common foodborne pathogens, including bacteria from both the Gram positive and Gram-negative families of bacteria (Zhu et al. 2011). Oil derived from *Z. shinifolium* seeds by pressing or hydro distillation has antiviral effects, but oil obtained by hydro distillation does not. The antibacterial or antiviral impact of the oil is not specified in either study. Two HRVs and four entero viruses can be neutralized by *Z. piperitum* extract (Choi 2016).

Antioxidant activity

Free radicals, including O2%− and %OH, are known to play a significant role in various diseases such as tissue-specific inflammations, thrombosis, neurodegeneration, and carcinogenesis. Natural food sources commonly incorporated into diets, such as Sichuan peppers, have gained recognition for their ability to scavenge free radicals, making them recommended for disease prevention and treatment. Cell-free in vitro studies utilizing DPPH or other radical assays have consistently demonstrated the potent antioxidant activities of all known extracts of Szechuan pepper. A previous study conducted in 1995 revealed the significant impact of Szechuan pepper's water extract (WESP) in reducing the production of malondialdehyde (MDA) in rat liver. Similarly, in hyperlipidemia model rats, treatment with Szechuan pepper seed oil (SOSP) not only decreased MDA levels but also significantly enhanced the activities of catalase (CAT), superoxide dismutase (SOD), and the ability to restrain hydroxyl free radicals (RAHFR) compared to the model groups. Li et al. (2015) demonstrated that the leaf extract of Szechuan pepper, as well as its isolated polyphenols (chlorogenic acid, hyperoside, and quercitrin), induced an active state of peroxidase systems (e.g., CAT, SOD, Gpx) in salted silver carp, while reducing the peroxide value (PV) and thiobarbituric acid-reactive substance (TBARS) value compared to the control groups (Hisatomi et al. 2000). Zhang et al. (2014) discovered that the toxic effects and apoptosis induced by H_2O_2 in primary rat hepatocytes significantly decreased when treated with WESP, resulting in reduced levels of reactive oxygen species (ROS) and increased levels of heme oxygenase-1 (HO-1) mRNA. To date, approximately 20 compounds from *Zanthoxylum* plants have been chemically or biochemically proven to effectively eliminate free radicals.

2.2.5 Market Potential

Fact.MR (2022) reported that the market potential of Sichuan pepper, also known as Timur, can vary based on factors such as regional demand, availability, and consumer preferences. Some potential market opportunities for Sichuan pepper are;

a. **Culinary Industry**: Sichuan pepper is renowned for its unique flavor profile, characterized by its citrusy and numbing sensation (Sengupta 2022). It is a key ingredient in Sichuan cuisine and is used in a variety of dishes, including stir-fries, soups, sauces, and marinades. The demand for authentic Sichuan cuisine and the popularity of Asian flavors in the culinary industry present market opportunities for Sichuan pepper as an essential spice.
b. **Spice Blends and Seasonings**: Sichuan pepper can be incorporated into spice blends and seasonings to add depth and complexity to various cuisines (Bader et al. 2014). It can be combined with other herbs, spices, and ingredients to create unique flavor profiles for rubs, marinades, or ready-to-use seasonings. This can cater to consumers looking for convenient and flavor-enhancing products.
c. **Artisanal and Gourmet Products**: Sichuan pepper's distinctive flavor and its growing recognition among food enthusiasts make it a desirable ingredient for

artisanal and gourmet food products (Petruzzello 2022). This includes items like specialty oils, infused salts, flavored chocolates, craft beverages, and unique condiments that showcase the unique qualities of Sichuan pepper.

d. **Ethnic and International Markets**: Sichuan pepper has gained popularity beyond its traditional origin. It has become sought after in international markets, including regions with a growing interest in Asian flavors and fusion cuisines (Yang 2008). This presents opportunities for exporting Sichuan pepper or developing products that cater to the specific tastes and preferences of diverse cultural backgrounds (Ivane et al. 2022).
e. **Health and Wellness**: Sichuan pepper is believed to possess certain health benefits, including antimicrobial and digestive properties. It may find a market in the health and wellness sector, where consumers seek natural and functional ingredients. This can include the development of herbal teas, dietary supplements, or traditional medicine formulations (Shin and Kim 2022).
f. **Farming and Agriculture**: As the demand for Sichuan pepper grows, there may be opportunities for farmers and agricultural enterprises to cultivate and supply Sichuan pepper. This can contribute to local economic development and promote sustainable farming practices (Zeng et al. 2018).

2.3 Citrus sinensis *(Malta Orange)*

Malta orange (*Citrus sinensis*) holds great significance as a vital fruit Plants within the citrus group due to its abundant nutritional and medicinal value (Barkley et al. 2006). It thrives in dry climates with distinct summer and winter seasons, along with low rainfall (Fig. 6). They can be grown on a wide range of soils, including clay and light sandy soil, but they are sensitive to salt. The ideal soils for malta orange cultivation are medium black, red, alluvial river bank loamy soil found in Maharashtra state and Goradu soil in Gujarat.

Botanically classified as *Citrus sinensis*, the malta orange is a key member of the Rutaceae family.

Its botanical classification includes (Parle and Chaturvedi 2012);

Kingdom: Plantae,
Division: Magnoliophyta,
Class: Dicotyledons,
Subclass: Sapindales,
Order: Rosidae,
Family: Rutaceae,
Subfamily: Aurantoideae,
Genus: Citrus.
Species: sinensis.

Citrus sinensis, commonly known as malta orange, not only offers a delightful and juicy fruit but also holds significant economic value due to its wide cultivation

Fig. 6 Malta (*Citrus sinensis*)

and medicinal properties. The global production of citrus fruits, including oranges, reaches about 120 million tons.

This variety of orange is cultivated in various countries, such as Brazil, China, Japan, Turkey, and India. In India, states like Andhra Pradesh, Maharashtra, Tamil Nadu, Karnataka, Madhya Pradesh, Assam, Bihar, Gujarat, Himachal Pradesh, Uttar Pradesh, Punjab, and Haryana are known for their production of *C. sinensis* (Pandey et al. 2011). One of the regions heavily dependent on Malta orange as a cash crop is Uttarakhand, situated in the western Indian Himalayas. With 90% of its area comprising high mountains and deep valleys, agriculture is crucial for the livelihoods of 65–78% of its population. However, the sector has experienced modest growth at around 2.4% annually over the past decade (GIZ and Doon University 2011).

In an effort to promote Malta oranges, the state horticulture and watershed departments have introduced and encouraged their cultivation through horticulture development programs in the hill districts (Choudhary et al. 2013). These oranges are typically grown on family farms at elevations ranging from 900 to 2200 m above sea level, with the harvest taking place in November and December. Despite these initiatives, Malta oranges face market challenges, often being perceived as a substitute for mousambi (sweet lime) (*Citrus limetta*) without establishing a distinct identity. Additionally, competition from other citrus fruits, especially oranges from western India, poses further obstacles to their market position. The sour taste and thick skin of Malta oranges also make them less appealing to consumers, limiting their potential for commercialization as fresh fruit.

Malta orange farmers in Uttarakhand face marketing issues similar to other mountain farmers. Low returns have led some farmers to neglect their orchards, and in some cases, even cut down their trees. Lack of institutional support, including access to credit, insurance, and price fluctuation buffers, further exacerbates their challenges. Farmers typically receive less than one-tenth of the price paid by consumers (Pandey et al. 2011). Nevertheless, due to the absence of other lucrative horticulture cash crops, many farmers continue to grow Malta oranges, as they still provide some cash income during the off-season when few other agricultural products are available. Local traders purchase the oranges at low prices, enabling farmers to sustain their livelihoods to some extent.

2.3.1 Physiochemical Properties

Native to Asia, *C. sinensis* can now be found in warm regions and the Pacific (Hernández-Favela et al. 2016). This evergreen tree, scientifically known as *C. sinensis*, can reach heights of 9–10 m and is characterized by its branches adorned with large spines. The leaf blades of *C. sinensis* are elliptical, oblong, or oval in shape, with bluntly serrated edges. They emit a pronounced citrus fragrance due to the abundant oil they contain (Goldhamer et al. 2012). The flowers of *C. sinensis* have five white petals and 20–25 yellow stamens. They grow individually or in whorls of six and have a width of approximately 5 cm. The fruits of *C. sinensis* come in shades of orange or yellow and can range in size from globose to oval, measuring around 6.5–9.5 cm in width. The fruit consists of two distinct parts: the pericarp, also known as the peel, skin, or rind, and the endocarp, or pulp, which houses the juice sac glands responsible for juice production (Orwa et al. 2009; Han 2008). The skin of the fruit has a unique aroma attributed to the presence of epicuticular wax and numerous small oil glands. The pericarp comprises the flavedo or epicarp and the cuticle, with the albedo or mesocarp lying beneath the flavedo (Goudeau et al. 2008; Sharon-Asa et al. 2003). The albedo consists of compact masses of tubular-like cells within the intercellular space. Most fruits contain delicious pulp filled with numerous seeds (Rao et al. 2011). On average, the fruit pulp consists of eleven juice-filled segments, each offering a distinct flavor profile ranging from sour to sweet. However, the fruit is susceptible to damage from frost when cultivated in orchards. As a perennial plant, *C. sinensis* has shown adaptability to various climates (Ulloa et al. 2012).

2.3.2 Phytochemical Properties

C. sinensis possesses a wealth of secondary metabolites that contribute to its noteworthy pharmacological activities (Hernández-Favela et al. 2016). Different parts of *C. sinensis*, such as the fruits, peel, leaves, juice, and roots, have been found to contain various types of chemical compounds. These compounds encompass a wide range of groups, including flavonoids, steroids, hydroxyamides, alkanes, fatty acids, coumarins, peptides, carbohydrates, carbamates, alkylamines, carotenoids, volatile compounds, as well as essential nutritional elements like potassium, magnesium, calcium, and sodium (Table 5).

Table 5 Groups of compounds, region of collection and plant organ

Compound	Region of collection	Plant organ	References
Flavonoids	United States: Washington, Florida India: Hisar, Shahjahanpur Pakistan Italy: Sicily, Messina Spain: Murcia, Huelva Germany: Braunschweig Czech Republic: Prague	Peel, flavedo, molasses, whole fruit, leaves	Gattuso et al. (2007), Takemoto et al. (2008), Manthey (2004), Rani et al. (2009), Intekhab and Aslam (2009), Lapcík et al. (2004), Saleem et al. (2010), Leuzzi et al. (2000), Truchado et al. (2009
Steroids	United States: Washington	Leaves	Rani et al. (2009)
Hydroxylamide, alkane, fatty acid	United States: Washington	Leaves	Rani et al. (2009)
Coumarins	India: Shahjahanpur United States: Florida (Lakeland)	Peel, root	Gil-Izquierdo et al. (2001), Peterson et al. (2006), Stöggl et al. (2006), Li et al. (2007)
Peptides	Japan: Wakayama	Peel	Matsubara et al. (1991)
Carbohydrates	Sweden: Stockholm	Fruit	Kolhed and Karlberg (2005)
Carbamates, alkylamines	Spain: Valencia	Fruit	Soler et al. (2006)
Carotenoids	Germany: Stuttgart	Fruit	Aschoff et al. (2015)
Volatile compounds	Spain: Huelva China: Songzi (Hubei) Turkey: Dortyol–Hatay, Kozan United States: Florida Germany: Steinheim	Fruit, orange blossom, peel, leave	Gómez-Ariza et al. (2004), Mirhosseini et al. (2008), Qiao et al. (2008), Kelebek and Selli (2011), Perez-Cacho et al. (2007), Selli et al. (2008)
Potassium, magnesium, calcium, and sodium	China: Beijing	Natural and commercial juices	Niu et al. (2009)

Source Hernández-Favela et al. (2016)

2.3.3 Traditional Uses

The refreshing fruit, which satisfies thirst, appeals to individuals of all age groups due to its numerous health benefits. *C. sinensis* fruit is a valuable source of vitamins, minerals, and dietary fibers that are vital for promoting healthy growth and development. Oranges offer various advantages, encompassing the pulp, seeds, leaves, and skin of the fruit. One noteworthy benefit is the ability to produce a healthy product free from antibiotics and harmful residues for human consumption by incorporating appropriate amounts of orange waste and by-products as a supplement in poultry diets. Worldwide, *C. sinensis* is used as a great source of vitamin C, which acts as an anti-oxidant and helps to develop immunity (Etebu and Nwauzoma 2014). Constipation, cramps, colic, diarrhea, bronchitis, and TB, coughing and colds, obesity, menstruation disorders and angina are just a few of the ailments it has been treated for in the past. *C. sinensis* has been utilized for its cooling properties in Chinese Traditional medicine for a considerable period, particularly in addressing coughs, colds, and respiratory ailments. Furthermore, the *C. sinensis* holds significant cultural significance in China, where it is revered as a traditional symbol of good luck.

2.3.4 Pharmacological Activities

Antibacterial Activity

Citrus sinensis essential oil, crude extracts, and purified chemicals have demonstrated antibacterial activity. The zones of inhibition were assessed against *Escherichia coli* (12.5 mm at 25 °C, 16.0 mm at 60 °C), *Pseudomonas aeruginosa* (11.7 mm at 25 °C, 13.4 mm at 60 °C), and *Staphylococcus* (7.8 mm at 25 °C, 9.2 mm at 60 °C) using silver nanoparticles generated from *C. sinensis* peel aqueous extract. Another study using silver nanoparticles produced by combining silver nitrate solution with *C. sinensis* juice found minimum inhibitory concentration (MIC) values of 20 μg/mL for *Bacillus subtilis* and *Shigella*, and 30 μg/mL for *S. aureus* and *E. coli*. An 80–90% antibiofilm activity was reported in the presence of 25 μg/ml (Kaviya et al. 2011; Naila et al. 2014). Cold-pressed terpeneless (CPT) *C. sinensis* oil in ethanol or dimethylsulphoxide (DMSO) exhibited MICs of 0.3% and 0.25% (v/v) for *Listeria monocytogenes*, and 1% (v/v) for *Salmonella typhimurium*, respectively. Each oil dispersion system displayed a 0.75% (v/v) inhibitory concentration for *Lactobacillus plantarum* (Chalova et al. 2010). At concentrations of 0.5% (v/v) in 10 μL, CPT inhibited methicillin-resistant and intermediate-resistant strains of *S. aureus* (76.67 ± 4.08 mm and 32.50 ± 2.74 mm, respectively). The test oil inhibited bacterial growth on test plates compared to untreated control plates (Chalova et al. 2010). Against *Pseudomonas aeruginosa* (Mayaud et al. 2008), 1,8-cineole and hydrocarbons showed MIC90% values ≥10% (v/v). In another study, *C. sinensis* oil demonstrated inhibitory effects against *E. coli* (18 ± 2 mm), *L. monocytogenes* (27 ± 2 mm), *B. cereus* (19 ± 2 mm), and *S. aureus* (14 ± 3 mm) at concentrations as low as 0.1 ml. Molecular distillation and column chromatography resulted in inhibitory bactericidal effects against *E. coli* (MIC 100–25 μg/mL; MBC 200–50 μg/mL), Staphylococcus aureus (MIC 100–50 μg/mL; MBC 200–100 μg/mL), *Saccharomyces cerevisiae*, and *Aspergillus fumigatus*. Additionally, molecular distillation and column chromatography yielded inhibitory effects against *Saccharomyces cerevisiae, Aspergillus fumigatus*, and *Aspergillus* species, respectively. A combination of *C. sinensis* and *C. chinensis* in a 1:1 (v/v) ratio was also investigated (Hernández-Favela et al. 2016).

A blend of essential oils derived from *C. sinensis* and *C. bergamia* demonstrated inhibitory effects, with a minimum inhibitory concentration (MIC) value of 0.25–0.5% (v/v) and a minimum inhibitory dose (MID) of 50 mg/L against both vancomycin-susceptible and vancomycin-resistant *Enterococcus faecium* and *E. faecalis* strains. The primary components of this mixture were limonene (45–73%), citral (0.7–3%), and linalool (0.5–15%) (Fisher and Phillips 2009a, b). Terpene oil extracted from *C. sinensis* exhibited significant antimicrobial activity against eleven strains/serotypes of S*almonella*, including *S. enteritidis, S. senftenberg, S. tennessee, S. kentucky, S. heidelberg, S. montevideo, S. michigan, S. typhimurium*, and *S. stanley*. The primary compound in the oil was d-limonene, constituting approximately 94% of the oil, with myrcene being the second most prevalent compound at around 3% (O'Bryan et al. 2008). Moreover, *C. sinensis* oil demonstrated strong antibacterial effects against *L. monocytogenes, E. coli, S. enteritidis, P. mirabilis,* and *B. cereus*. An anti-acne formulation containing *C. sinensis* (3%), *Ocimum basilicum* L. (5%) essential oils, and acetic acid (12%) effectively inhibited *Propionibacterium* acnes. The antibacterial activity of *C. sinensis* was mainly attributed to the high concentration of limonene (94.0%), while *O. basilicum* L. contributed limonene (2.54%), linalool (21.0%), and eugenol (7.17%). Furthermore, the peel hexane extract of *C. sinensis* displayed antimycobacterial activity against drug-sensitive (MIC 200 μg/mL), isoniazid-resistant (MIC 25 μg/mL), and ethambutol-resistant (MIC 50 μg/mL) variants of Mycobacterium tuberculosis H37Rv. Standard drugs, including streptomycin, isoniazid, ethambutol, and rifampicin, exhibited superior activity compared to the tested extracts, but the active extracts hold promise for obtaining compounds with potentially improved efficacy. Additionally, acetone and hexane extracts of *C. sinensis* leaf displayed inhibition zones of 27 mm against Helicobacter pylori, with clarithromycin (0.05 μg/mL) serving as a positive control, showing better activity than the tested extracts (Guzeldag et al. 2013). Nonetheless, it is essential to highlight that these active extracts may contain compounds with superior antibacterial activity. The wide-ranging antibacterial properties of *C. sinensis* justify its potential use as an antibacterial agent.

Antifungal Activity

Various studies have reported the antifungal potential of plant crude extracts, oils, and secondary metabolites derived from *C. sinensis*. One compound, 3-[4-hydroxy,3-(3-methyl-2-butenyl)-phenyl]-2-(E)-propenal, isolated from the hexane extract of injured peel of *C. sinensis* L. Osbeck cv. Valencia or *C. paradisa* MacFaden cv. Marsh, demonstrated activity against *Penicillium digitatum* and *Cladosporium cucumerinum* on Si gel tlc plates when tested at 7 μg. Moreover, aqueous, ethanol, and petroleum ether extracts of *C. sinensis* L. (Osbeck) exhibited activity against *Candida albicans* (Trovato et al. 2000). Additionally, a combination of oils (1:1) from *C. maxima* Burm and *C. sinensis* L. (Osbeck), obtained through hydrodistillation, displayed 100% inhibition of mycelial growth *in Aspergillus fumigatus, A. terreus, Alternaria alternate, Fusarium oxysporum, Helminthosporium oryzae*, and Trichoderma viride at 750 ppm (Singh et al. 2010). Furthermore, polymethoxylated flavones obtained from *C. sinensis* peel extract, including flavone-7-O-[6-acyl]-glucoside, tetramethyl-O-scutellarein, nobiletin, natsudaidai, tangeretin, and heptamethoxyflavone, exhibited activity against Aspergillus niger with a minimum inhibitory concentration (MIC) $\geq$1.6 mg/mL using a microbroth dilution assay (Liu et al. 2012). Hydrodistilled essential oils from six different varieties of *C. sinensis* showed antifungal efficacy against *P. digitatum* (ED50 2389.9–1004.6 ppm) and *P. italicum* (ED50 5407.5–3142.2 ppm). Additionally, essential oil extracted by the cold-pressing method from *C. sinensis* peels displayed activity against *Mucor hiemalis, P. expansum* and *F. proliferatum*, inhibiting their growth by 36.5%, 34.9%, and 59.5%, respectively, using the agar dilution technique (Van-Hung et al. 2013). Given the increasing global incidence of fungal infections, the search for new antifungal agents has become crucial, and in this context, *C. sinensis* offers a diverse range of compounds with potential antifungal activity.

Antiparasitic Activity

C. sinensis shows potential in treating and controlling various diseases caused by potential pathogens. The hexane, chloroform, ethyl acetate, acetone, and methanol extracts of *C. sinensis* peel exhibited significant antimalarial activity against chloroquine-sensitive strains (3D7) of malaria parasites (Bagavan et al. 2011). Several standard drugs were used in this study, including artemisinin, chloroquine, CQ diphosphate, mefloquine, and quinine (Hernández-Favela et al. 2016).

Antiproliferative Activity

Extracts of *C. sinensis* red orange juice standardized at 103 g/mL and lung fibroblast cell line V79-4 inhibited the activity of regular person prostatic epithelial cell line PZ-HPV-7 at 104 g/mL. The fruit juice of *C. sinensis* (cv. Washington Navel and cv. Sanguinello) exhibited 100% antiproliferative activity against K562 (human chronic myelogenous leukemia) and HL-60 cell lines (human leukemia) (Camarda et al. 2007). Furthermore, the juice showed 90.5% antiproliferative activity against MCF-7 cells (human breast adenocarcinoma) at a 10% concentration (Hernández-Favela et al. 2016).

Antioxidant Activity

The potential health-promoting properties of plant antioxidants have garnered significant attention. *C. sinensis* juice obtained from a local supermarket exhibited antioxidant activity, as indicated by hydrogen peroxide scavenging kinetics. The refined extract demonstrated antioxidant activities by scavenging DPPH•, OH•, and ABTS•+ radicals and reducing iron (Karyakina et al. 2009; Barreca et al. 2014). It effectively quenched DPPH radicals and hydroxyl radicals, exhibiting antioxidant power equivalent to Trolox alternatives. Activity in Cardiovascular System Citrus Plants, including *C. sinensis*, are rich in phenolic antioxidants that contribute to reducing the risk of cardiovascular diseases (Asgary and Keshvari 2013; Oliveira et al. 2005). Consumption of commercial *C. sinensis* juice (CSJ) led to a reduction in diastolic and systolic blood pressure in healthy individuals. However, a four-week administration of natural CSJ did not have significant effects on diastolic or systolic blood pressure (Hernández-Favela et al. 2016).

Antiosteoporotic Activity

C. sinensis has been found to possess osteoporosis-protective properties. Administration of an ethanol extract of *C. sinensis* leaves and peel to ovariectomized rats enhanced trabecular bone mineral content and bone density of the tibia, along with increased levels of phosphorus and calcium, thereby minimizing bone loss (Shalaby et al. 2011; Morrow et al. 2009).

Cardiovascular Activity

Dietary flavonoids present in citrus Plants, including *C. sinensis*, are associated with reducing the risk of cardiovascular diseases. Consumption of commercial *C. sinensis* juice (CSJ) resulted in reduced diastolic and systolic heart rate in healthy individuals (Asgary and Keshvari 2013). However, a four-week administration of natural CSJ did not have major impacts on diastolic or systolic blood pressure. Water–ethanol and acetone leaf extracts of *C. sinensis* exhibited inotropic distress in the atria of guinea pigs (Oliveira et al. 2005).

Hypercholesterolemic Activity

C. sinensis has demonstrated beneficial properties related to cholesterol management. Administration of lyophilized *C. sinensis* juice in an aqueous vehicle to rats resulted in decreased plasma levels of cholesterol, LDL, and triglycerides (Trovato et al. 1996). Microsized insoluble fibers derived from *C. sinensis* fruits also showed the ability to reduce serum triglyceride and total cholesterol levels by promoting the excretion of cholesterol and bile acids in feces. Further research is needed to explore the hypocholesterolemic effects of *C. sinensis* (Wu et al. 2009).

2.3.5 Market Potential

Citrus sinensis, commonly known as *C. sinensis* or Malta, has a significant market potential due to its widespread consumption and versatile applications. Here are some key market opportunities:

a. **Fresh Fruit Market**: Oranges are widely consumed as fresh fruits due to their appealing taste, juiciness, and high vitamin C content. The fresh orange market is robust, with oranges being sold in grocery stores, farmers' markets, and fruit stands. The demand for quality oranges remains steady throughout the year. Malta can be a good choice, equally tasty and rich in health benefits.

b. **Juice and Beverage Industry**: The regular Oranges are a primary source for producing orange juice, a popular beverage worldwide. The juice industry can utilize *Citrus sinensis* for both packaged and freshly squeezed orange juices. Additionally, Malta can be used in the production of flavored drinks, soft drinks, smoothies, and other citrus-based beverages.
c. **Food Processing and Preserves**: *Citrus sinensis* finds applications in the food processing industry for producing various products (Choudhary et al. 2013). They can be used for making marmalades, jams, fruit-based desserts, bakery fillings, and confectionery items. Their peel can be processed into candied malta peels or used for flavoring and garnishing purposes.
d. **Essential Oils and Fragrances**: *Citrus sinensis* produces essential oils that have a fresh, citrusy aroma. These oils can be widely used in the fragrance industry, toiletries, perfumes, aromatherapy products, and scented candles (Di et al. 2021). The demand for natural and citrus-based scents may grow, offering opportunities for *Citrus sinensis* essential oil producers.
e. **Nutraceuticals and Functional Foods**: Malta are known for their high vitamin C content and can be utilized in the production of nutraceuticals, dietary supplements, and functional food products. These products can cater to consumers seeking natural sources of vitamins, antioxidants, and health-promoting compounds.
f. **Cosmetics and Skincare**: Extracts, oils, and powders derived from *C. sinensis* are utilized in the cosmetic and skincare industry (Klimek-Szczykutowicz et al. 2020). They are incorporated into various products such as moisturizers, cleansers, toners, and masks due to their rejuvenating, brightening, and clarifying properties (Gajraj and Peart 2019).
g. **Agricultural and Horticultural Sector**: *C. sinensis* cultivation presents opportunities for farmers and horticultural businesses. The demand for *C. sinensis* and their by-products creates a market for citrus orchards, nurseries, and the supply of saplings or young orange trees.

2.4 Cleome viscosa *(Jakhya)*

The Cleomaceae family is a diverse group of flowering plants found within the order Brassicales, consisting of approximately 300 species spread across nine genera. Despite its relatively smaller size, Cleomaceae plays a crucial role in various ecosystems. These plants are commonly distributed in tropical and warm temperate climates, with the genus Cleome having a well-known and widespread range. In Hindi, it is referred to as “Hur hur” and is often utilized as fodder for livestock. This species is recognized by its yellow flowers and long, slender seed pods, emitting a strong, penetrating odor akin to mustard seeds. The leaves and stem surfaces of *C. viscosa* are adorned with secretary glandular trichomes, displaying club cylinder and cylinder morphologies.

Cleome viscosa Linn. commonly known as "wild or dog mustard," is an annual, sticky plant that thrives in the plains and tropical regions of India and across the globe. In traditional and folkloric systems of medicine, various parts of the *C. viscosa* plant, such as leaves, seeds, and roots, are used for medicinal purposes (Nadkarni 1982). It is believed to possess a wide range of therapeutic properties, including being antiparasitic, antiseptic, carminative, antiscorbutic, sudorific, febrifuge, and a heart stimulant. To validate the traditional medicinal claims of *C. viscosa*, researchers have conducted scientific pharmacological screenings. These studies have revealed several pharmacological properties, such as being antihelmintic, antibacterial, analgesic, anti-inflammatory, immunomodulatory, antipyretic, psychopharmacological, antispasmodic, and hepatoprotective (Mohtasheem ul Hasan et al. 2011). The plant is known to contain various phytochemical compounds that contribute to its therapeutic potential Plants belonging to the Cleome genus, including *C. viscosa*, are upright and grooved, featuring scented glands and sticky branches. The root of *C. viscosa* can be either white or brown, and its taproot is rounded, solid, and covered in fine hairs. The leaves are variable in size, elliptic-oblong, and obovate, measuring 1.5–2.5 cm wide and up to 5 cm long (Devi et al. 2003; Sudhakar et al. 2006; Panduraju et al. 2011).

Cleome viscosa typically grows to a height of 30–90 cm and is branched. The leaves are 3–5 foliate, obovate, and obtuse, with their size decreasing upwards. The flowers are yellow, appearing as axillary flowers that grow in loose racemes. When the seeds ripen, they become newly transversely striate and subglobose, turning brownish-black. The fruits are capsules, compressed, and covered in fine hairs. Plants belonging to the Cleome genus, including *C. viscosa,* are upright and grooved, featuring scented glands and sticky branches. The root of *C. viscosa* can be either white or brown, and its taproot is rounded, solid, and covered in fine hairs. The leaves are variable in size, elliptic-oblong, and obovate, measuring 1.5–2.5 cm wide and up to 5 cm long.

Cleome viscosa thrives in the tropical and plains regions of India (Nadkarni 1982). It has successfully spread across the hot and humid areas of India, particularly in the Indo-Gangetic plains. This hardy and resilient annual plant flourishes in various environments, including farmlands, roadsides, garbage piles, and coconut groves. It is commonly found in abundance in abandoned areas throughout the country.

This adaptable plant is well-suited to sunny locations with light soil, making it an ideal choice for such areas. It can even thrive in sandy or limestone soils. Additionally, *Cleome viscosa* has been observed to grow successfully in Eastern Java, where the soil is newly developed, porous, and light due to volcanic activity, despite being prone to erosion (Figs. 7 and 8). The plant has also been found in coastal areas and savannahs, reaching altitudes of up to 500 m above sea level. *Cleome viscosa* is particularly abundant in the hot and damp climate zones of India and follows an annual growth pattern during the rainy season (Vaidyaratnam 1994). Throughout the plains of India and Pakistan, this ubiquitous plant can be found in agriculture fields, as well as in areas with trash and grassy landscapes. Its presence extends beyond the Indian subcontinent, with Cleome varieties also being found in Tropical Africa and Southern Arabia. The adaptability and widespread presence of *Cleome viscosa* make

Fig. 7 *Cleome viscosa* flower

Fig. 8 *Cleome viscosa* seed

it a fascinating and important plant in various regions, serving as both a common weed and an essential component of various ecosystems.

The Taxonomic classification of *Cleome viscosa* (Rojas-Sandoval 2022);

Domain: Eukaryota
Kingdom: Plantae
Phylum: Spermatophyta
Subphylum: Angiospermae
Class: Dicotyledonaew
Order: Capparidales

Family: Capparaceae
Genus: Cleome
Species: *Cleome viscosa*

2.4.1 Physiochemical Properties

Various parts of CV have yielded a wide range of chemical components. It has been reported that the Plants of CV have nutritional quality, and that they are safe to eat. This oil is comprised of five fats and seven amino acids, along with the sweetener sucrose (Rukmini and Deosthale 1979). Linoleic acid, palmitic acid, stearic acid, oleic acid, and linolinic acid are all found in the product extracted from its seeds (Rukmini 1978; Afaq et al.1984; Deora et al. 2003).

2.4.2 Phytochemical Properties

Singh et al. (2015) reviewed various phytochemical analysis conducted on various parts of the *Cleome viscosa* plant, including the root, stem, leaf, and seed, to isolate and identify different compounds. The preliminary screening of the extracts revealed the presence of terpenes, flavonoids, phenol carboxylic acid, and polyphenols. Subsequent studies using Gas chromatography (GC), Gas chromatography/mass spectrometry (GC–MS), and H NMR techniques identified specific compounds in each part of the plant (Badiaga 2011).

In the leaves extract, the several compounds identified (Packialakshmi et al. 2014; Singh et al. 2015) were Heptane-4-one, α-pinene, camphene, dehydrosabenene, 6-Methylhept-5-ene-2-one, β-pinene, myrcene, p-cymene, limonene, E-ocimene, α-tepeniol, alloocimene, citronellic acid, coumarin, cedrene, α-amorphene, and ethyl palmitate. In the roots extract, the compounds included Oct-1-ene, α-pinene, β-pinene, myrcene, p-cymene, E-ocimene, dehydrolinalool, undecan, allo-ocimene, limonene oxide, α-tepeniol, Decan-2-ol, citronellic acid, and Deca-2,4-dien-1-al. The seeds extract contained Oct-1-ene, Heptane-4-one, Heptane-2-one, Non-1-ene, α-pinene, dehydrosabenene, 6-Methylhept-5-ene-2-one, E-ocimene, myrcene, p-cymene, limonene, dehydrolinalool, undecan, limonene oxide, α-tepeniol, benzoic acid, Deca-2,4-dien-1-al, Decan-2-ol, Gerniol, Undec-10-e-1-al, and coumarin (Gabriel et al. 2005).

Additionally, specific compounds were identified in the seeds, including viscocic and viscosin (monomethoxy trihydroxyflavone) (Gupta and Dutta 1938). The whole plant extract revealed the presence of Eriodictyol5-rhamnoside, a novel glycoside. Furthermore, Cleomiscosin A and B were detected in the seed's extracts (Ray et al. 1982). Glucocapparin and glucocleomin (glucosinolates), as well as cleomaldeic acid ((3E, 7E, 11E) 20-oxocembra-3,7,11,15-tetraen-19-oic acid), a macrocyclic diterpene, were isolated from the whole plant. These phytochemical findings highlight the diverse range of compounds present in *Cleome viscosa* and provide valuable insights into its potential medicinal and ecological significance.

2.4.3 Traditional Use

Humanity has relied on plant products of medicine since the dawn of time. Numerous indigenous medical systems, including such Ayurveda, Siddha, Unani and other systems outside India have been developed and validated using the traditional languages of many indigenous societies (Chatterjee and Prakashi 1991). CV is regarded to have cooling, tonic, laxative, diuretic, and anthelmintic characteristics in Ayurvedic medicine. When used in the diagnosis of malaria transmission fevers, indigestion-induced fevers, leprosy, and blood diseases, as well as uterine complaints, it has been reported to be effective (Kirtikar and Basu 1984). Kapha (phlegm) can also be removed, as well as earaches, and ulcers. Fever and diarrhoea are treated with the plant's Plants in Unani medicine, which classify them as anthelmintic and detergent (Chopra et al. 1956). To treat earache, malaria and piles, the leaves' juice is said to be beneficial.

2.4.4 Pharmacological Activities

Scientifically, *C. viscosa* (CV) has been screened for numerous pharmacological activities, including anthelmintic, antimicrobial, analgesic, anti-inflammatory, immunomodulatory, antipyretic, and psychopharmacological activities.

Uses ascribed in folkloric medicine

Anthropological studies have received a lot of attention in recent years, bringing to light the many little-known and unidentified medicinal uses, especially those of plant origin (Maheshwari et al. 1980; Singh 1945; Singh and Pandey 1980; Shah 1984; Sudhakar and Rolla 1985; Ramchandran and Nair 1981; Rajwar 1983). Modern scientific methods such as preliminary phytochemical, biological screenings, and clinical studies are clearly needed to evaluate them (Mali et al. 2006). For the most part, ethnobotanical research has shown that CV has medicinal benefits. The leaves are used for treating boils, earache, headache, ulcers, and wounds (Bedi 1978; Singh et al. 1987; Singh 1945; Shah et al. 1983; Malhotra and Moorthy 1973; Purohit et al. 1985).

Antipyretic activity

Devi et al. (2003) conducted a study to investigate the antipyretic activity of the methanol extract of *C. viscosa* (CVME) in albino rats. The administration of CVME at doses of 200, 300, and 400 mg/kg BW p.o. resulted in a significant dose-dependent reduction in normal body temperature and yeast-induced fever, with the effect lasting up to 5 h after administration. The antipyretic effect of CVME was comparable to that of paracetamol (150 mg/kg p.o.), used as a reference standard in the study.

Analgesic activity

The analgesic activity of the methanol extract of CV was evaluated in mice using various methods such as the acetic acid-induced writhing test and the tail flick, tail clip, and tail immersion methods. The results revealed significant analgesic activity at a higher concentration of 400 mg/mL compared to diclofenac sodium, a reference standard used in the study (Devi et al. 2003). In another study, Singh and West (1991) evaluated the analgesic activity of the aqueous extract of CV seeds in mice and found it to possess significant analgesic properties.

Anti-inflammatory activity

The anti-inflammatory ability of the methanol extract of CV was tested toward carageenin-, histamine-, and dextran-induced rat paw edema. Diclofenac sodium (20 mg/kg) was used as a guideline for comparison. A significant difference was found between the extract's action and the reference standard (Devi et al. 2003).

Antimalarial activity

According to an ethnomedical study conducted by Saxena et al. (2000), the Santhal tribes of Madhya Pradesh, India, use the smoke from the leaves of CV to repel mosquitoes and other insects. To test its larvicidal activity against 2nd and 4th stage larvae of Anopheles stephensi, a malaria vector in India, ethanol extract of the leaves is used.

Antimicrobial activity

Sudhakar et al. (2006) examined the ethanol extracts of CV leaves and flowers for antimicrobial activity. Both extracts exhibited a broad spectrum of antimicrobial activity, particularly showing significance against Escherichia coli, Proteus vulgaris, and Pseudomonas aeruginosa, while the leaf extract displayed moderate activity against pathogenic fungi. Williams et al. (2003) evaluated the hexane extract of CV leaves and stems for various biological activities, including antibacterial, antifungal, contact insecticidal, and nematicidal properties. The extract showed potent antibacterial activity, with a cembranoid diterpene identified as one of the effective agents. The diterpene exhibited minimum inhibitory concentrations (MIC) values of 5.0 μg/spot and 1.0 μg/spot against *Bacillus subtilis* (Gram-positive) and *Pseudomonas fluorescens* (Gram-negative), respectively. However, it did not inhibit the growth of *Cladosporium cucumerinum* fungus. The extract also displayed pyrethroid-type contact insecticidal activity on adult *Cylas formicarius* (Coleoptera: Curculionidae) and high nematicidal activity against Meloidogyne incognita Chitwood, although its potency diminished upon subfractionation. In another study, Samy et al. (1999) evaluated the antimicrobial activity of the aqueous extract of CV aerial parts and found maximum inhibition against *Aeromonas hydrophila* and *Bacillus cereus*. Furthermore, Mishra et al. (1991) reported the toxicity of the aqueous macerate of CV leaves against ringworm-causing fungi, Epidermophyton floccosum, Trichophyton mentagrophytes, and Microsporum gypseum, demonstrating good mycotoxic activity of the plant.

Antidiarrheal activity

A study was conducted to assess the antidiarrheal potential of the methanol extract of the entire plant of *C. viscosa* using rat models of diarrhea. The CVME displayed significant inhibitory activity against castor oil-induced diarrhea and prostaglandin E2 (PGE2)-induced enteropooling in rats. Moreover, the extract demonstrated a noteworthy reduction in gastrointestinal motility in the charcoal meal test conducted on rats. These findings provide strong evidence supporting the folklore claim of CV as an effective antidiarrheal agent (Devi et al. 2002).

Hepatoprotective activity

In a separate study, the hepatoprotective potential of the aqueous seed extract of CV was evaluated against liver damage induced by carbon tetrachloride (CCl4) in Wistar rats. The animals with hepatotoxicity induced by CCl4 were orally administered the extract at a dosage of 200 mg/kg, while the reference standard silymarin was given at the same dosage. The group of rats treated with the CV seed extract showed a significant reduction in serum enzymes, including aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (ALP), γ-glutamyl transpeptidase, and lipid peroxidase. Additionally, an increase in reduced glutathione (GSH) was observed compared to the CCl4-treated control group. The histopathological observations further supported the significant protective effects of the extract, like those observed in the positive control group treated with silymarin (Sengottuvelu et al. 2007).

Gastroprotective activity

Helicobacter pylori (HP) is a Gram-negative bacterium known to be the primary cause of gastritis, dyspepsia, peptic ulcer disease, and gastric cancer. Bhamarapravati et al. (2003) conducted research to assess the in vitro susceptibility of 18 strains of HP to methanol extracts from 20 spice and food plants commonly used in Thai traditional medicine, including CV (*C. viscosa*), which is known for its efficacy in treating gastrointestinal disorders. The methanol extract of CV demonstrated an inhibitory effect on the growth of HP, with a minimum inhibitory concentration of 50 microg/mL, indicating its potential gastroprotective activity.

2.4.5 Market Potential

Cleome viscosa, commonly known as Prickly ash or Asian spider flower or tickweed, has some market potential in various industries. Here are some potential market opportunities for *Cleome viscosa*:

- **Traditional Medicine**: In traditional medicine systems, *Cleome viscosa* is believed to have medicinal properties. It is used to treat ailments such as skin conditions, digestive issues, and respiratory disorders. There may be a market for *Cleome viscosa*-based herbal remedies, extracts, or supplements within the traditional medicine sector (Devi Parimala et al. 2004).
- **Cosmetics and Skincare**: *Cleome viscosa* extracts or oils may have potential applications in the cosmetics and skincare industry. The plant is believed to have antioxidant and anti-inflammatory properties, which could be valuable in

the formulation of natural skincare products such as creams, lotions, serums, or facial oil (Kirtikar and Basu 1984).

- **Ethnobotanical and Traditional Crafts**: *Cleome viscosa* has cultural significance in certain regions, and it is sometimes used in traditional crafts. The plant's fibers and seeds can be utilized for making ropes, baskets, or decorative items. There may be niche markets for handmade crafts or artisanal products incorporating *Cleome viscosa* materials (Singh et al. 2017).
- **Biodiversity Conservation and Landscaping**: *Cleome viscosa* is a native plant species, and its cultivation or inclusion in landscaping projects can contribute to biodiversity conservation efforts. The plant's attractive flowers and foliage make it suitable for ornamental purposes in gardens, parks, or public spaces. Nurseries and landscaping businesses may find a market for *Cleome viscosa* plants or seeds (Sharma et al. 2009).

3 Conclusion

Many unused crops were grown in India, but are used less or no longer used today due to a variety of agronomic, genetic, economic, and cultural factors. Farmers and consumers use these crops less because they are somehow uncompetitive with other crops. Species in the same agricultural environment. Large losses, inadequate infrastructure paralyze the marketing prospects, the low production of underutilised crops and plants lead to a lower yield of processed products and increases the production costs during processing. To minimize losses in post-harvest handling, and technologies suitable for specific processing purposes, Product development and storage of fresh and processed products. Regardless of the research and field projects carried out, these are mostly fragmented and information about them is difficult to collect.

The chapter sheds light on the importance of exploring native indigenous plant resources as a solution to the increasing global population and depletion of natural resources. Various studies focus on underutilized plant species and unveils their potential for food, nutrition, income generation, and environmental services. These underutilized plants are rich sources of vitamins, minerals, and other nutrients, making them valuable for improving food and nutrition security in economically marginalized areas. Various study emphasizes the untapped potential of underutilized plants and highlights the need for more research and development in exploring and promoting their uses.

Recognizing the economic and health benefits of these native plants can pave the way for sustainable agriculture and improved food security. These underutilized plants can play multiple roles in enhancing food security, including supporting livelihoods, diversifying diets, reducing agricultural inputs, and celebrating cultural and nutritional diversity.

To improve the utilization of underutilized plants and crops, several steps can be taken:

- **Awareness and Education**: Raise awareness among farmers, agricultural organizations, and the general public about the value and potential of underutilized plants. Educate people about the nutritional benefits and various uses of these plants to create a demand for them in the market.
- **Research and Development**: Invest in research and development to identify and understand the functional properties, health benefits, and potential uses of underutilized plants. This can lead to the development of new products and applications, expanding their market opportunities.
- **Promotion and Marketing**: Develop marketing strategies to promote underutilized plants and crops as viable alternatives to mainstream crops. Highlight their unique flavors, health benefits, and cultural significance to attract consumers and businesses.
- **Policy Support**: Provide policy support and incentives for farmers and businesses involved in cultivating and processing underutilized crops. This can include financial assistance, subsidies, and favorable regulations.
- **Capacity Building**: Build the capacity of farmers, processors, and other stakeholders in the value chain of underutilized plants. This includes training in cultivation practices, post-harvest handling, and value addition.
- **Collaboration and Networking**: Foster collaboration between research institutions, government agencies, NGOs, and private sectors to work together in promoting and utilizing underutilized plants. Networking can help in sharing knowledge, resources, and best practices.
- **Conservation Efforts**: Implement conservation programs to protect the genetic diversity of underutilized plant species. Preservation of these plants in their natural habitats ensures their availability for future generations.

In conclusion, the chapter highlights the potential of underutilized plants and crops in Northern India to contribute significantly to food security, nutrition, and economic development. By recognizing their value and taking concrete steps to promote their utilization, India can harness the benefits of these native plants, contributing to sustainable agriculture and improved livelihoods. The exploration and adoption of underutilized crops and plants can pave the way for a more resilient and diverse food system in the region.

References

Acharya K, Giri S, Biswas G (2011) Comparative study of antioxidant activity and nitric oxide synthase activation property of different extracts from *Rhododendron arboreum* flower. Int J Pharmtech Res 3(2):757–762

Afaq SH, Khan ZA, Asif M (1984) Studies on oil, sugars and amino acids of *Cleome viscosa* Linn. Indian J Pharm Sci 46:91–93

Agarwal SS, Kalpana S (1988) Anti-inflammatory activity of flowers of *Rhododendron arboreum* (Smith) in Rat's hind paw oedema induced by various phlogistic agents. Indian J Pharmacol 20(2):86

Albin KC, Simons CT (2010) Psychophysical evaluation of a sanshool derivative (alkylamide) and the elucidation of mechanisms subserving tingle. PLoS ONE 5(3):e9520

Ali S, Nisar M, Qaisar M, Khan A, Khan AA (2017) Evaluation of the cytotoxic potential of a new pentacyclic triterpene from *Rhododendron arboreum* stem bark. Pharm Biol 55(1):1927–1930

Artaria A, Maramaldi G, Bonfigli A, Rigano L, Appendino G (2011) Lifting properties of the alkamide fraction from the fruit husks of *Zanthoxylum* bungeanum. Int J Cosmet Sci 33:328–333

Aschoff JK, Kaufmann S, Kalkan O, Neidhart S, Carle R, Schweiggert RM (2015) In vitro bioaccessibility of cartenoids, flavonoids, and vitamin C from differently processed oranges and range juices (*Citrus sinensis* (L.) Osbeck). J Agric Food Chem 63:578–587

Asgary S, Keshvari M (2013) Effects of *Citrus sinensis* juice on blood pressure. ARYA Atheroscler 9:98–101

Bader M, Stark TD, Dawid C, Lösch S, Hofman T (2014) All-trans-configuration in *Zanthoxylum* alkylamides swaps the tingling with a numbing sensation and diminishes salivation. J Agric Food Chem 62:2479–2488

Badiaga M (2011) Etude ethnobotanique, phytochimique et activités biologiques de Nauclea latifolia Smith, une plante médicinale africaine récoltée au Mali. PhD thesis, University of Blaise Pascal—Clermont-Ferrand II. NNT:2011CLF22187

Bagavan A, Rahuman AA, Kamaraj C, Kaushik NK, Mohanakrishnan D, Sahal D (2011) Antiplasmodial activity of botanical extracts against Plasmodium falciparum. Parasitol Res 108:1099–1109

Barkley NA, Roose ML, Krueger RR, Federici CT (2006) Assessing genetic diversity and population structure in a citrus germplasm collection utilizing simple sequence repeat markers (SSRs). Theor Appl Genet 112:1519–1531

Barreca D, Bellocco E, Leuzzi U, Gattuso G (2014) First evidence of C- and O glycosyl flavone in blood orange (*Citrus sinensis* (L.) Osbeck) juice and their influence on antioxidant properties. Food Chem 149:244–252

Bedi SJ (1978) Ethnobotany of the Ratan mahal hills, Gujarat, India. Econ Bot 32:278–284

Berry SK, Kalra CL (1987) Cultivation and processing of jackfruit. Indian Ed Pack 42(5):62–67

Bhamarapravati S, Pendland SL, Mahady GB (2003) Extracts of spice and food plants from Thai traditional medicine inhibit the growth of the human carcinogen Helicobacter pylori. In Vivo 17:541–544

Bhandary MR, Kawabata J (2008) Antidiabetic activity of Lali gurans (*Rhododendron arboreum* Sm.) flower. J Food Sci Technol Nepal 4:61–63

Bhartiya A, Aditya JP, Kant L (2015) Nutritional and remedial potential of an underutilized food legume horse gram (Macrotyloma uniflorum), a review. J Anim Plant Sci 25(4):2

Bhatt M, Abrol GS, Kumar S, Nautiyal BP (2017a) Preparation and evaluation of functionally enriched squash from *Rhododendron* (*Rhododendron arboreum* Sm.) flowers. Int J Food Ferment Technol 7:191–196

Bhatt V, Sharma S, Kumar N, Sharma U, Singh B (2017b) Simultaneous quantification and identification of flavonoids, lignans, coumarin and amides in leaves of *Zanthoxylum* armatum using UPLC-DAD-ESI-QTOF-MS/MS. J Pharm Biomed Anal 132:46–55

Bhattacharya D (2011) Rhododendron species and their uses with special reference to Himalayas—a review. Assam Univ J Sci Technol: Biol Environ Sci 7(1):161–167

Buchbauer G (2000) The detailed analysis of essential oils leads to the understanding of their properties (Perfume, Flavourist). 25:64–67

Camarda L, di Stefano V, del Bosco SF, Schillaci D (2007) Antiproliferative activity of Citrus juices and HPLC evaluation of their flavonoid composition. Fitoterapia 78:426–429

Cardeal ZL, MD Gomes da Silva, Marriott PJ (2006) Comprehensive two-dimensional gas chromatography/mass spectrometric analysis of pepper volatiles. Rapid Commun Mass Spec 20:2823–2836

Chadha KL, Pareek OP (1988) Genetic resources of fruits crops: achievements and gaps. IJPGR 1:43–48

Chalova VI, Crandall PG, Ricke SC (2010) Microbial inhibitory and radical scavenging activities of cold-pressed terpeneless Valencia orange (*Citrus sinensis*) oil in different dispersing agents. J Sci Food Agric 90:870–876

Chatterjee A, Prakashi SC (1991) The treatise on Indian medicinal plants. CSIR New Delhi 1(2):155

Chauhan P, Singh J, Sharma RK, Easwari TS (2016) Anti-bacterialactivity of *Rhododendron arboreum* plant against Staphylococcus aureus. Ann Hortic 9(1):92–96

Chen K, Xue L, Li Q, Li Y, Mao Y, Fan S, Zhang L, Zhao L (2021) Quantitative structure-pungency landscape of sanshool dietary components from *Zanthoxylum* species. Food Chem 363:130286

Chettri N, Sharma E (2009) A scientific assessment of traditional knowledge on firewood and fodder values in Sikkim, India. For Ecol Manag 257(10):2073–2078

Choi HJ (2016) Evaluation of antiviral activity of *Zanthoxylum* species against picornaviruses Osong Publ. Health Res Perspect 7(6):400–403

Chopra RN, Nayar SL, Chopra IC (1956) Glossary of Indian medicinal plants. CSIR, New Delhi, pp 70–71

Choudhary D, Ghosh S, Chauhan S, Bhati MJ (2013) Case studies on value chain approach for mountain development in Uttarakhand. ICIMOD, Nepal

Crops for the Future (2009–13) Crops for the future strategic plan 2009–2013. http://www.cropsforthefuture.org/wp-content/uploads/2009/03/strategic-plan-2009-2013

Deng S, Rong H, Tu H, Zheng B, Mu X, Zhu L, Zhou X, Peng W, Wu M, Zhang E, Li X, Shen H (2019) Molecular basis of neurophysiological and antioxidant roles of Szechuan pepper. Biomed Pharmacother 112:108696

Deora MA, Jaiswal P, Mathur A, Sherwani MR (2003) Fatty acid composition of some minor seed oils from arid zone of Rajasthan. J Indian Chem Soc 80:141–142

Devi S, Vats CK (2017) Physico-chemical characteristics of *Rhododendron* flowers available in different regions of Himachal Pradesh. Int J Agric Innov Res ISSN (Online) 6(3):1473–2319

Devi BP, Boobinathan R, Mandal SC (2002) Evaluation of anti-diarrhoeal activity of *Cleome viscosa* Linn extract in rats. Phytomedicine 9:739–742

Devi BP, Boominathan R, Mandal SC (2003) Evaluation of antipyretic potential of *Cleome viscosa* Linn (Capparidaceae) extract in rats. J Ethnopharmacol 87:11–13

Devi Parimala B, Boominathan R, Mandal SC (2004) Studies on psychopharmacological effects of *Cleome viscosa* Linn. (extract in rats and mice). Phytother Res 18:169–172

Dhyani SK, Maikhuri RK, Rao KS (2010) Reviving traditional plants to ensure household food security under changing climate in the Indian Himalayas. IJTK 9(2):311–318

Di Z, Xiaoxia S, Maurizio B, Xiaoou W, Jiyong S, Lei Z, Si L, Jianbo X, Bolin S, Xiaobo Z (2021) A comparative overview on chili pepper (capsicum genus) and Sichuan pepper (*Zanthoxylum* genus): from pungent spices to pharma-foods. Trends Food Sci 117:148–162

Etebu E, Nwauzoma AB (2014) A review on sweet orange (*Citrus sinensis* Osbeck): health, diseases, and management. Am J Res Commun 2(2):33–70

Fact.MR (2022) Sichuan peppercorn market is to rear excessive growth during 2022–2030. https://www.factmr.com/report/5182/sichuan-peppercorn-market

Fisher K, Phillips C (2009a) The mechanism of action of a citrus oil blend against Enterococcus faecium and Enterococcus faecalis. J Appl Microbiol 106:1343–1349

Fisher K, Phillips C (2009b) In vitro inhibition of vancomycin-susceptible and vancomycin-resistant Enterococcus faecium and E. faecalis in the presence of citrus essential oils. Br J Biomed Sci 66:180–185

Gabriel O, Peter W, Stephen O (2005) Chemical investigation of volatile constituents of *Cleome viscosa* from Nigeria. Bull Chem Soc Ethop 19(1):139–143

Gajanana TM, Gowda IND, Reddy BMC (2010) Exploring market potential and developing linkages—a case of underutilized fruit products in India. Agric Econ Res Rev 23:437–443

Gajraj R, Peart L (2019) Evaluation of essential oils from *Citrus sinensis* peel for cosmetic applications. J Cosmet Sci 70(3):219–227

Galopin CC, Furrer SM, Goeke (2004) Pungent and tingling compounds in Asian cuisine. In: Ho C-T, Hofmann T, Pickenhagen W (eds) Challenges in taste chemistry and biology. Amer Chem Soc Symp Ser 867:139–152

Gattuso G, Barreca D, Gargiulli C, Leuzzi U, Caristi C (2007) Flavonoid composition of Citrus juices. Molecules 12:1641–1673

Gautam A, Chand S, Sharma R (2014) Phytochemical analysis and in vitro antioxidant activity of different fractions of *Rhododendron arboreum* leaves. Int J Pharmacogn Phytochem Res 6(2):146–152

Gautam V, Kohli S, Arora S, Bhardwaj R, Kazi M, Ahmad A, Ahmad P (2018) Antioxidant and antimutagenic activities of different fractions from the leaves of *Rhododendron arboreum* Sm. and their GC-MS profiling. Molecules 23:2239

Geetha S, Asheesh G (2011) Medicinal and therapeutic potential of Sea buckthorn (Hippophae rhamnoides L): a review. J Ethnopharmacol 138:268–278

Ghimeray A, Lee H, Kim Y, Ryu E, Chang M (2015) Evaluation of antioxidant and anti-Inflammatory effect of *Rhododendron* brachycarpum extract used in skin care product by in vitro and in vivo test. Technol Invest 6:105–111

Gil-Izquierdo A, Gil MI, Ferreres F, Tomas-Barberan FA (2001) In vitro availability of flavonoids and other phenolics in orange juice. J Agric Food Chem 49:1035–1041

GIZ and Doon University (2011) Uttarakhand diagnostic study of building a mountain state 2000–2010. GIZ and Doon University, Dehradun

Goldhamer DA, Intrigliolo DS, Castel JR, Fereres E (2012) Citrus. In: Pasquale Steduto P, Theodore C, Hsiao TC, Elias Fereres E, Dirk Raes D (eds) Crop yield response to water: FAO irrigation and drainage paper 66, 1st edn, vol 49. Food and Agriculture Organization of the United Nations, Rome, pp 300–315

Gómez-Ariza JL, García-Barrera T, Lorenzo F (2004) Determination of flavour and off-flavour compounds in orange juice by on-line coupling of a pervaporation unit to gas chromatography-mass spectrometry. J Chromatogr A 1047:313–317

Gong Y, Sun W-H, Xu T-T, Zhang L, Huang X-Y, Tan Z-H, Di D-L (2021) Chemical constituents from the pericarps of *Zanthoxylum* bungeanum and their chemotaxonomic significance. Biochem Syst Ecol 95:104213

Gopalan C, Rama shastri BV, Balasubramaniam SC (1982) Report. National Institute of Nutrition, Hyderabad, AP

Goudeau D, Uratsu SL, Inoue K, da Silva FG, Leslie A, Cook D, Reagan L, Dandekar AM (2008) Tuning the orchestra: selective gene regulation and orange fruit quality. Plant Sci 174:310–320

Gruere G, Giuliani A, Smale M (2006) Marketing under utilized plant species for the benefit of the poor: a conceptual framework. International Food Policy Research Institute. EPT discussion paper 151

Gruere G, Nagarajan L, King O (2009) The role of collective action in the marketing of underutilized plant species: lessons from a case study on minor millets in South India. Food Policy 34(1):39–45

Gugal A, Kotiyal A (2022) A review on current status and challenges in cultivation of underutilised fruits crops of India. J Pharm Innov 11(5):2255–2259

Gupta RK, Dutt S (1938) Chemical examination of seeds of Cleome icosandra. J Indian Chem Soc 15(1):532–533

Guzeldag G, Kadioglu L, Mercimek A, Matyar F (2013) Preliminary examination of herbal extracts on the inhibition of Helicobacter pylori. Afr J Tradit Complement Altern Med 11:93–96

Han ST (2008) Medicinal plants in the South Pacific. World Health Organization (WHO) Regional Publications, Western Pacific Series; Manila, Philippines, no 1, pp 49–50

Harborne JB, Williams CA (1971) Leaf survey of flavonoids and simple phenols in the genus *Rhododendron*. Phytochem 10(11):2727–2744

Hernández-Favela JM, González-Santiago O, Ramírez-Cabrera MA, Esquivel-Ferriño PC, Camacho-Corona MR (2016) Chemistry and pharmacology of *Citrus sinensis*. Molecules 21(2):247

Hisatomi E, Matsui M, Kobayashi A, Kubota K (2000) Antioxidative activity in the pericarp and seed of Japanese pepper (Xanthoxylum piperitum DC). J Agric Food Chem 48:4924–4928
Huang S, Zhao L, Zhou XL, Ying M, Wang CJ, Weng J (2012) New alkylamides from pericarps of *Zanthoxylum* bungeanum. Chin Chem Lett 23:1247–1250
Intekhab J, Aslam M (2009) Isolation of a flavonoid from the roots of *Citrus sinensis*. Malays J Pharm Sci 7:1–8
Ivane NM, Haruna SA, Zekrumah M, Elysé FK, Hassan MO, Hashim SB, Tahir HE, Zhang D (2022) Composition, mechanisms of tingling paresthesia, and health benefits of Sichuan pepper: a review of recent progress. Trends Food Sci 126:1–12
Jang KH, Chang YH, Kim DD, Oh KB, Oh U, Shin J (1978) New polyunsaturated fatty acid amides isolated from the seeds of *Zanthoxylum* piperitum. Arch Pharm Res 31:569–572
Ji Y, Li S, Ho C-T (2019) Chemical composition, sensory properties, and application of Sichuan pepper (*Zanthoxylum* genus). Food Sci Hum Wellness 8:115–125
Jiang L, Kubota K (2004) Differences in the volatile components and their odor characteristics of green and ripe fruits and dried pericarp of Japanese pepper (Xanthoxylum piperitum DC). J Agric Food Chem 52:4197–4203
Kala CP (2015) Medicinal plants of the high-altitude cold desert in India: diversity, distribution, and traditional uses. Int J Biodivers Sci Ecosyst Serv Manag 11(3–4):236–253
Karki S, Rijal S, Swamy S (2023) Evaluation of adaptogenic and antidepressant activity of Rhododendron *arboreum* Flower. J Pharma Res Inter 35(16):27–39
Karyakina EE, Vokhmyanina DV, Sizova NV, Sabitov AN, Borisova AV, Sazontova TG, Arkhipenko YV, Tkachuk VA, Zolotov YA, Karyakin AA (2009) Kinetic approach for evaluation of total antioxidant activity. Talanta 80:749–753
Kaviya S, Santhanalakshmi J, Viswanathan B, Muthumary J, Srinivasan K (2011) Biosynthesis of silver nanoparticles using *Citrus sinensis* peel extract and its antibacterial activity. Spectrochim Acta A Mol Biomol Spectrosc 79:594–598
Kelebek H, Selli S (2011) Determination of volatile, phenolic, organic acid and sugar components in a Turkish cv. Dortyol (*Citrus sinensis* L. Osbeck) orange juice. J Sci Food Agric 91:1855–1862
Kirtikar KR, Basu BD (1984) Indian medicinal plants, vol I, pp 181–185
Klimek-Szczykutowicz M, Szopa A, Ekiert H (2020) Citrus limon (Lemon) phenomenon—a review of the chemistry, pharmacological properties, applications in the modern pharmaceutical, food, and cosmetics industries, and biotechnological studies. Plants (Basel) 9(1):119
Kolhed M, Karlberg B (2005) Capillary electrophoretic separation of sugars in fruit juices using on-line mid infrared Fourier transform detection. Analyst 130:772–778
Koo JY, Jang Y, Cho H, Lee CH, Jang KH, Chang YH, Shin J, Oh U (2007) Hydroxy-alpha-sanshool activates TRPV1 and TRPA1 in sensory neurons. Eur J Neurosci 26(5):1139–1147
Krishna H, Attri BL, Kumar A (2014) Improvised *Rhododendron* squash: processing effects on antioxidant composition and organoleptic attributes. J Food Sci Technol 51(11):3404–3410
Kumar M, Sharma CM (2009) Fuelwood consumption pattern at different altitudes in rural areas of Garhwal Himalaya. Biomass Bioenergy 33(10):1413–1418
Kumar V, Sheenam S, Rasane P (2019) Bioactive compounds, health benefits and utilization of *Rhododendron*, a comprehension review. Agric Food Secur 8:6
Kumar Rana S, Sen Oli P, Kala Rana H (2015) Traditional botanical knowledge (TBK) on the use of medicinal plants in Sikles area, Nepal. Asian J Plant Sci Res 5:8–15
Lahlou M (2013) The success of natural products in drug discovery. Pharmacol Pharm 4:17–31
Lan Y, Wu Q, Mao YQ, Wang Q, An J, Chen YY, Wang WP, Zhao BC, Liu N, Zhang YW (2014) Cytotoxicity and enhancement activity of essential oil from *Zanthoxylum* bungeanum Maxim as a natural transdermal penetration enhancer. J Zhejiang Univ Sci B 15(2):153–164
Lapcík O, Klejdus B, Davidová M, Kokoska L, Kubán V, Moravcová J (2004) Isoflavonoids in the Rutaceae family: 1. Fortunella obovata, Murraya paniculata and four Citrus species. Phytochem Anal 15(5):293–299
Leuzzi U, Caristi C, Panzera V, Licandro G (2000) Flavonoids in pigmented orange juice and second-pressure extracts. J Agric Food Chem 48:5501–5506

Li S, Lambros T, Wang Z, Goodnow R, Ho CT (2007) Efficient and scalable method in isolation of polymethoxyflavones from orange peel extract by supercritical fluid chromatography. J Chromatogr B Anal Technol Biomed Life Sci 846:291–297

Li J, Wang F, Li S, Peng Z (2015) Effects of pepper (*Zanthoxylum* bungeanum Maxim.) leaf extract on the antioxidant enzyme activities of salted silver carp (Hypophthalmichthys molitrix) during processing. J Funct Foods 18:1179–1190

Liu L, Xu X, Cheng D, Yao X, Pan S (2012) Structure-activity relationship of citrus polymethoxylated flavones and their inhibitory effects on Aspergillus niger. J Agric Food Chem 60:4336–4341

Madhvi S K, Sharma M, Iqbal J, Younis M (2019) Phytochemistry, traditional uses and pharmacology of *Rhododendron arboreum*: a review. Res J Pharm Tech 12(9)

Maheshwari JK, Singh KK, Saha S (1980) Ethnomedicinal uses of plants by Tharus in Kheri district, U.P. Bull Med Ethno-Bot Res 1:318–337

Malhotra SK, Moorthy S (1973) Some useful and medicinal plants of Chandrapur district (Maharashtra State). Bull Bot Serv India 15:13–21

Mali RG, Hundiwale JC, Gavit RS, Patil DA, Patil KS (2006) Herbal abortifacients used in North Maharashtra. Nat Prod Res 5:315–318

Mali RG, Mahajan SG, Mehta AA (2007) In vitro screening of *Cleome viscosa* extract for anthelmintic activity. Pharm Biol 45:766–768

Manthey JA (2004) Fractionation of orange peel phenols in ultrafiltered molasses and mass balance studies of their antioxidant levels. J Agric Food Chem 52:7586–7592

Matsubara Y, Yusa T, Sawabe A, Iizuka Y, Takekuma S, Yoshida Y (1991) Structures of new cyclic peptides in young unshiu (Citrus unshiu Marcov.), orange (*Citrus sinensis* Osbeck.) and amanatsu (Citrus natsudaidai) peelings. Agric Biol Chem 55:2923–2929

Mayaud L, Carricajo A, Zhiri A, Aubert G (2008) Comparison of bacteriostatic and bactericidal activity of 13 essential oils against strains with varying sensitivity to antibiotics. Lett Appl Microbiol 47:167–173

Mayes S, Massawe PG, Alderson JA, Roberts SN, Azam A, Hermann M (2011) The potential for underutilized crops to improve security of food production. J Exp Bot 1–5

McGee H (2004) On food and cooking. Scribner

Mirhosseini H, Tan CP, Yusof S, Hamid NS (2008) Solid-phase microextraction for determining twelve orange flavour compounds in a model beverage emulsion. Phytochem Anal 19:429–437

Mishra DN, Dixit V, Mishra AK (1991) Mycotoxic evaluation of some higher plants against ringworm causing fungi. Indian Drugs 28:300–303

Mizutani K, Fukunaga Y, Tanaka O, Takasugi N, Saruwatari YI, Fuwa T, Yamauchi T, Wang J, Jia MR, Li FY, Ling YK (1988) Amides from Huajiao, pericarps of *Zanthoxylum* bungeanum MAXIM. Chem Pharm Bull 36:2362–2365

Mohtasheem ul Hasan M, Salman A, Munnawar S, Iqbal A (2011) Analgesic and antiemetic activity of *Cleome viscosa* L. Pak J Bot 43(1):112–119

Morrow R, Deyhim F, Patil BS, Stoecker BJ (2009) Feeding orange pulp improved bone quality in a rat model of male osteoporosis. J Med Food 12:298–303

Moza AK, Rohde SE, Leffingwell JC, Leffingwell D (2008) Use of a liquid cooling sensate to provide a pungent, warming or tingling sensate composition. United States US 2008/0038386 A1

Mudagal MP, Goli D (2011) Preventive effect of *Rhododendron arboreum* on cardiac markers, lipid peroxides and antioxidants in normal and isoproterenol-induced myocardial necrosis in rats. Afr J Pharm Pharmacol 5(6):755–763

Nadkarni AK (1982) The Indian Materia Medica. Bombay, Popular Prakashan I, pp 351–352

Naila A, Nadia D, Zahoor QS (2014) Stable silver nanoparticles synthesis by *Citrus sinensis* (orange) and assessing activity against food poisoning microbes. Biomed Environ Sci 27:815–818

Neeraj VB, Purwar S (2020) Chironji (Buchanania lanzan) Wonder tree: nutritional and therapeutic values. Int J Curr Microbiol App Sci 9(2):3033–3042

Negi VS, Maikhuri KR, Rawat LS, Chandra A (2013) Bio respecting of *Rhododendron arboreum* for livelihood Enhancement in Central Himalaya, India. Environ We Int J Sci Tech 8:61–70

Nisar M, Ali S, Qaisar M, Gilani SN, Shah MR, Khan I, Ali G (2013) Antifungal activity of bioactive constituents and bark extracts of *Rhododendron arboreum.* Bangladesh J Pharmacol 8(2):218–222

Nisar M, Ali S, Muhammad N, Gillani SN, Shah MR, Khan H, Maione F (2016) Antinociceptive and anti-inflammatory potential of *Rhododendron arboreum* bark. Toxicol Ind 32(7):1254–1259

Niu LY, Hu XS, Zhao L, Liao XJ, Wang ZF, Wu JH (2009) The characteristic analysis of several mineral contents in Chinese orange juice. Guang Pu Xue Yu Guang Pu Fen Xi 29(1):259–262

O'Bryan CA, Crandall PG, Chalova VI, Ricke SC (2008) Orange essential oils antimicrobial activities against Salmonella.spp. J Food Sci 73:M264–M267

Oh M, Chung MS (2014) Effects of oils and essential oils from seeds of *Zanthoxylum* schinifolium against foodborne viral surrogates. Evid Based Complement Altern Med 135797

Oliveira ED, Leite TS, Silva BA, Conde-Garcia EA (2005) Inotropic effect of *Citrus sinensis* (L.) Osbeck leaf extracts on the guinea pig atrium. Braz J Med Biol Res 38:111–118

Orwa C, Mutua A, Kindt R, Jamnadass R, Simons A (2009) Agroforestree database: a tree species reference and selection guide version 4.0. ICRAF Nairobi KE. US, pp 1–5

Packialakshmi N, Banu Musbira M, Oviya K (2014) Analysis of IR—spectroscopy by using different Nelumbo nucifera samples. Int J Pharm Res Appl 4(1):14–19

Painuli V, Gupta R, Yadav AK (2012) Phytochemical analysis of *Rhododendron arboreum* with special reference to its antioxidant activity. J Pharm Pharmacol 64(10):1325–1330

Pandey D, Kumar A, Singh R (2011) Marketing of sweet orange (Malta) in Kumaon region of Uttarakhand. J Recent Adv Appl Sci 26:6–11

Pandey A, Lepcha UP, Gaira KS, Joshi R, Chettri N (2020) Nettle plant (Girardinia diversifolia) fibre extraction and yarn making. NIHE, p 18

Panduraju T, Parvathi B, Rammohan M, Reddy SC (2011) Wound healing properties of *Cleome viscosa* Linn. Res Artic Hygeia J D Med 3:41–45

Parcha V, Yadav N, Sati A, Dobhal Y, Sethi N (2017) Cardio protective effect of various extract of *Rhododendron arboreum* Sm flower on Albino rats. J Pharmacogn Phytochem 6(4):1703–1707

Parle M, Chaturvedi D (2012) Orange: range of benefits. Int Res J of Pharma 3(7):59–63

Perez-Cacho PR, Mahattanatawee K, Smoot JM, Rouseff R (2007) Identification of sulfur volatiles in canned orange juices lacking orange flavor. J Agric Food Chem 55:5761–5767

Peterson JJ, Beecher GR, Bhagwat SA, Dwyer JT, Gebhardt SE, Haytowitz DB, Holden JM (2006) Flavanones in grapefruit, lemons, and limes: a compilation and review of the data from the analytical literature. J Food Comp Anal 19:S74–S80

Petruzzello M (2022) "Sichuan pepper". Encyclopedia Britannica

Phondani PC, Maikhuri RK, Rawat LS, Farooquee NA, Kala CP, Vishvakarma SCR, Rao KS, Saxena KG (2010) Ethnobotanical uses of plants among the Bhotiya tribal communities of Niti Valley in central Himalaya, India. Ethnobot Res Appl 8:233–244

Prakash D, Upadhyay G, Singh BN, Dhakarey R, Kumar S, Singh KK (2007) Free-radical scavenging activities of Himalayan *Rhododendron*s. Curr Sci 92(4):526–532

Prakash V, Rana S, Sagar A (2016) Studies on antibacterial activity of leaf extracts of *Rhododendron arboreum* and *Rhododendron* campanulatum. Int J Curr Microbiol Appl Sci 5(4):315–322

Purohit VP, Silas RA, Gaur RD (1985) Ethnobotanical studies of some medicinal plants used in skin diseases from Raath (Pauri) Garhwal Himalaya. J Sci Res Plant Med 6:39–47

Pushpamma P, Ejeta G, Mertz ET, Rooney LW, Schaffert R, Yohe J (1990) Importance of sorghum as food in Asia. In: Proceedings of international conference an Sorghum nutritional quality, pp 229–241

Qiao Y, Xie BJ, Zhang Y, Zhang Y, Fan G, Yao XL, Pan SY (2008) Characterization of aroma active compounds in fruit juice and peel oil of Jinchen C. Sinensis fruit (*Citrus sinensis* (L.) Osbeck) by GC-MS and GC-O. Molecules 13:1333–1344

Rajwar GS (1983) Low altitude medicinal plants of south Garhwal. Bull Med Ethno-Bot Res 4:14–28

Ramchandran VS, Nair VJ (1981) Ethnobotanical observations on Irulars of Tamil Nadu (India). J Econ Tax Bot 2:183–190

Rana SK, Oli PS, Rana HK (2015) Traditional botanical knowledge (TBK) on the use of medicinal plants in Sikles area, Nepal. Asian J Plant Sci Res 5(11):8–15

Rani G, Yadav L, Kalidhar SB (2009) Chemical examination of *Citrus sinensis* flavedo variety pineapple. Indian J Pharm Sci 71:677–679

Ranjitkar S, Sujakhu NM, Jati R, Xu J, Schmidt-Vogt D (2014) Yield and household consumption of *Rhododendron arboreum* as a fuelwood species in Eastern Nepal. Biomass Bioenergy 61:245–253

Rao MN, Soneji JR, Sahijram L (2011) Citrus: genoics resources developed; wild plants relatives: genomic and breeding resources. Springer (I) Berlin/Heidelberg; New York, NY

Ravi BS (2004) Neglected millets that save the poor from starvation. LEISA India 1:34–36

Ravi SB, Hrideek TK, Kumar ATK, Prabhakaran TR, Mal B, Padulosi S (2010) Mobilizing neglected and underutilized crops to strengthen food security and alleviate poverty in India. Indian J Plant Genet Resour 1(23):110–116

Ravindran PN, Divakaran M, Pillai GS (2012) Other herbs and spices: achiote to Szechuan pepper. In: Handbook of herbs and spices, pp 534–556

Rawat P, Bachheti RK, Kumar N, Nishant R (2018) Phytochemical analysis and evaluation of in vitro immunodulatory activity of *Rhododendron arboreum* leaves. Asian J Pharm Clin Res 11(8):123–128

Ray AB, Chattopadhyay SK, Konno C, Hikino H (1982) Cleomiscosin B, a coumarino-lignan from seeds of *Cleome viscosa.* Heterocycles 19:19–20

Rojas-Sandoval J (2022) *Cleome viscosa* (Asian spiderflower). CABI compendium. CABI International

Roy JD, Handique AK, Barua CC, Talukdar A, Ahmed FA, Barua IC (2014) Evaluation of phytoconstituents and assessment of adaptogenic activity in vivo in various extracts of *Rhododendron arboreum* (leaves). Indian J Pharm Biol Res 2(2):49–56

Rukmini C (1978) Chemical, nutritional and toxicological evaluation of the seed oil of *Cleome viscosa.* Indian J Med Res 67:604–607

Rukmini C, Deosthale YG (1979) Nutritive value of defatted seed cake of *Cleome viscosa.* J Am Oil Chem Soc 56:503–505

Saleem M, Ahmad FA, Shafiq N, Riaz N, Jabbar A, Arshad M, Malik A (2010) Chemical constituents of *Citrus sinensis* var. Shukri from Pakistan. J Asian Nat Prod Res 12:702–706

Samy RP, Ignacimuthu S, Raja DP (1999) Preliminary screening of ethnomedicinal plants from India. J Ethnopharmacol 66:235–240

Saranya D, Ravi R (2016) The leaf of Nilgiri *Rhododendron*: a potent antimicrobial agent against medically critical human pathogens. Int J Pharmacogn 3(6):251–256

Saxena BR, Koli MC, Saxena RC (2000) Preliminary ethnomedical and phytochemical study of *Cleome viscosa* L. Ethnobotany 12:47–50

Selli S, Canbas A, Varlet V, Kelebek H, Prost C, Serot T (2008) Characterization of the most odor-active volatiles of orange wine made from a Turkish cv. Kozan (*Citrus sinensis* L. Osbeck). J Agric Food Chem 56:227–234

Semwal DP, Saradhi PP, Kala CP, Sajwan BS (2010) Medicinal plants used by local Vaidy as in Ukhimath block, Uttarakhand. Indian J Tradit Knowl 9(3):480–485

Sengottuvelu S, Duraisamy R, Nandhakumar J, Sivakumar T (2007) Hepatoprotective activity of *Cleome viscosa* against carbon tetrachloride induced hepatotoxicity in rats. Pharmacog Mag 3:121–124

Sengupta S (2022) Timur: Uttarakhand's Szechuan pepper is a Himalayan gem

Shah GL (1984) Some economically important plants of Salsette Island near Bombay. J Econ Tax Bot 5:753–765

Shah GL, Yadav SS, Badri N (1983) Medicinal plants from Dahanu forest division in Maharashtra State. J Econ Tax Bot 4:141–151

Shalaby NMM, Abd-Alla HI, Ahmed HH, Basoudan N (2011) Protective effect of *Citrus sinensis* and Citrus aurantifolia against osteoporosis and their phytochemical constituents. J Med Plants Res 5:579–588

Sharma A (2012) Scientific harvesting for quality seed collection of Buchanania lanzan Spreng for its conservation and sustainable management–case study of Chhindwara Madhya Pradesh, India. Int J Bio Sci Biotechnol 4(1)

Sharma BC (2013) In vitro antibacterial activity of certain folk medicinal plants from Darjeeling Himalayas used to treat microbial infections. J Pharmacogn Phytochem 2(4):1–4

Sharma P, Samant SS (2014) Diversity, distribution, and indigenous uses of medicinal plants in Parbati Valley of Kullu district in Himachal Pradesh, Northwestern Himalaya. Asian J Adv Basic Sci 2(1):77–98

Sharma U, Saini R, Kumar N, Singh B (2009) Steroidal saponins from Asparagus racemosus (roots). Chem Pharm Bull (Tokyo) 57:890–893

Sharma PK, Chauhan NS, Lal B (2010) Conservation of phyto-diversity of Parvati Valley in Northwestern Himalayas of Himachal Pradesh-India. Med Aromat Plant Sci Biotechnol 4(1):47–63

Sharma M, Gargi A, Borah A (2022) *Rhododendron arboreum* and its potential health benefit: a review. J Pharm Innov SP-11(6):926–933

Sharon-Asa L, Shalit M, Frydman A, Bar E, Holland D, Or E, Lavi U, Lewinsohn E, Eyal Y (2003) Citrus fruit flavor and aroma biosynthesis: isolation, functional characterization, and developmental regulation of Cstps1, a key gene in the production of the sesquiterpene aroma compound valencene. Plant J 36:664–674

Shimizu T, Shigeta Y, Kunieda S (2007) Food products containing a fruit component. United States US 2007(0092623):A1

Shin GH, Kim W (2022) Antibacterial and antiseptic activities of various spices to the mala food ingredients. Food Sci Technol Campinas 42:e115821

Shrestha U (2009) Uses of *Rhododendron* on Tinjure-Milke-Jaljale area, Eastern Nepal. Case study, p 17

Sichuna pepper. Retrieved from Wikipedia

Singh H (1945) Some useful wild plants of Delhi Province. Indian J Agric Sci 15:297–307

Singh S (2007) Chironji underutilized and underexploited crops. In: Peter KV (ed). New India Publishing Agency, New Delhi, vol 2, pp 295–309

Singh V, Pandey RP (1980) Medicinal plant lore of the tribals of eastern Rajasthan. J Econ Tax Bot 1:137–147

Singh PD, West ME (1991) Pharmacological investigations of sticky viscome extract (*Cleome viscosa* Linn) in rats, mice and guinea-pigs. Phytother Res 5:82–84

Singh AK, Singh RN, Singh SK (1987) Some ethnobotanical plants of Terai region of Gorakhpur district, India. J Econ Tax Bot 9:407–410

Singh P, Shukla R, Prakash B, Kumar A, Singh S, Mishra PK, Dubey NK (2010) Chemical profile, antifungal, antiaflatoxigenic and antioxidant activity of Citrus maxima Burm. and *Citrus sinensis* (L.) Osbeck essential oils and their cyclic monoterpene, dl-limonene. Food Chem Toxicol 48:1734–1740

Singh H, Mishra A, Mishra AK (2015) *Cleome viscosa* Linn (Capparaceae): a review. Pharmacogn J 7(6)

Singh CJ, Mehta SC, Yashwant (2017) Cleome viscose: a review on ethnobotany and pharmacology uses. Int J Pharm Qual Assur 8(2):72–77

Soler C, Hamilton B, Furey A, James KJ, Mañes J, Picó Y (2006) Comparison of four mass analyzers for determining carbosulfan and its metabolites in citrus by liquid chromatography/mass spectrometry. Rapid Commun Mass Spectrom 20:2151–2164

Sonar PK, Singh R, Bansal P, Balapure AK, Saraf SK (2012a) *R. arboreum* flower and leaf extracts: RP-HPTLC screening, isolation, characterization, and biological activity. Rasayan J Chem 5(2):165–172

Sonar PK, Singh R, Khan S, Saraf SK (2012b) Isolation, characterization, and activity of the flowers of *Rhododendron arboreum* (Ericaceae). J Chem 9(2):631–636
Sood S, Kumar A, Yadav R (2017) Small millets: An underutilized nutri-cereal for nutritional security and better livelihood in northern hilly region of India. Curr Sci 112(2):259–265
Sreeramulu D, Reddy VK, Raghunath M (2012) Antioxidant activity of commonly consumed cereals, millets, pulses and legumes in India. Indian J Biochem Bio 46:112–115
Srivastava A, Bishnoi SK, Sarkar PK (2017) Value addition in minor fruits of Eastern India: an opportunity to generate rural employment. In: Dutta AK, Mondal B (eds) Fruits for livelihood: production technology and management practices Agro Bios (India), Jodhpur, pp 395–417
Stöggl WM, Huck CW, Stecher G, Bonn GK (2006) Capillary electrochromatography of biologically relevant flavonoids. Electrophoresis 27:787–792
Sudhakar S, Rolla RS (1985) Medicinal plants of Upper East Godavari District (Andhra Pradesh) and need for establishment of medicinal farm. J Econ Tax Bot 7:399–406
Sudhakar M, Rao CV, Rao PM, Raju DB (2006) Evaluation of anti-microbial activity of Cleome viscosa and Gmelina asiatica. Fitoterapia 77:47–49
Suryakumar G, Gupta A (2011) Medicinal and therapeutic potential of Sea buckthorn (*Hippophae rhamnoides* L.). J Ethnopharmac 138:268–278
Swamidasan R, Sanil Kumar R, Manasa Deepa R (2018) Medicinal values of *Rhododendron* arboretum: a comprehensive review. ISSN: 2319-7064 Research Gate Impact Factor (2018): 0.28 | SJIF (2019): 7.583
Takemoto JK, Remsberg CM, Yáñez JA, Vega-Villa KR, Davies NM (2008) Stereospecific analysis of sakuranetin by high-performance liquid chromatography: pharmacokinetic and botanical applications. J Chromatogr B Anal Technol Biomed Life Sci 875:136–141
Tang X, Zhou X, Wu J, Li J, Bai (2014) A novel function of sanshools: the alleviation of injury from metolachlor in rice seedlings. Pestic Biochem Physiol 110:44–49
Thakur M (2014) Underutilized food crops: treasure for the future India. Food Sci Res J 5(2):174–183
Thakur M, Modi VK (2020) Emerging technologies in food science—focus on the developing world. Springer Nature
Thakur M, Sharma V (2022) *Macrotyloma uniflorum*: an underutilized pulse crop as a sustainable plant-based protein. Future Food: J Food Agri Soc 10(3)
Thakur M, Singh K, Khedkar R (2018) Underutilized food crops: role in food security and sustainable development. In: Food frontiers. New Delhi, pp 37–56
Thapliyal V, Singh K (2014) 'Nutrition transition': a paradigm shift in Uttarakhand. J Nutr Food Sci 4:298
Thapliyal V, Singh K (2015) Finger millet: potential millet for food security and power house of nutrients. Int J Res Agric For 2(1):22–33
The ayurvedic formulary of India, Part I. Ministry of Health, and Family Welfare, New Delhi, pp 22–23 (2003)
The ayurvedic pharmacopoeia of India, Part I, vol III. Government of India, Ministry of Health and Family Welfare, Department of Indian System of Medicine and Homeopathy, New Delhi, pp 34–35
The plant list: *Cleome viscosa* (n.d.). http://www.theplantlist.org/tpl1.1/record/kew-2729211
Trends Food Sci Technol 126
Trovato A, Monforte MT, Barbera R, Rossitto A, Galati EM, Forestieri AM (1996) Effects of fruit juices of *Citrus sinensis* L. And Citrus limon L. On experimental hypercholesterolemia in the rat. Phytomedicine 2
Trovato A, Monforte MT, Forestieri AM, Pizzimenti F (2000) In vitro anti-mycotic activity of some medicinal plants containing flavonoids. Boll Chim Farm 139:225–227
Truchado P, Ferreres F, Tomas-Barberan FA (2009) Liquid chromatography-tandem mass spectrometry reveals the widespread occurrence of flavonoid glycosides in honey, and their potential as floral origin markers. J Chromatogr A 1216:7241–7248

Ulloa FV, García SS, Estrada MC, López DLP, Cruz MCR, García PS (2012) Interpretation methods of nutrient diagnosis in orange CV. Valencia (*Citrus sinensis* L. Osbeck) Terra Latinoam. 30:139–145

Upadhyay RK (2015) *Cleome viscosa* Linn: a natural source of pharmaceuticals and pesticides. Int J Green Pharm 9:71–85

Vaidyaratnam PSV (1994) Indian medicinal plants—a compendium of 500 species, vol II. Orient Longman Ltd., Madras, pp 116–118

Van-Hung P, Chi PT, Phi NT (2013) Comparison of antifungal activities of Vietnamese citrus essential oils. Nat Prod Res 27:506–508

Verma N, Singh AP, Gupta A, Sahu PK, Rao CV (2011) Anti diarrheal potential of standardized extract of *Rhododendron arboreum* Smith flowers in experimental animals. Indian J Pharmacol 43(6):689

Verma K, Kumar I, Thakur N (2020) Human A Complete Review on *Rhododendron arboretum:* phytochemistry pharmacological activities and future prospectives. IJPPR 19(3):161–176

Wang B, Lin L, Ni Q, Su CL (2011) Hippophae rhamnoides Linn. For treatment of diabetes mellitus: a review. J Med Plants Res 5:2599–2607

Wei S, Zhang H, Wang Y, Wang L, Li X, Wang Y, Zhang H, Xu X, Shi Y (2011) Ultrasonic nebulization extraction-heating gas flow transfer-headspace single drop microextraction of essential oil from pericarp of *Zanthoxylum* bungeanum Maxim. J Chromatogr A 1218(29):4599–4605

Williams JT, Haq N (2002) Global research on underutilized crops—an assessment of current activities and proposals for enhanced cooperation. International Centre for Underutilized Crops, Southampton. ISBN 92-9043-545-3

Williams LA, Vasques E, Reid W, Porter R, Kraus W (2003) Biological activities of an extract from *Cleome viscosa* L. (Capparaceae). Naturwissenschaften 90:468–472

Wu SC, Wu SH, Chau CF (2009) Improvement of the hypocholesterolemic activities of two common fruit fibers by micronization processing. J Agric Food Chem 57:5610–5614

Xiang L, Liu Y, Xie C, Li X, Yu Y, Ye M, Chen S (2016) The chemical and genetic characteristics of Szechuan pepper (*Zanthoxylum* bungeanum and Z. armatum) cultivars and their suitable habitat. Front Plant Sci 7:467

Yang XG (2008) Aroma constituents and alkylamides of red and green huajiao (*Zanthoxylum* bungeanum and *Zanthoxylum* schinifolium). J Agric Food Chem 56(5)

Yang B, Kallio H (2002) Composition, and physiological effects of sea buckthorn (Hippopha) lipids. Trends Food Sci Technol 160–167

Yilmaz HO, Nurcan Y, Meric CS (2020) Buckwheat: a useful food and its effects on human health. Curr Nutr Food Sci 16(1)

Yoon OK, Lee DS (2009) Mulberry paper bag μ-solid phase extraction for the analysis of five spice flavors by gas chromatography-mass spectrometry. Bull Korean Chem Soc 30:35–42

Zeng M, Wang J, Zhang M, Chen J, He Z, Qin F, Xu Z, Cao D, Chen J (2018) Inhibitory effects of Sichuan pepper (*Zanthoxylum* bungeanum) and sanshoamide extract on heterocyclic amine formation in grilled ground beef patties. Food Chem 239:111–118

Zhang Y, Luo Z, Wang D, He F, Li D (2014) Phytochemical profiles and antioxidant and antimicrobial activities of the leaves of *Zanthoxylum* bungeanum. Sci World J 181072

Zhang M, Wang J, Zhu L, Li T, Jiang W, Zhou J, Peng W, Wu C (2017) *Zanthoxylum* bungeanum Maxim. (Rutaceae): a systematic review of its traditional uses, botany, phytochemistry, pharmacology, pharmacokinetics, and toxicology. Int J Mol Sci 18(10):2172

Zhao ZF, Zhu RX, Zhong K, He Q, Luo AM, Gao H (2013) Characterization and comparison of the pungent components in commercial *Zanthoxylum* bungeanum oil and *Zanthoxylum* schinifolium oil. J Food Sci 78(10):C1516–C1522

Zhong K, Li X-J, Gou A-N, Huang Y-N, Gao Q, Bu H (2014) Antioxidant and cytoprotective activities of flavonoid glycosides-rich extract from the leaves of *Zanthoxylum* bungeanum. J Food Nutr Res 2(7):349–356

Zhu RX, Zhong K, Zeng WC, He XY, Gu XQ, Zhao ZF, Gao H (2011) Essential oil composition and antibacterial activity of *Zanthoxylum* bungeanum. Afr J Microbiol Res 5:4631–4637

Unlocking the Potential of Organic Farming: Balancing Health, Sustainability, and Affordability in India

Shruti Roy, Anuradha Singh, and Anupam Prakash

1 Introduction

Organic farming is gaining global recognition for its focus on sustainability, environmental responsibility, and human well-being. In India, it has emerged as a popular alternative to conventional agriculture, addressing the challenges posed by traditional farming methods. Understanding the health implications, sustainability aspects, economic viability, and policy frameworks associated with organic farming in India is crucial. This review aims to contribute to evidence-based decision-making, policy formulation, and the further advancement of organic farming practices within the country.

Organic farming is characterized by the use of natural inputs and techniques, avoiding synthetic pesticides and fertilizers (Fess et al. 2018). In India, where agriculture plays a vital role in the economy and the livelihoods of many, exploring the potential of organic farming is particularly significant. It emphasizes strategies like crop rotation, companion sowing, and the utilization of organic-based fertilizers, ensuring the avoidance of synthetic or chemical products in agriculture. The origins of organic farming can be traced back to the early twentieth century as a response to evolving farming methods (Šrůtek et al. 2008).

Certified organic agriculture covers over half of the world's 70 million hectares, with Australia having a significant share. The promotion of organic farming continues to be widespread, focusing on mixed cropping, insect predator development, and biological pest management. Organic standards aim to limit or regulate the use of synthetic compounds while promoting the use of naturally occurring

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substances. For example, synthetic fertilizers and pesticides are generally prohibited, while naturally occurring alternatives like pyrethrin and rotenone are allowed (Organic farming. 2017). Some synthetic compounds, such as ivermectin, copper sulphate, and elemental sulphur, are permitted. However, certain practices and substances, including nanotechnology, human sludge, plant development regulators, pheromones, and the use of antibiotics in cattle husbandry, are prohibited. Organic farming reflects advantages such as sustainability, openness, individuality, wellness, food security, and food safety.

The debate around the risks of intensive agricultural production, the industrialization of food, and food-related concerns has reignited interest in organic farming. This chapter aims to achieve the following objectives:

- Assess the current status of organic farming in India, including adoption rates, key crops, and the scope of operations.
- Examine the health benefits of organic farming, including the absence of pesticide residues, a comparison of nutritional value between organic and conventional crops, and the potential health advantages associated with consuming organic products.
- Evaluate the ecological impacts of organic farming practices, focusing on soil protection, water management, biodiversity preservation, and carbon sequestration.
- Analyse the affordability of organic food for various demographic groups, considering manufacturing costs, retail prices, and accessibility. Explore strategies to enhance affordability and availability.

This chapter intends to provide a comprehensive review of organic agriculture in India, highlighting its potential benefits and the challenges that need to be addressed. The outcomes can inform the development of data-driven policies and promote sustainable agricultural practices in India, striking a balance between affordability, sustainability, and health.

The subsequent sections will delve into the current context of organic farming in India, discuss initiatives and policies promoting it, identify challenges faced by organic farmers, and explore ways to integrate organic farming practices into Indian agriculture more effectively. This research holds immense significance for stakeholders such as policymakers, farmers, consumers, and the general public. It can lead to informed decision-making, contribute to food safety enhancements, create market opportunities for farmers, promote healthier food choices, encourage sustainable farming methods, support environmental conservation, and improve public health outcomes. Overall, by unlocking the potential of organic farming in India and finding the right equilibrium between health, sustainability, and affordability, this research can have a transformative impact on agriculture, public health, and the environment.

2 Overview of Organic Farming in India

In recent years, the organic food market in India has experienced significant growth. This can be attributed to various factors, including the rise in health consciousness among consumers. Many are now paying closer attention to the food they consume and feed their families. The concern for nutrition and quality of food is high, particularly in urban areas where healthier options are available. Economic growth and increased income levels have led to a rise in spending on health and wellness products. The Indian government's investment in organic farming has driven demand for certified organic products. Programs like the National Food Security Mission and National Mission for Sustainable Agriculture provide support to farmers adopting organic farming practices.

2.1 Evolution and Growth of Organic Farming in India

The organic farming industry in India has witnessed substantial growth due to traditional agricultural practices prioritizing sustainability. The development of organic farming in India has roots in cultural heritage and ancient techniques like Vrikshayurveda, emphasizing crop rotation and natural pest control (Singh et al. 2018).

Key figures such as Vinoba Bhave and religious groups contributed to the organic agriculture movement, promoting ecological farming practices (Nelliyat et al. 2007). The Indian government recognized the value of organic farming and implemented programs like the National Project on Organic Farming (NPOF) to provide financial aid and technical assistance to farmers transitioning to organic methods (Ministry of Agriculture and Farmers' Welfare n.d.) (Fig. 1).

Establishing organic certification standards was crucial for ensuring credibility and consumer confidence. The National Programme for Organic Production (NPOP) was established in 2001 by the Agricultural and Processed Food Products Export Development Authority (APEDA) to regulate organic farming and facilitate export opportunities (APEDA n.d., Table 1).

India's organic farming industry has experienced remarkable growth, with an increase in the number of organic farmers and certified land. This growth has

Fig. 1 Logo of NPOP India

Table 1 List of Macronutrients important for the growth of plant (*Source* Wander et al. 2009)

Element	Cationic	Anionic	Other
Nitrogen	$NH4^+$ (ammonium ions)	$NO_2{}^-$, $NO3^-$	Organic
Phosphorus	–	$HPO4^{-2}$, $H2PO^{3-}$, polyphosphates	Organic
Potassium	K^+	–	–
Calcium	Ca^{+2}	–	–
Magnesium	Mg^{+2}	–	–
Sulphur	–	$SO4^{-2}$, $S2^{-2}$	Organic

been driven by rising national and international demand for organic products and supportive government initiatives. In summary, organic farming in India has gained momentum due to traditional practices, influential figures, government programs like the NPOF, and the establishment of certification standards through the NPOP. The industry has witnessed significant growth in recent years, driven by increased consumer demand and government support.

Figure 2, based on data from APEDA, highlights the trends in organic crop production in India from 2018–19 to 2022–23 (APEDA n.d.). The analysis reveals moderate initial growth, a significant boost in 2020–21, and a slight decrease thereafter. Factors influencing these trends include market demand, government support, weather conditions, and farming practices.

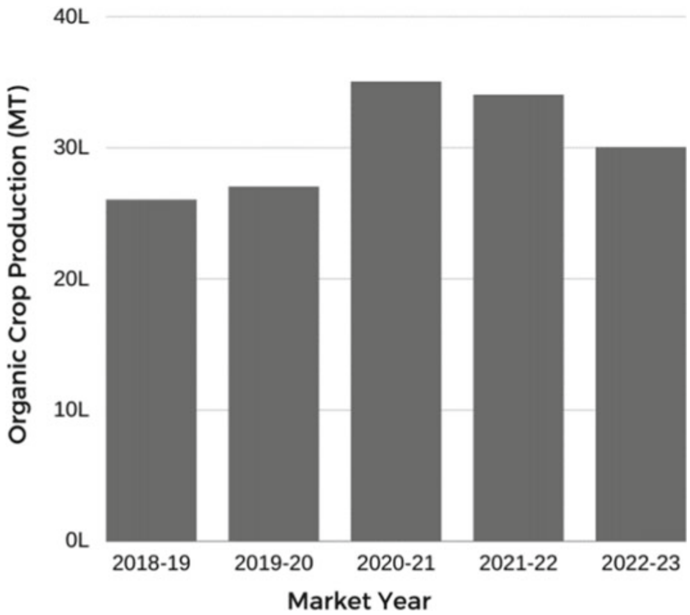

Fig. 2 Organic Crop Production (MT) from the Market Year 2018–2023; *Source* APEDA

India ranks fifth globally and first in Asia in terms of organic farming, with 23 lakh hectares of land dedicated to organic cultivation (FiBL 2021). The country has experienced a strong drive towards organic farming, adding approximately 3.6 lakh hectares of organic farming land. Increasing health consciousness has led to significant growth in the organic food industry, reaching a value of $849.5 million in 2020, up from $200 million in 2018 (IFOAM 2017). North India dominates the organic food market, and it is expected to grow at a compound annual growth rate (CAGR) of around 25% from 2022 to 2027.

2.2 Current State of Organic Farming Practices

Organic farming uses cultural practices and preventative measures to minimize external inputs. It involves techniques like crop rotation, soil management, pest and disease control, integrated weed management, and pasture-based livestock management. Soil health is improved through organic matter incorporation, composting, and cover crops, while pest control relies on integrated pest management and natural barriers. Weed suppression is achieved through mechanical cultivation, mulching, and hand weeding, reducing the need for synthetic herbicides. Crop rotation regulates nutrients, disrupts pest cycles, and improves soil health. Livestock management adheres to organic standards, limiting antibiotics and hormones. Overall, organic farming prioritizes sustainability, biodiversity, and reduces reliance on synthetic inputs.

3 Trends and Patterns in Organic Farming Adoption

India has seen significant growth in organic farming, with over 15 million hectares of agricultural land dedicated to organic production, making it the country with the highest percentage of organic farmers worldwide (Abdelgawwad et al. 2013). The adoption of organic farming has increased across different regions and crops, with states like Uttarakhand, Sikkim, Kerala, and Himachal Pradesh leading in organic farming practices (Roychowdhury et al. 2013). Organic cultivation extends to various crops such as rice, wheat, oilseeds, pulses, fruits, vegetables, and livestock. In recent years, India's embrace of organic agricultural methods has revealed some interesting trends (Fig. 3).

The implementation of organic farming in India is driven by several factors. Market demand, both domestically and globally, has encouraged farmers to embrace organic practices due to increased consumer awareness of the benefits, such as lower pesticide residues and higher nutritional value. Environmental concerns, including soil erosion, water pollution, and biodiversity loss associated with conventional

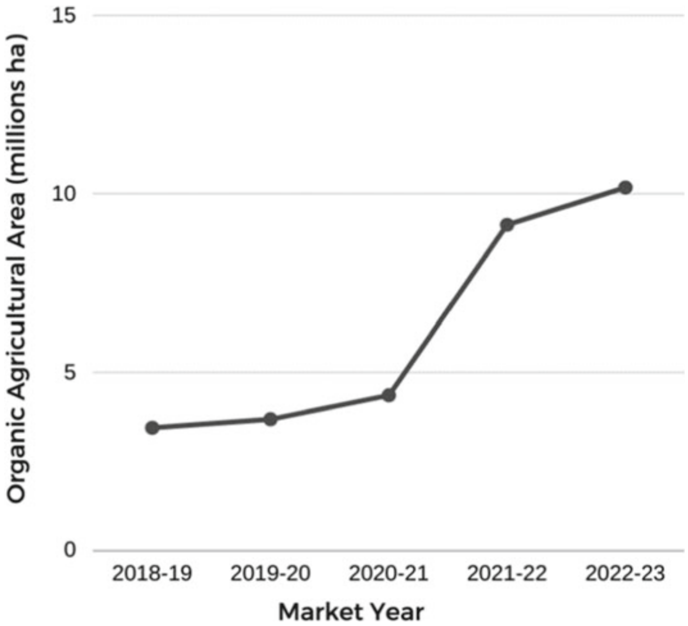

Fig. 3 Organic agricultural area (millions Ha) from the market year 2018 to 2023 (*Source* APEDA)

farming, have motivated farmers to adopt organic methods, aligning with their preference for sustainable practices and biodiversity preservation. Furthermore, government support through programs like the Rashtriya Krishi Vikas Yojana (RKVY), National Programme for Organic Production (NPOP), and state-level initiatives has played a crucial role in promoting organic farming among farmers (Ministry of Agriculture and Farmers' Welfare n.d.).

In summary, India has experienced significant growth in organic farming, with widespread adoption across regions and crops. Factors such as market demand, environmental concerns, and government support have contributed to the expansion of organic farming practices in the country.

4 Health Implications of Organic Farming

Organic farming is proven to be healthier for humans and the planet, offering nutrient-dense food without harmful residues (Beyond Pesticides n.d.). Pesticide use is regulated in organic farming, reducing human exposure to residues found in conventional food. Some pesticides in conventional farming have been linked to negative effects on children's cognitive growth. Creating sustainable food systems is a priority for intergovernmental groups, considering the long-term viability of agriculture. Various agricultural practices can impact human health, animal welfare, food security, and environmental sustainability.

5 Reduction of Pesticide Exposure and Health Benefits

Excessive use of pesticides and fertilizers in agriculture can lead to biodiversity degradation and pose risks to food safety (Dahiri et al. 2021). Fresh produce, such as fruits and vegetables, are particularly susceptible to pesticide residues, which are regulated by governments to protect consumer health. Pesticide residue testing plays a crucial role in assuring the safety of food items, as prolonged exposure to pesticide residues can be harmful to human health, potentially causing cancer and impacting various bodily systems (Indian Institute of Horticulture Research n.d.).

In contrast, organic farming relies on biological preventative measures and plant protection methods, such as crop rotation, intercropping, resistant varieties, and biological management, reducing the need for synthetic pesticides. While some pesticides are authorized for use in organic farming after thorough assessment, they generally pose minimal risks to consumers, either due to their low toxicity or limited potential for entering the food chain (Beck et al. 2014).

The terms "toxicity" and "risk" have distinct meanings when discussing pesticide safety (Fig. 4). Toxicity refers to a substance's intrinsic capacity for poison, assessed through laboratory tests, while risk is determined by the interaction between exposure and toxicity (Frank et al. 2011). The potential danger from a pesticide depends on its toxicological properties, volume of exposure, and mode of application (Damalas et al. 2016).

Consumer studies show that the desire to limit pesticide exposure is a significant motivation for people choosing organic foods (Raab et al. 2005). To minimize pesticide exposure, it is essential to transition towards agricultural systems that rely less on pesticides. This can be achieved by adopting ecological crop protection strategies based on current ecological knowledge. Sustainable pest, disease, and weed management systems should focus on prevention, decision-making, and control. Prevention

Fig. 4 Toxicity and exposure determines risk, *Source* Adapted from Damalas et al. (2016)

involves maximizing the use of biological processes, inhibiting harmful species, optimizing system diversity, and promoting the reuse of internal resources (Ratnadass et al. 2012).

6 Nutritional Value of Organic Produce

Organic food is widely perceived as a healthier option, offering higher nutritional value and reduced exposure to harmful chemicals compared to conventionally grown produce. Numerous studies have explored the nutritional composition of organic foods and have yielded varying results, highlighting the complexity of this subject.

When comparing organic and conventional crops, some studies suggest that organic produce may contain higher levels of certain vitamins and minerals. For instance, research has shown that organic fruits and vegetables can have greater concentrations of vitamin C, magnesium, iron, and antioxidants (Barański et al. 2014). These nutrients play crucial roles in supporting overall health and well-being.

Antioxidants, found abundantly in fruits and vegetables, help protect the body against oxidative stress and cellular damage. Some studies indicate that organic crops may exhibit higher antioxidant activity compared to conventionally grown counterparts. The presence of elevated levels of antioxidants, such as flavonoids and phenolic compounds, in organic produce could potentially contribute to a reduced risk of chronic diseases like cardiovascular ailments and certain cancers. Additionally, organic agricultural practices may influence the levels of secondary metabolites in crops. These compounds are responsible for the distinctive flavours, scents, and potential health benefits of plants. Organic farming methods, which avoid synthetic fertilizers and pesticides, have been associated with higher concentrations of certain secondary metabolites like phytochemicals and polyphenols. While further research is needed to fully understand the implications of these compounds on human health, they are believed to offer potential health advantages.

Furthermore, organic produce tends to have lower nitrate levels compared to conventionally grown crops. Nitrate, a naturally occurring compound, can be converted to harmful nitrites and nitrosamines, which have been linked to certain cancers. By choosing organic options, consumers may reduce their exposure to these potentially harmful substances.

It is important to note that the nutritional composition of organic foods can be influenced by various factors, including crop type, soil quality, and environmental conditions. Therefore, focusing on a diverse and balanced diet that includes a variety of fruits, vegetables, and whole foods, regardless of whether they are organic or conventionally grown, is key to optimal nutrition and overall health.

7 Impact on Consumer Health and Well-Being

Choosing organic vegetables reduces exposure to synthetic pesticides used in conventional farming. Research shows organic produce has lower pesticide residue levels. While organic farming doesn't eliminate all pesticides, it can help minimize potential health risks. Organic vegetables may contain higher nutrient concentrations, such as vitamin C and antioxidants (Barański et al. 2014). However, nutrient content can vary based on crop variety and farming methods. Organic farming may also reduce allergenic substances in food (Bourn et al. 2002). Consumers associate organic food with improved well-being and sustainability. It's important to consider overall dietary patterns for optimal health, incorporating a variety of foods and safe handling practices.

8 Sustainability in Organic Farming

The institutions responsible for establishing rules and policies for agriculture need to be improved. Sustainable agriculture is crucial for preserving ecosystems, ensuring the responsible use of resources, and achieving global food security. It should prioritize profitability, environmental health, social development, and economic progress. To transition to sustainable agriculture, significant progress is required in resource efficiency, environmental protection, and system resilience.

8.1 Environmental Benefits of Organic Farming

Organic farming promotes sustainability through ecological balance, resource conservation, and long-term profitability. It avoids synthetic chemicals and instead relies on biological processes to maintain soil fertility and crop health. Soil management in organic farming focuses on enhancing fertility through compost and organic matter, supporting soil organisms and nutrient cycling (Fig. 5). Preservation of biodiversity is prioritized through habitat conservation and crop rotations, benefiting natural pest control and ecological balance. Water conservation is achieved through reduced use of synthetic pesticides and fertilizers, along with practices like crop rotation and efficient irrigation. Organic farming also contributes to climate resilience by improving soil health, water management, and reducing greenhouse gas emissions associated with chemical inputs.

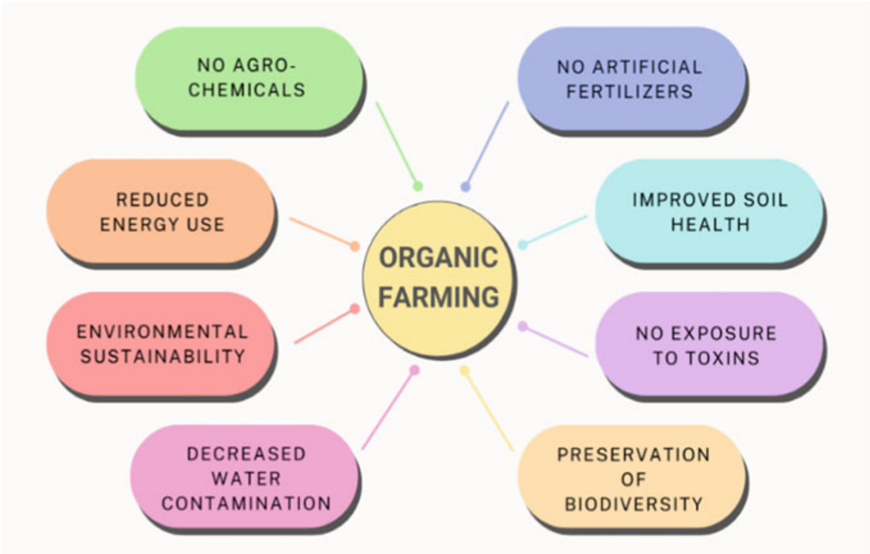

Fig. 5 Environmental benefits of organic farming

9 Conservation of Biodiversity and Ecosystem Services

Promoting biodiversity in agricultural systems is crucial for reducing biodiversity loss and maintaining ecosystem services. Agroecological management aims to balance biodiversity conservation and agricultural production, utilizing ecological processes to enhance ecosystem services. However, trade-offs between productivity and biodiversity conservation can hinder the widespread adoption of agroecological practices. Understanding factors that promote synergies and reduce trade-offs is essential for agricultural reform and biodiversity conservation.

Organic farming plays a significant role in biodiversity preservation by creating favourable habitats for a variety of organisms. It supports the preservation of beneficial insects, fauna, and wildlife through practices like crop rotation, intercropping, and habitat preservation. Organic farms have been found to have higher biodiversity compared to conventional farms. Organic farming also sustains and promotes pollinator populations by providing flowering vegetation, minimizing pesticide use, and reducing habitat loss. Organic farming facilitates natural pest management by preserving beneficial insects, birds, and other species that feed on crop pests. This reduces the need for chemical pesticides and contributes to a more stable and resilient ecosystem. Soil microbial populations are also prioritized in organic agriculture, as they play a vital role in nutrient cycling and disease control. Organic practices support diverse soil microbial communities, enhancing soil fertility and ecosystem function.

The preservation of biodiversity in organic farming leads to various ecosystem services such as soil fertility, water purification, pest management, and climate regulation. These services contribute to resilient ecosystems, sustainable agriculture, and human well-being. Organic farming exemplifies the potential of agricultural systems to promote biodiversity conservation and the provision of ecosystem services.

10 Soil Health and Organic Farming Practices

Organic farming focuses on promoting healthy soil through practices that enhance soil fertility and biological activity. Organic farmers prioritize the use of compost, cover crops, and crop residues to improve soil organic content, microbial activity, and nutrient retention. This results in higher levels of soil organic matter compared to conventional farming systems. Soil organic matter improves soil structure, nutrient availability, water-holding capacity, and overall soil health (Stockdale et al. 2001). Organic farming also relies on cover crops, mulching, and reduced tillage to maintain soil health and prevent erosion.

The soil biological community, which includes organisms like bacteria, fungi, earthworms, and insects, plays a crucial role in organic farming. Soil microorganisms contribute to nutrient cycling, organic matter decomposition, and plant growth promotion (Stockdale et al. 2001). Beneficial microorganisms help release nutrients for plants, while pathogenic microorganisms can harm crop health and yield. Organic farming practices support a diverse and balanced soil microbial community, contributing to soil fertility and ecosystem functioning. It also has positive environmental impacts. It contributes to greenhouse gas reduction by storing carbon in the soil. They minimize nitrogen losses, resulting in lower emissions of nitrous oxide, a potent greenhouse gas. Organic farmers prioritize nutrient management to ensure optimum plant nutrition, utilizing natural resources and nutrient-recycling techniques (Wander et al. 2009). Crop rotation is a key practice in organic farming, breaking disease and pest cycles, reducing weed growth, and improving soil health. By rotating crops, organic farmers enhance soil biodiversity, nutrient cycling, and pest management (Tables 1, 2 and 3).

To minimize soil disturbance, organic farmers adopt reduced tillage or conservation tillage practices. These practices promote soil structure preservation, organic matter decomposition, moisture retention, erosion control, and overall soil health. Reduced tillage in organic systems improves carbon sequestration and enhances soil physical qualities. Organic farming's focus on soil health and sustainable practices contributes to long-term productivity, environmental preservation, and the overall viability of agriculture.

Table 2 List of Micronutrients important for the growth of plant (*Source* Wander et al. 2009)

Element	Cationic	Anionic	Other
Iron	Fe, Fe^{+2}, Fe^{+2}	–	Organic-chelated
Manganese	Mn, Mn^{+2}	–	Organic-chelated
Copper	Cu, Cu^{+2}	–	Organic-chelated
Zinc	Zn, Zn^{+2}	–	Organic-chelated
Molybdenum	–	Mo, MoO4−	–
Boron	–	Bo, B(OH)4−, H3BO3	H3BO3
Chlorine	–	Cl-	–
Nickel	–	Ni, Ni^{+}	–

Table 3 List of Micronutrients important for the growth of animal depending on vegetation, *Source* Adapted from (Wander et al. 2009)

Element	Cationic	Anionic	Other
Cobalt	Co+2	–	-
Selenium	–	$SeO4^{-2}$, $SeO_3{}^{-2}$, Se^{-2}	Organic
Sodium	Na+	–	–
Silicon	–	SiO_2	–

11 Water Conservation and Organic Agriculture

Water resources and clean water security are crucial for global development. Organic farming practices contribute to water conservation and quality preservation. Organic farmers prioritize soil health, which directly affects water retention in agricultural soils. By maintaining organic matter levels, promoting soil aggregation, and minimizing soil compaction through reduced tillage, organic farming enhances soil water-holding capacity and reduces runoff. Organic farmers also select crop varieties that are drought-resistant and adapted to local climate conditions, improving water use efficiency and crop resilience. Water-saving techniques such as drip irrigation, mulching, and accurate watering are commonly employed in organic farming, further reducing water requirements and improving irrigation efficiency (Mäder et al. 2002). Additionally, organic farming reduces water pollution by minimizing the use of synthetic pesticides and chemical fertilizers, thereby protecting water quality and promoting the health of aquatic ecosystems.

12 Economic Viability and Affordability of Organic Farming

The rising demand for organic products has led to higher prices for organic vegetables. Organic farms face additional production costs, such as increased labour inputs and certification expenses, which are reflected in the price premiums. Despite the higher prices, consumers who value health, environmental sustainability, and quality are willing to pay for organic produce. These price premiums provide economic opportunities for organic farmers and help offset the higher production expenses associated with organic farming practices.

13 Cost Analysis of Organic Farming Methods

Analysing the economic feasibility of organic farming requires understanding the costs associated with organic practices. Organic inputs like fertilizers, pest control methods, and seeds may be more expensive than conventional alternatives. However, studies show that long-term savings on synthetic inputs can outweigh the initial expenses of organic farming (Röös et al. 2018).

Labor inputs are also higher in organic farming due to manual weeding and crop rotations, but efficient farm planning and labour-sharing arrangements can help minimize costs. Organic certification comes with fees, but it offers market access, pricing premiums, and consumer trust. Financial sustainability depends on market demand, prices, production costs, yields, and management effectiveness. Organic farms can be as profitable as, or even more profitable than, conventional farms in the long run. Cost-saving strategies include efficient resource use, proper crop planning, pest and disease control, and cooperative marketing. Investing in on-farm facilities can improve operational efficiency and reduce input costs.

14 Market Demand and Price Premiums

The demand for organic products is influenced by customer preferences for nutritious and sustainable options, concerns about environmental impact, and increasing awareness of food safety issues. Organic farming practices align with these ideals, leading to a rising demand for organic produce. Customers are willing to pay higher prices for organic products due to their perceived benefits and the premium placed on organic farming practices. Understanding market dynamics, such as supply and demand patterns, competition, and consumer preferences, is crucial for organic farmers to succeed. Building relationships with merchants, participating in farmers' markets, and engaging in consumer education campaigns can help organic farmer's access target customers and benefit from price premiums.

The distribution chain for organic products includes various levels, from government support and certification to production, packaging, and market representation. Market access is essential for organic producers, and working with organic farmer organizations, direct marketing campaigns, and joining community-supported agriculture (CSA) models can enhance market access and reduce marketing expenses.

15 Income Generation and Poverty Alleviation

Organic farming offers potential revenue generation opportunities for small-scale farmers and rural populations. By demanding price premiums for their products, organic farmers can increase their profits. Additionally, organic farming practices, such as diverse cropping systems and direct marketing avenues like farmer's markets and community-supported agriculture (CSA) models, can create additional income streams and enhance financial security for small-scale farmers. Organic farming's labour-intensive nature also generates job opportunities in rural areas, particularly in regions heavily reliant on agribusiness. Moreover, organic agriculture can strengthen the economic resilience of smallholder farmers by reducing production costs through a decreased reliance on expensive external inputs like chemical pesticides and fertilizers. By empowering small-scale farmers through training programs, technical assistance, and market access, organic farming can enhance the efficiency and sustainability of small-scale agriculture. This, in turn, contributes to poverty reduction by generating income, employment, and empowering marginalized groups, such as women, indigenous peoples, and smallholder farmers. The principles of organic farming, including environmental sustainability, biodiversity preservation, and social responsibility, align with the goals of equitable and inclusive development, supporting broader efforts to reduce poverty.

16 Access to Credit and Financial Support

Access to financial resources is crucial for organic farming as it enables farmers to cover initial investment costs, ongoing expenses, infrastructure development, and marketing efforts. However, organic farmers may face challenges in obtaining loans from traditional financial institutions due to a lack of understanding of organic farming's specific needs and associated risks. Additionally, smaller farmers and those in remote areas may have limited access to financial services. To address these issues, specialized financing programs for organic agriculture have been established, providing tailored credit packages, flexible repayment terms, and technical support. Cooperatives of organic farmers also facilitate resource sharing and collective bargaining, improving access to financing and financial services. Governments may offer grants and subsidies specifically targeted at organic farming, helping farmers with marketing strategies, organic practices, and certification fees. Socially responsible investors and impact investment funds are also recognizing the potential of organic farming to contribute to environmental and social goals and provide financial support accordingly. Enhancing financial literacy and providing training on managing the business aspects of organic farming are essential for organic producers to make informed financial decisions. Capacity-building programs that include financial strategy, cash flow management, and credit access training can equip organic farmers with the necessary skills to navigate the financial landscape successfully.

17 Policy Framework and Government Initiatives

Governments throughout the world, including India, have adopted extensive laws and programmes that encourage and promote organic agricultural practises in light of the importance of sustainable farming and the rising demand for organic products. In this part, we examine the Indian government's policies and programmes that have helped to promote the development of organic agriculture.

17.1 National and State-Level Policies Supporting Organic Farming

India has implemented regulations at the national and state levels to support and promote organic farming. The National Programme for Organic Production (NPOP) is a comprehensive regulatory framework that establishes standards for organic certification and labelling (Ministry of Agriculture and Farmers' Welfare n.d.). It accredits certifying agencies and facilitates the growth of organic agriculture. India also has a dedicated Organic Farming Policy that focuses on sustainable practices, organic inputs, and farmer engagement (MoAFW 2020). Additionally, various states like Sikkim, Himachal Pradesh, Madhya Pradesh, Kerala, and Karnataka have their own organic farming policies and programs in place to encourage organic farming (MoAFW 2020). These initiatives aim to create a systematic and disciplined environment for the organic food industry.

17.2 Government Schemes and Subsidies

The government of India has implemented several programs and incentives to promote organic farming and support farmers in this sector. The Paramparagat Krishi Vikas Yojana (PKVY) encourages small and marginal farmers to adopt organic farming practices through financial support, training, and accreditation (MoAFW 2020). The Rashtriya Krishi Vikas Yojana (RKVY) provides financial assistance to state governments to implement state-specific projects for promoting organic farming (MoAFW 2020). The National Horticulture Mission (NHM) supports horticultural development using organic farming methods through funding for inputs, training, and market linkages (MoAFW 2020). The National Bank for Agriculture and Rural Development (NABARD) offers subsidized loans and credit support for farmers practicing organic farming (NABARD Schemes n.d.).

Additionally, the government provides incentives such as assistance in setting up organic production and distribution facilities, crop insurance programs, discounted organic certification, and subsidies for organic inputs. The focus on research and development is evident through the establishment of organic farming research facilities and funding for cooperative projects. These initiatives aim to enhance capacity, improve infrastructure, and facilitate market access for organic farmers in India.

17.3 Regulatory Framework for Organic Certification

India has established a robust administrative framework for organic certification to ensure the credibility and integrity of organic farming practices. The National Programme for Organic Production (NPOP) has established organic standards to bring consistency and clarity to organic certification across the country (MoAFW n.d.). Accreditation organizations are responsible for accrediting certifying bodies, conducting inspections, and awarding organic certifications to producers and farmers (NABCB Organic Certification n.d.). The certification process involves multiple steps, including documentation review, site visits, sample collection and analysis, and verification of compliance with organic standards. Certification organizations assess farmers' adherence to organic practices such as the use of certified inputs, crop rotation, pest control, and record-keeping. Once certified, farmers and producers are authorized to use the organic mark on their products as proof of compliance (NCOF Organic Certification Process n.d.).

In India, various organizations and institutions are involved in the implementation and supervision of organic certification. The Agricultural and Processed Food Products Export Development Authority (APEDA) plays a key role in promoting organic agriculture and managing the national database of certified organic products (APEDA n.d.). The National Centre of Organic Farming (NCOF) and the National Accreditation Body for Certification Bodies (NABCB) provide accreditation, technical assistance, and training for organic certification. India's organic certification process is recognized by several foreign trade partners, including the US, Canada, EU, and Switzerland, through mutual recognition agreements on organic equivalence (Ministry of Commerce and Industry 2020). These agreements facilitate the export of Indian organic products to international markets by eliminating the need for additional certificates or inspections, as the organic standards and certification processes are considered comparable.

18 Challenges and Opportunities in Policy Implementation

In India, the penetration of organic products in the market has been slow, despite having the largest organic acreage. Several factors contribute to this:

- ***Partial consumer awareness***: Organic food is often associated with luxury and prestige rather than being seen as a standard choice. Limited knowledge about organic farming leads to consumers viewing it as a posh option, hindering sustainable market growth.
- ***Farmer education and support***: Many farmers hesitate to switch to organic farming due to concerns about lower yields and income loss. Extensive sensitization, education, and compensation for initial yield losses are necessary to encourage farmers to embrace organic practices.
- ***Governmental support***: The government plays a crucial role in supporting organic farming through subsidies, infrastructure development, and farmer education. Creating awareness about the benefits of organic agriculture and implementing support systems can enhance market expansion.
- ***Affordability of organic products***: Price-sensitive consumers in India often opt for cheaper alternatives, resulting in a smaller market for organic foods. Making organic products more affordable and price-competitive can increase their accessibility.
- ***Retail challenges***: Retailers prioritize fast-moving, inexpensive products over organic alternatives due to uncertainties in the market. Organic brands need to offer greater incentives to retailers for shelf space, which can increase the cost of organic products.
- ***Storage and shelf life***: Organic foods require specialized storage methods and have a shorter shelf life compared to conventional foods. This increases storage and preservation costs, posing challenges for organic farmers.
- ***Balancing supply and demand***: The supply of organic food products is not evenly distributed, leading to gaps between consumer demand and availability. Strengthening local production clusters and bridging supply gaps can create a more balanced organic market.

To further promote organic agriculture, certain measures can be taken:

- Enhancing extension services to provide technical assistance and knowledge-sharing to farmers adopting organic practices.
- Investing in research and development to address organic farming challenges and develop location-specific methods.
- Developing robust market links, infrastructure, and price discovery mechanisms for organic products.
- Strengthening quality assurance and certification processes to ensure the credibility of organic goods.
- Integrating organic farming policies across sectors and ministries to create a comprehensive approach.

These measures can improve policy implementation, increase market potential, and advance the growth of organic agriculture in India.

19 Challenges and Barriers in Scaling up Organic Farming

This section looks at the main difficulties and hindrances that organic farming encounters in India, from operational and technical issues to financial and market-related limitations. To successfully scale up organic agricultural practises, it is essential to recognise these obstacles and develop plans and regulations to address them.

19.1 Knowledge and Technical Capacity

The lack of knowledge and understanding of organic farming practices among farmers and stakeholders is a significant challenge. To address this, focused awareness initiatives, farmer training programs, and capacity-building efforts are needed to spread knowledge about organic farming practices, including soil fertility management, pest control, and post-harvest procedures.

Technical support and guidance are essential for the successful implementation of organic farming. However, there is a limited supply of agronomists, pest management specialists, and organic farming experts. Training programs and the development of qualified professionals can provide farmers with the necessary technical assistance to adopt and apply organic agricultural practices effectively. Research and development (R&D) play a crucial role in addressing technical challenges and knowledge gaps in organic farming. More research is needed on region-specific organic farming practices, natural pest control methods, and soil health enhancement. Collaborative research projects involving research organizations, educational institutions, and organic farmers can contribute to the development of technical knowledge and best practices in organic farming.

Promoting farmer-to-farmer information sharing networks can help bridge educational gaps in organic farming. Encouraging the creation of farmer-led organizations, organic farming groups, and community-based platforms can facilitate peer learning, information sharing, and the dissemination of best practices in organic agriculture. By sharing experiences and knowledge, farmers can become more technically literate and promote the adoption of organic farming methods.

19.2 Infrastructure and Logistics

To successfully adopt organic agricultural practices, farms need appropriate infrastructure for storage, processing, and irrigation. However, small and marginal farmers often face challenges in accessing such infrastructure, which can lead to post-harvest losses and lower market value for organic crops. Investing in farm-level infrastructure development and providing financial assistance or subsidies for storage and processing facilities can enhance the effectiveness and efficiency of organic farming practices.

Establishing reliable certification and traceability procedures is essential for ensuring the integrity and legitimacy of organic products. This requires infrastructure for certifying organizations, sample analysis facilities, and record-keeping systems to monitor the entire supply chain from farm to market. Improving certification and traceability infrastructure can increase consumer confidence, facilitate market access, and support the growth of organic farming.

Efficient market access and infrastructure development are crucial for the advancement of organic farming. This includes creating specialized organic markets, as well as establishing processing, packaging, and cold storage centres. Insufficient specialized markets and logistics support can result in longer supply chains, higher transaction costs, and limited access to premium markets. Reducing post-harvest losses, improving market connections, and establishing effective organic supply networks can enhance the financial viability of organic agriculture.

Capacity development and training are necessary for all stakeholders in the organic product supply chain, including farmers, transportation workers, processors, and retailers, to address logistical challenges. Training programs can cover proper storage and distribution of organic products, maintaining quality during handling and transportation, and understanding organic certification and labelling requirements. Enhancing the capabilities of logistics service providers and increasing awareness of the unique needs of organic products can strengthen the overall logistics system for organic farming.

20 Market Linkages and Access

Establishing effective market connections and gaining access to high-end markets remain significant challenges despite the increasing demand for organic goods. Lack of specialized distribution networks, storage and processing units, and infrastructure for value-added services hinder the efficient distribution system for organic products. To address this, establishing specialized organic trade routes, cold-storage centres, and processing units can streamline the gathering, storage, and production of organic products, increasing market connections and accessibility for customers.

Price differentials and market fluctuations pose challenges for farmers in the organic sector (Bisht et al. 2020). Strategic marketing activities, consumer education, and raising awareness about the benefits of organic products can boost consumer demand and create a more stable and dependable market for organic producers. Certification and quality assurance play a crucial role in building consumer trust and maintaining market access for organic food. Simplifying the certification process, reducing certification costs, and providing financial assistance or subsidies for organic accreditation can enhance farmer participation in organic marketplaces. Strengthening quality assurance systems, such as third-party authentication, residue evaluation, and compliance monitoring, can raise consumer confidence and improve market access for organic farmers.

Access to reliable and timely market information is essential for farmers to make informed decisions about production, pricing, and marketing strategies. Developing platforms for information exchange, farmer-centric market data systems, and market linkages between producers, aggregators, processors, and retailers can improve market transparency and empower farmers to make educated decisions.

Building strong value chains and market networks is crucial for linking organic farmers with customers and ensuring the efficient flow of organic goods. Contract farming, farmer-producer organizations, and partnerships can enhance interactions between stakeholders, facilitate direct market access, and reduce reliance on middlemen. Supporting the growth of inclusive value chains with both forward and backward linkages can help organic farmers capture a larger share of the value created in the supply chain.

21 Transitioning from Conventional to Organic Farming

Farmers transitioning to organic farming require education and training in organic farming concepts, certification criteria, pest and disease control, and soil fertility management. Training programs and information sharing platforms can aid in a smooth transition. Restoring soil health through natural techniques and adopting integrated pest management strategies are crucial during the switch. Farmers need support in understanding pests and diseases and implementing preventive measures.

Market dynamics change during the transition, requiring farmers to understand consumer preferences, market demands, and certification standards (MoAFW 2018). Collaborating with organic customers, forming farmer groups, and exploring contractual arrangements can facilitate market access. Financial assistance in the form of funding, low-interest loans, and grants can help farmers manage the costs associated with the transition. Evaluating economic sustainability and providing financial literacy programs are essential.

22 Success Stories and Best Practices

For the development and growth of sustainable agricultural practises, the success cases and best practises in organic farming offer insightful information and vital motivation. This section explores some well-known success stories and identifies the crucial elements that were crucial to their success. We may use their experiences to inform future attempts to promote and expand organic farming practises by comprehending these examples of achievement and best practises.

23 Case Studies of Successful Organic Farming Models

23.1 Sikkim

Sikkim, an Indian state in the northeast, has emerged as a pioneer in organic farming. By transitioning all agricultural practices to organic methods in 2016, Sikkim became the first fully organic state in India. The state's success can be attributed to strong political will, supportive legislation, and engaged farmers. Key initiatives included capacity-building programs, subsidized organic inputs, market linkages, and strict adherence to organic standards. Sikkim's organic farming model highlights the importance of government commitment, stakeholder participation, and a comprehensive policy framework (Kumar et al. 2018).

23.2 Maragoli Farmer Cooperative Society

The Maragoli Agricultural Cooperative Society in Karnataka demonstrates the benefits of collective effort and collaborative farming in organic agriculture. Comprised of marginal and small-scale farmers who have transitioned to organic methods, the cooperative has established an efficient supply chain for organic vegetables through resource pooling, knowledge sharing, and collective marketing. The cooperative focuses on market access, capacity building, farmer training, and quality assurance. The success of the Maragoli Farmer's Cooperative Society underscores the significance of cooperation, knowledge exchange, and group marketing strategies for small-scale organic producers (Kareemulla et al. 2017).

23.3 Dharmapuri Organic Farmers Association

The Dharmapuri Organic Farmers Association in Tamil Nadu is recognized for its innovation in organic farming, particularly in paddy cultivation. The association promotes the System of Rice Intensification (SRI), an organic rice cultivation technique that emphasizes water management, soil health, and natural pest control. Through farmer-to-farmer mentoring, training programs, and knowledge exchange, the association supports farmers in adopting SRI and organic farming methods. Farmers using SRI and organic practices report higher yields, lower production costs, and improved soil health. The accomplishments of the Dharmapuri Organic Farmers Association highlight the importance of farmer-led initiatives, context-specific approaches, and sustainable rice production techniques in organic farming (Rajendran et al. 2016).

23.4 Innovative Approaches and Lessons Learned

Zero Budget Natural Farming (ZBNF), pioneered by Subhash Palekar, is a regenerative approach that promotes natural farming techniques with minimal external inputs. It emphasizes the use of indigenous microorganisms, cow dung and urine, mulching, and intercropping to improve soil fertility, reduce costs, and enhance crop resilience. Valuable lessons from ZBNF include harnessing local resources, promoting soil health, and minimizing reliance on external inputs for sustainable agriculture (Sobhana et al. 2019).

Community-supported Agriculture (CSA) establishes direct connections between farmers and consumers. Consumers subscribe to a share of the farm's produce, providing upfront support to farmers and receiving regular supplies of fresh, organic food. CSA fosters transparency, trust, and shared risks and rewards. Lessons from CSA include building direct links between farmers and consumers, engaging the community, and creating a reliable market for farmers (Woods et al. 2017). Permaculture integrates ecological principles and sustainable farming practices to create self-sustaining systems. It employs techniques such as companion planting, agroforestry, water harvesting, and soil conservation. Valuable lessons from permaculture include designing resilient farming systems, optimizing resource utilization, and enhancing ecosystem services for sustainable agriculture (Mollison et al. 1991).

24 Replicability and Scalability of Best Practices

Replicability and scalability of successful organic farming models depend on knowledge exchange among farmers, adapting practices to local contexts, strong policy support, and collaboration between stakeholders. Sharing successful practices through farmer field schools, demonstration plots, and community-based training programs promotes peer learning and capacity building.

Adapting best practices to local agro-climatic conditions and resources increases their likelihood of success and wider adoption. Flexibility and tailoring strategies to specific contexts enhance replicability. Supportive policies, including incentives, subsidies, and technical assistance, encourage farmers to replicate successful practices on a larger scale. Dedicated institutions like agricultural extension services and research organizations provide guidance and resources. Collaboration and partnerships between stakeholders, including public–private partnerships, leverage collective strengths to facilitate knowledge transfer, resource mobilization, and market access. These collaborations bridge gaps in knowledge, technology, and market opportunities, supporting the replicability and scalability of best practices.

25 Future Directions and Recommendations

As the organic farming sector in India progresses, it is crucial to envision future directions and offer recommendations for its continual advancement and improvement. This section highlights potential areas of expansion, emerging trends, and essential suggestions to ensure the sustainable and successful growth of organic agriculture in the years ahead. By identifying opportunities and addressing challenges, we can shape the future trajectory of organic farming in India, fostering a resilient and environmentally conscious agricultural system.

26 Research and Innovation in Organic Farming

Research and innovation are vital for advancing organic farming in India. Research on soil health and nutrient management can improve fertility and nutrient availability through biofertilizers, vermicomposting, and green manuring. Effective pest and disease management can be achieved through research on biological control, biopesticides, and ecological pest management approaches. Agroecology and crop diversification research can promote resilient and sustainable farming systems by exploring biodiversity, ecological intensification, and diverse cropping strategies (Sullivan et al. 2003). Integrating technology and digital solutions, such as precision agriculture and online platforms, can streamline operations and facilitate knowledge dissemination. Research efforts should focus on developing context-specific technologies to empower farmers and enhance the efficiency of organic farming practices.

27 Strengthening Extension Services and Knowledge Dissemination

Strengthening the capacity of extension workers through training programs, continuous professional development initiatives, and knowledge-sharing platforms is crucial to effectively support organic farmers. Utilizing innovative communication channels, including digital platforms, radio, and television, enhances the dissemination of organic farming knowledge to a wide range of farmers. Promoting farmer-to-farmer knowledge exchange through farmer field schools, study circles, and local farmer groups facilitates peer learning and sharing of best practices. Encouraging participatory research and on-farm trials involving farmers, researchers, and extension workers allows for collaborative learning and the co-creation of knowledge tailored to organic farming contexts. By empowering extension workers and facilitating knowledge exchange, we can accelerate the adoption and success of organic farming practices.

28 Enhancing Market Infrastructure and Linkages

Consumer education and awareness campaigns are essential for increasing demand for organic products. Promoting the benefits of organic farming, highlighting the environmental and health advantages, and raising awareness about organic certification and labelling can enhance consumer trust and willingness to choose organic products (MoEFCC 2018). Education initiatives can include workshops, community outreach programs, and consumer guides that provide information on organic farming practices and the importance of supporting organic agriculture.

Leveraging technology and digital platforms can expand market reach and facilitate direct connections between organic farmers and consumers. Online marketplaces, e-commerce platforms, and social media channels enable farmers to showcase their products, reach a wider consumer base, and engage in direct marketing. Utilizing digital tools for traceability and transparency, such as blockchain technology, can enhance product integrity and build consumer confidence in organic products (Hamzaoui et al. 2012).

Promoting regional and international trade of organic products can provide new market opportunities for organic farmers. Participating in organic trade fairs, exhibitions, and networking events allows farmers to connect with potential buyers, distributors, and importers. Developing organic export strategies, complying with international organic standards, and establishing partnerships with certification bodies can facilitate access to global markets and improve the competitiveness of Indian organic products. In summary, developing market infrastructure, conducting market research, fostering market linkages, implementing supportive policies, promoting consumer education, leveraging technology, and exploring regional and international trade opportunities are key strategies to strengthen the organic farming sector and ensure its long-term sustainability and growth.

29 Policy Recommendations for Promoting Organic Farming

Implementing strict regulations and standards for organic certification is crucial for maintaining the integrity of organic farming and instilling consumer confidence. Governments should establish robust certification bodies and accreditation processes to ensure that organic products meet the required standards (Barik et al. 2017). Regular inspections, testing, and verification should be conducted to prevent fraud and maintain the authenticity of organic products. Additionally, promoting transparency in the certification process and providing clear labelling guidelines can help consumers make informed choices and support organic farmers. Collaboration between different stakeholders, including farmers, policymakers, researchers, and consumer organizations, is essential for the growth and development of the organic farming sector. Creating platforms for dialogue and engagement, such as organic farming associations, industry networks, and stakeholder forums, can facilitate knowledge exchange, address challenges, and foster collective decision-making. Engaging farmers in policy development processes and incorporating their perspectives and experiences can lead to more effective and farmer-centric policies for organic farming. Finally, raising awareness and promoting the benefits of organic farming among consumers and the general public is crucial. Governments can invest in public awareness campaigns, educational programs, and promotional activities to highlight the advantages of organic products for human health, the environment, and sustainable agriculture. Encouraging partnerships between organic farmers and local communities, schools, and restaurants can create direct connections and build trust, further boosting demand for organic products. In conclusion, providing incentives and financial support, investing in research and development, building capacity, creating a supportive market environment, ensuring strict certification standards, fostering collaboration, and raising awareness among consumers are all key strategies for policymakers to promote and strengthen the organic farming sector. By implementing a comprehensive and holistic approach, governments can foster the transition to organic farming, support farmers, and contribute to sustainable and resilient food systems.

30 Conclusion

In summary, the chapter has provided a thorough investigation of the advantages and obstacles linked with organic farming techniques in India. Within the confines of this chapter, we have deeply examined the intricate aspects of organic farming, underscoring its capacity to transform the agricultural vista while simultaneously tackling significant issues relating to well-being, durability, and economic feasibility. In addition, the cultivation of organic crops promotes biodiversity, resulting in healthier ecosystems and increased resistance to pests and diseases. The adoption of organic practices by farmers offers the opportunity to curtail their dependence on synthetic inputs, mitigate environmental harm, and preserve crucial natural resources. Furthermore, the cultivation of organic crops facilitates biodiversity, resulting in healthier ecosystems and heightened resistance to pests and diseases. The chapter has emphasized the crucial significance of organic farming in augmenting human health and overall welfare. By eradicating the employment of detrimental pesticides and chemicals, organic crops provide consumers with a more secure and wholesome range of food alternatives. Researches have demonstrated that organic fruits, vegetables, and grains consist of elevated amounts of vital nutrients and reduced quantities of harmful residues, rendering them an astute preference for individuals who are health-conscious. Moreover, the social and economic facets of organic agriculture have been duly considered, recognizing its capability to empower small-scale farmers and foster inclusivity in the agricultural industry. Although the adoption of organic farming techniques may pose difficulties, especially for farmers lacking in resources, this chapter has identified several approaches and support mechanisms that can facilitate this transition and promote the accessibility of organic inputs.

As such, the achievement of organic farming's complete potential in India necessitates a combined exertion from all stakeholders, including policymakers, farmers, consumers, and the private sector. Critical strides in cultivating its growth include the implementation of policies that both incentivize and support organic agriculture, funding research and development to enhance organic farming techniques, and increasing consumer awareness of the advantages of organic produce.

Further investigation is necessary to assess the enduring impacts of organic farming, encompassing its implications on soil health, preservation of biodiversity, and provision of ecosystem services. Comparative analyses of productivity and crop yield in organic farming systems can aid in the identification of optimal techniques for maximizing productivity while ensuring sustainability. Research on the contribution of organic farming to resilience against climate change is imperative, including its efficacy in carbon sequestration, water management, and adaptation strategies. Detailed economic evaluations and market studies are essential to appraise the economic feasibility and profitability of organic farming. An understanding of the perception and behaviour of consumers towards organic products can help in the formulation of marketing strategies and targeted awareness campaigns. The exploration of technological innovations relevant to organic farming, such as precision agriculture and alternative pest management approaches, can augment efficiency and sustainability. Addressing these research gaps will lead to a more comprehensive comprehension of organic farming and enable its further development in India.

References

Abdelgawwad M (2013). Status, trends and prospects of organic farming in India. Rev J Plant Biol Res 2

Agricultural and Processed Food Products Export Development Authority (APEDA) (n.d.) National program for organic production

Barański M, Srednicka-Tober D, Volakakis N, Seal C, Sanderson R, Stewart GB, Benbrook C, Biavati B, Markellou E, Giotis C, Gromadzka-Ostrowska J, Rembiałkowska E, Skwarło-Sońta K, Tahvonen R, Janovská D, Niggli U, Nicot P, Leifert C (2014) Higher antioxidant and lower cadmium concentrations and lower incidence of pesticide residues in organically grown crops: a systematic literature review and meta-analyses. Brit J Nutr 112(5):794–811

Barik A, Sarkar N (2017) Organic farming in India: present status, challenges and technological break-through

Beck A, Alexander C, Eduardo H, Anna Maria K, Koopman J, Michelon C, Moeskop B, Niggl U, Rasmussen IA (2014) Strategic research and innovation agenda for organic food and farming. Belgium

Bisht I, Singh JC, Pradhan M, Singh N (2020) The future of smallholder farming in India: some sustainability considerations. Sustain 12(9):3751

Bourn D, Prescott J (2002) A comparison of the nutritional value, sensory qualities, and food safety of organically and conventionally produced foods. Crit Rev Food Sci Nutr 42(1):1–34

Dahiri B, Martín-Reina J, Carbonero-Aguilar P, Aguilera-Velázquez JR, Bautista J, Moreno I (2021) Impact of pesticide exposure among rural and urban female population. An overview. Intern J Environ Res Pub Healt 18(18):9907

Damalas CA, Koutroubas SD (2016) Farmers' exposure to pesticides: toxicity types and ways of prevention. Toxics 4(1):1

Wander M, Andrews N, McQueen J (2009) Organic soil fertility. eOrganic

Fess TL, Benedito VA (2018) Organic versus conventional cropping sustainability: a comparative system analysis. Sustain 10:272

Frank P, Ottoboni MA (2011) The dose makes the poison: a plain-language guide to toxicology, 3rd ed. John Wiley and Sons Inc

Hamzaoui-Essoussi L, Zahaf M (2012) The organic food market: opportunities and challenges

Indian Institute of Horticulture Research, Department of Agricultural Research and Education, Ministry of Agriculture & Farmers Welfare, Government of India (n.d.) Pesticide residue analysis

International Federation of Organic Agriculture Movements (2017) India Organic—India's growth story. In: Proceedings of the 19th organic world congress, pp 3–11

Kareemulla KR, Dr V, Samuel M (2017) An analysis on agricultural sustainability in India. Curr Sci 112:258

Kumar J, Pradhan M (2018) Sustainable organic farming in Sikkim: an inclusive perspective

Leigh A, Ransom B, Coley M (2017) Organic farming. In what is sustainable agriculture? UC Division of Agriculture and Natural Resources

Mäder P, Fliessbach A, Dubois D, Gunst L, Fried P, Niggli U (2002) Soil fertility and biodiversity in organic farming. Sci 296:1694–1697

Ministry of Agriculture and Farmers Welfare, Regional Centre of Organic Farming (2018) Transition from conventional farming to organic farming. https://www.jaivikkheti.in/DMS/TRANSAITION_FROM_CONV_TO_ORGANIC_FARMING.pdf. Accessed on 15 March 2023

Ministry of Agriculture and Farmers Welfare (2020) National Horticulture Mission (NHM). https://www.midh.gov.in/. Accessed on 15 March 2023

Ministry of Agriculture and Farmers Welfare (2020) Organic farming policy. https://agricoop.nic.in/sites/default/files/Web%20copy%20of%20AR%20%28Eng%29_7.pdf. Accessed on 15 March 2023

Ministry of Agriculture and Farmers Welfare (2020) Paramparagat Krishi Vikas Yojana (PKVY). https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1739994. Accessed on 15 March 2023

Ministry of Agriculture and Farmers Welfare (2020) Rashtriya Krishi Vikas Yojana (RKVY). https://agricoop.gov.in/en/RashtriyaDiv. Accessed on 15 March 2023

Ministry of Agriculture and Farmers Welfare (2020) Sikkim organic mission. https://sikkim.gov.in/Mission/Mission-info/1?Mission=Sikkim%20Organic%20Mission. Accessed on 15 March 2023

Ministry of Commerce and Industry (2020) Bilateral trade agreements. https://commerce.gov.in/international-trade/trade-agreements/. Accessed on 15 March 2023

Ministry of Agriculture and Farmers' Welfare (n.d.) National Program for Organic Production (NPOP). https://ncof.dacnet.nic.in/ThirdPartyCertification-NPOP. Accessed on 15 March 2023

MoEFCC (Ministry of Environment, Forest and Climate Change) (2018) Guidelines for organic farming. https://moef.gov.in/wp-content/uploads/2020/01/final-version-and-printed-wetland-guidelines-rules-2017-03.01.20.pdf. Accessed on 15 March 2023

Mollison B, Slay RM, Girard JL (1991) Introduction to permaculture
National Accreditation Board for Certification Bodies (NABCB) (n.d.) Organic certification. https://nabcb.qci.org.in/. Accessed on 16 March 2023
National Bank for Agriculture and Rural Development (NABARD) (n.d.) Schemes. https://www.nabard.org/#:~:text=NABARD%20has%20taken%20an%20initiative,corpus%20of%20Rs.%2050%20crore. Accessed on 16 March 2023
National Centre of Organic Farming (NCOF) (n.d.) Organic certification process. https://ncof.dacnet.nic.in/. Accessed on 16 March 2023
Nelliyat P, Shrivastava P (2007) Greening rural development in India: a case for organic farming. Dev Prac 17(2):183–196
Organic Farming (2017) What is sustainable agriculture? Web source. https://sarep.ucdavis.edu/sustainable-ag/organic-farming. Accessed on 01 March 2023
Beyond Pesticides (n.d.) Health benefits of organic agriculture. https://www.beyondpesticides.org/programs/organic-agriculture/why-organic/health-benefits. Accessed on 16 March 2023
Raab C, Grobe D (2005) Consumer knowledge and perceptions about organic food. J Exten 43
Rajendran T (2016) Impact of system of rice intensification [SRI] technology in Tamil Nadu. Int J Adv Multidiscipl Res 3(12):1–5
Ratnadass A, Fernandes P, Avelino J, Habib R (2012) Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agron Sustain Dev 32:273–303
Röös E, Mie A, Wivstad M et al (2018) Risks and opportunities of increasing yields in organic farming: a review. Agron Sustain Dev 38(1):14
Roychowdhury R, Abdelgawwad M, Banerjee U, Bishnu S, Tah J (2013) Status, trends and prospects of organic farming in India: a review. J Plant Biol Res 2:38–48
Singh RP, Singh YV (2018) Traditional Indian organic farming wisdom: current relevance. Ind J Tradit Knowl 17(4):597–604
Sobhana E, Swaminathan C, Swaminathan V, Pandian K, Sankarapandian S (2019) Zero budget natural farming
Šrůtek M, Urban J (2008) Organic farming. In: Jørgensen SE, Fath BD (eds) Encyclopedia of ecology. Academic Press, pp 2582–2587
Stockdale E, Lampkin N, Hovi M, Keatinge R, Lennartsson M, Macdonald D, Padel S, Tattersall F, Wolfe MS, Watson C (2001) Agronomic and environmental implications of organic farming systems. Adv Agron 70. https://doi.org/10.1016/S0065-2113(01)70007-7
Sullivan P, Williams P, Hardy G (2003) Intercropping principles and production practices
IFOAM (2021) The world of organic agriculture: statistics and emerging trends 2021. In: Willer H, Trávníček J, Meier C, Schlatter B (eds) The research institute of organic agriculture FiBL. International federation of organic agriculture movements
Woods T, Tropp D (2017) Community supported agriculture: new models for changing markets. https://ideas.repec.org/p/ags/uamsrr/316239.html. Accessed on 16 March 2023

Polyphenolic Compounds from Diet: Potential Role in Regulation of Gut Microbiota and Effects on Human Body

Sadhana Jadaun, Usha Sharma, Ringshangphi Khapudang, and Saleem Siddiqui

1 . Introduction

Polyphenols are a diverse and large group of naturally occurring compounds occurring in a wide range of plant-based foods. They are involved in plants natural defence mechanisms against harmful microorganisms, insects, and UV radiation. Over the past few decades, there has been an enormous amount of research conducted due to their potential health benefits for humans. They possess powerful antioxidant activity, which provides protection against oxidative damage by free radicals. They also exhibit anti-inflammatory, antimicrobial, anticancer, and neurogenerative properties that are beneficial for disease prevention and treatment. Polyphenols in plants predominantly exist in their glycosylated forms, however, other modifications, such as esterification or polymerization are often observed. The bioavailability of polyphenols from the diet is quite low as compared to other nutrients because the polyphenols are often identified as xenobiotics after consumption (Das et al. 2023). In the small intestine, only a minor fraction of polyphenols (5–10%) is absorbed and enters the bloodstream, while remaining majority of unabsorbed dietary polyphenols (90–95%) are sent to the large intestine (Ma and Chen 2020), where they interact with gut microbiota and are metabolised as depicted in Fig. 1. These polyphenols considerably modify the abundance of gut bacteria, showing significant effects on human health. By supporting the growth of beneficial microbes, a balanced gut microbiota is maintained, leading to better nutrient absorption and consequently better overall well-being. Contrarily, dietary polyphenols inhibit the growth of pathogens that have

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defence mechanisms, lowering the risk of infections and disorders associated with the gut. Simultaneously, gut microbiota (GM) plays a significant role in enhancing polyphenol bioavailability by reducing them into smaller, more readily absorbable molecules that may be taken up by the cells lining the gut wall for absorption (Samsøe et al. 2019). GM not only affects the metabolism and bioactivity of polyphenols but also strengthens the immune system (Drozd et al. 2021). The complicated relationship between diet, gut flora, and human health is highlighted by this two-way interaction among dietary polyphenols and gut microbiota. As a result of their interaction, short-chain fatty acids (SCFAs), such as acetic, propionic, and butyric are produced, which provide energy to the cells lining the colon and sustain their healthy function (Catalkaya et al. 2020). These bacteria also stimulate mucus secretion in the intestines, creating a physical barrier against pathogens and indirectly lowering blood cholesterol levels. They also support a healthy immunological response by lowering the risk of inflammatory disorders in the gut. These bacteria possess various enzymes to carry out phenolic metabolism via catabolic pathways. The catabolic processes involved in polyphenol metabolism vary based on the structure of polyphenols and bacterial species. The host health benefits resulting from the production of bioactive polyphenol-derived metabolites and the compositional modulation of gut microbiota are likely to be influenced by both the processes, although the underlying mechanism have not been fully elucidated yet. The beneficial effects on host health arising from the formation of bioactive metabolites derived from polyphenols and the regulation of the colonic microbiota are probably influenced by both of these processes. However, the precise mechanisms underlying these impacts, nevertheless, are still not fully known. The fundamental objective of this chapter is to provide an in-depth description of impact of dietary polyphenols on human health, regulation of gut microbiota, and their interactions associated with health benefits.

2 Polyphenolic Compounds: An Overview

Polyphenols are a large group of secondary metabolites that are characterised by the presence of multiple phenol rings. On the basis of their biological function, chemical structure, origin, and source, they have been categorised into four distinct groups: phenolic acids, flavonoids, stilbenes, and lignans (Fig. 2) (Cvitanović et al. 2018). Phenolic acids are widely distributed nonflavonoid compounds and constitute one-third of the polyphenolic compounds in our diet. They possess remarkable antioxidant properties and are present in all plant materials, but most abundantly in acidic fruits. They are further classified into two groups, i.e., benzoic acid derivatives (e.g., gallic acid, Protocatechuic acid, Vanillic acid) and cinnamic acid derivatives (e.g., ferulic acid, caffeic acid, *p*-coumaric and sinapic acids), and consist of a phenolic ring with attached a carboxylic acid group (Kumar et al. 2019). Generally, the benzoic acid content of most edible plants is relatively low. However, there are certain exceptions where specific plants or parts of plants possess good concentrations of hydroxybenzoic acids, particularly in the case of certain red fruits, black

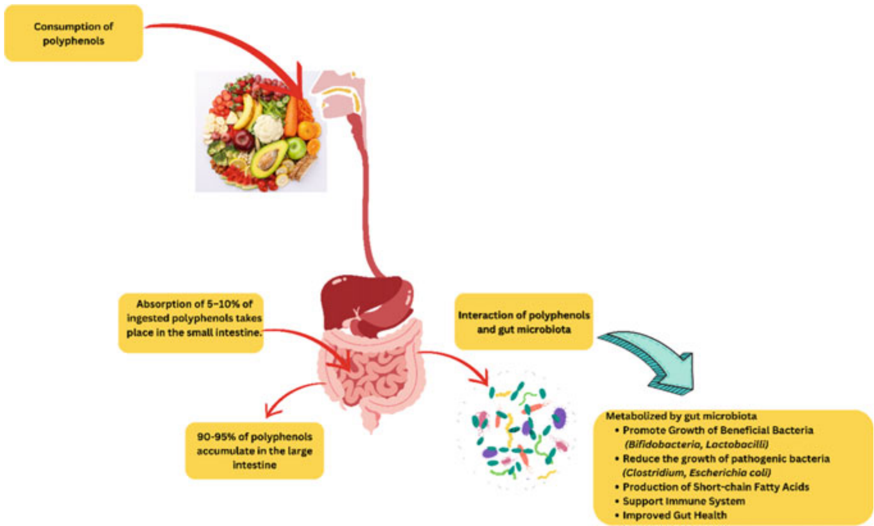

Fig. 1 Interaction of polyphenols and gut health

radish, and onions (Beslo et al. 2022). Cinnamic acid derivatives are more common in nature compared to benzoic acid. They are present in cinnamon, fruits, vegetables, tea, cocoa, and honey. They exist in two isomeric forms: cis and trans, but in plants, trans isomers are generally more abundant and stable. Flavonoids, the largest and most studied subclass, are further divided into flavan-3-ols, flavones, anthocyanidins, flavanones, flavonols, and isoflavones based on the different types of heterocycles present in their chemical structure (Ramesh et al. 2021). The flavonoids content present in fruits and vegetables can be affected by several factors, such as genetic traits, agro-environmental circumstances, ripening phases, and post-harvest situations. The high bioactivity of flavonoids is often limited by their low bioavailability. Flavanols, or flavan-3-ols (catechins), are prominently present in tea, cocoa, chocolate, grapes, berries, apples, lotus root, and red wine. Flavones, an important subgroup of flavonoids, include luteolin, apigenin, and tangeretin, which are commonly found as glucosides in the leaves, flowers, and fruits of various plants. The principal dietary sources of flavones include celery, red peppers, thyme, mint, green olives, parsley, chamomile and ginkgo biloba. Anthocyanidins are a class of water-soluble pigments that mainly exist in their glycosidic form (Khoo et al. 2017) and are abundantly found in cranberries, black currants, strawberries, blueberries, cherries, bilberries, grapes, raspberries, blackberries, and purple cabbage. Flavanones (e.g., hesperetin, naringenin, eriodictyol, and apigenin) are primarily found in citrus fruits, such as oranges, lemons, grapefruits, and tangerines. Flavanones are responsible for the bitter taste of citrus fruits and contribute to their characteristic aroma. Kaempferol, quercetin, and myricetin are the most studied flavonols, which are found in onions, kale, lettuce, asparagus, tomatoes, apples, grapes, berries, red wine, and tea. Isoflavones occur mainly in legumes and soybeans. Some common isoflavones

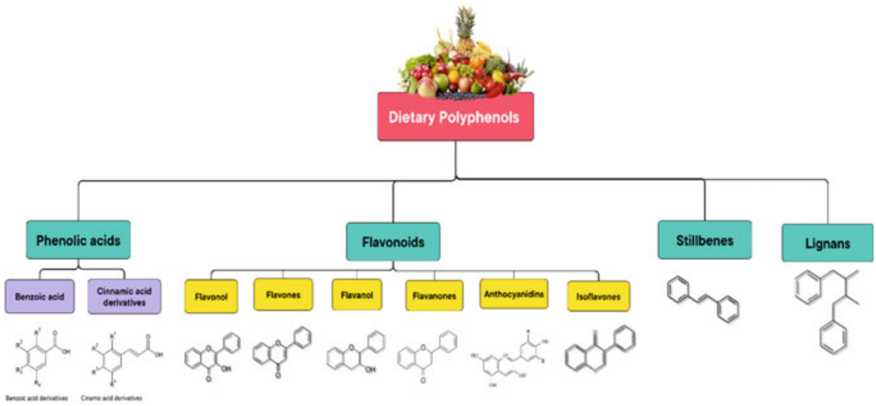

Fig. 2 Classification of dietary polyphenols

include genistein, daidzein, and glycitein. Stillbenes are found in very low amounts in the human diet and are produced by plants as a defence mechanism in response to pathogens and environmental issues (Pandey and Rizvi 2009). The most well-known stilbene is resveratrol, which is mostly found in grapes, red wines, and some berries. Lignans are mainly found in linseeds, which predominantly contain secoisolariciresinol (Kezimana et al. 2018). It occurs in a lower amount in oats, rye, wheat, barley, strawberries, apricots, and broccoli.

3 Beneficial Effects of Polyphenols on Human Health

3.1 Antioxidant Property of Dietary Polyphenols

In recent years, antioxidant property of dietary polyphenols has garnered considerable attention due to its significant implications on human health. They impart the ability to scavenge free radicals, stimulate endogenous antioxidant defense systems, and exert numerous other protective effects against oxidative stress-related diseases. By donating hydrogen atoms from the OH group to unstable free radicals, polyphenols break the chain reaction of oxidation. Under certain conditions, the highly reactive OH group in flavonoids carry out direct oxidation of free radicals leading to generation of radical with enhanced stability and minimized reactivity. Certain flavonoids have the ability to directly eliminate superoxides, others specifically target a peroxynitrite, a highly reactive short-lived oxygen-derived radical (Hanasaki et al. 1994). Through this distinct mechanism, flavonoids may effectively hinder the oxidation of low-density lipoprotein (LDL) and consequently reduction of risk of developing atherosclerosis.

Polyphenols present in the plasma membrane can interact with nonpolar compounds located in the inner layer of the membrane. These interactions have the potential to reduce the oxidation stress of proteins and lipids. Certain flavonoids located within the hydrophobic core of the membrane exhibit the ability to hinder the entry of oxidants and thus protecting the integrity of membrane. In order to scavenge reactive oxygen species, plants have developed efficient antioxidant defense mechanism by utilizing enzymatic components like catalase, glutathione reductase, ascorbate peroxidase, superoxide dismutase, guaiacol peroxidase, dehydroascorbate reductase and monodehydroascorbate reductase, and non-enzymatic systems such as ascorbic acid, α-tocopherol, glutathione, flavonoids, carotenoids and proline (Das and Choudhary 2014). Tea polyphenols can increase the levels of antioxidants enzymes like catalase, glutathione peroxidase, and superoxide dismutase which helps to protect against oxidative stress. Along with this, they decrease the production of malondialdehyde indicating their ability to regulate oxidoreductase system (Ahmed et al. 2016). In a study by Zhang et al. (2020), tea polyphenols showed positive effect in reducing inflammation, oxidative stress, improving the expression of tight proteins, and recovering intestinal flora disturbance caused by *Salmonella typhimurium* infection.

3.2 Antibacterial Property

Polyphenols have been reported to exhibit the antibacterial activity against pathogenic bacteria through various mechanism such as cell membrane destruction, induction of oxidative stress and inhibition of biofilm formation and enzymatic activities. Polyphenols disrupt bacterial growth by binding to membrane proteins leading to the formation of soluble or insoluble complexes that denature the proteins and thus inhibiting their vital functions and showing antibacterial effects (Makarewicz et al. 2021). The condensed tannins were able to bind with porin, outer membrane protein, and permease enzymes, which resulted into inhibition of growth of *Streptococcus faecalis, Streptococcus aureus, Bacillus subtilis, Salmonella enterica, and Enterococcus faecium* (Joseph et al. 2016; Zarin et al. 2016). Gallic and ferulic acid interacted with the cell membranes of Gram-positive bacteria like *Staphylococcus aureus, Listeria monocytogenes,* and *Pseudomonas aeruginosa* as well as Gram-negative bacteria like *E. coli* and *Pseudomonas aeruginosa* resulting into altered surface properties and eventually exerting antibacterial effects (Borges et al. 2013; Miklós Takó et al. 2020). According to Zhao et al. (2002), EGCG (Epigallocatechin gallate) has a direct affinity for the peptidoglycan layer of the cell wall *in Staphylococcus aureus* and showed negative effects on the bacterial cell such as changes in osmotic pressure and ionic strength. However, proanthocyanidins from cranberries considerably reduced the swarming motility and decreased the production of *Pseudomonas aeruginosa* biofilms (Ulrey et al. 2014), while red wine flavonoids with hydroxyl bonds greatly hindered the formation of *Staphylococcus aureus* biofilm (Cho et al. 2015).

3.3 Neuroprotective Properties

The neuro-protective benefits of dietary polyphenols have been a subject of growing interest in scientific research in recent years, indicating their potential role in protecting the brain from neurodegenerative diseases and age-related cognitive decline. Resveratrol has been found to exert neuroprotective properties by inhibiting microglial-mediated neuroinflammatory response, safeguarding the brain from hypoxia–ischemia-induced damage and improvement in cognitive performance in Alzheimer's disease animal model (Rao et al. 2020; Zhang et al. 2022). A clinical trial conducted in women found that the administration of a resveratrol supplement at a low dosage could serve as a potential preventive measure against age-related factors, including cognitive decline (Zaw et al. 2021). EGCG exhibited promising neuroprotective effects in Parkinson's disease by inhibiting neurotoxin and neuroinflammation in both in vitro and in vivo models (Wang et al. 2022). EGCG may also provide protection by modulating cell signalling pathways, genes controlling cell survival and cell death (Singh et al. 2015). Curcumin, with its diverse effects on the nervous system such as reducing amyloid burden, inflammation and antioxidant activity showed therapeutic potential for neurological diseases caused by protein misfolding (Maiti et al. 2018).

3.4 Anti-Inflammatory

Dietary polyphenols regulate immunity and potentially inhibit the inflammatory pathways by targeting signalling pathways NF-κB (nuclear factor kappa-light-chain-enhancer of activated B cells) and MAPKs (mitogen-activated protein Kinase) and resulting in the reduction of pro-inflammatory molecules (cytokines and chemokines) production (Yahfoufi et al. 2018). They are involved in the inhibition of cyclooxygenase and lipoxygenase which are responsible for inflammatory mediator synthesis. Likewise, polyphenols aid in the protection of epithelial tissues and there by alleviates the risk of chronic inflammation (Pietro et al. 2020). They produce compounds with anti-inflammatory properties as a result of their interaction with the gut flora, which is an intriguing aspect of their overall impact on inflammation reduction.

4 Gut Microbiota: An Essential Player in Human Health

The diverse population of microorganisms residing in our digestive system, known as gut microbiota, plays a vital role in maintaining the health and well-being. The large surface area (250–400) m^2 of human gut provides an interface for interaction between internal environment, external factors and antigens. Over the millions of years, trillions of microbes such as bacteria, archaea, viruses, fungi and other microbes has interacted with our body in number of ways, forming a symbiotic relationship and influencing significant aspects of well beings. The growth of gut microbiota is impacted by environmental factors including dietary factors, host genetics, age and antibiotics etc. (Hasan et al. 2019). The human gastrointestinal (GI) tract contains complex and essential community of microorganisms i.e., gut microbiota which are vital for maintaining intestinal homeostasis. Maintaining this delicate balance of intestinal microorganisms are crucial for ensuring gut integrity, preventing pathogens growth and helping in maintaining healthy immune system. During initial phases, the microbial colonisation of infant gut microbiota is considered an erratic, as diversity progressively increases with the passage of time. Typically, GI of foetus is initially free from bacteria but initial colonisation starts as it passes through birth canal and comes in contact with microbes from environment (Catalkaya et al. 2020). Contrarily, it does not occur in caesarean section births, which leads in a different microbiota from that of vaginally delivered babies. The predominant microorganism in vaginally born babies are *Lactobacillus, Atopobium* and *Prevotella* whereas babies born from caesarean section acquires microbes from mother's skin such as *Staphylococcus* and *Propionibacterium* spp. being the prevailing species (Nicholson et al. 2012). Other perinatal factors, such as duration of gestation, feeding type, and administration of antibiotics or probiotics-prebiotics, in addition to the method of birth, have also been shown to exert substantial impact on the microbial colonisation of infant gut (Penders et al. 2006).

Various techniques of molecular profiling indicated that the gut harbours an estimated more than one thousand bacterial species, mainly anaerobes. *Firmicutes* and *Bacteroidetes* are the most predominant phyla in the gut, accounting for around 90%, although there are also subdominant taxa such as *Actinobacteria, Proteobacteria, Fusobacteria*, and *Verrucomicrobia* (Rinninella et al. 2019).The predominant genera in the phylum *Firmicutes* include *Bacillus, Lactobacillus, Clostridium, Enterococcus,* and *Ruminicoccus* (Rinninella et al. 2019), which are both beneficial and pathogenic to human health and play a significant role in the metabolism of the host. On the other hand, in the phylum Bacteroidetes, the predominant genera include *Bacteroides*, *Parabacteroides*, *Prevotella, and Alistipes* (Gibiino et al. 2018), which are involved in the degradation of complex carbohydrates and the synthesis of secondary metabolism. Young adults and elderly people exhibit distinct differences in their microbial composition, especially in terms of the proportions of *Bacteroides* spp. and *Clostridium* groups (Salazar et al. 2017). Age-related changes in the gut microbiota can have a substantial effect on an individual's gut health. Furthermore, the diverse community of the gut microbiome may be influenced the use of drugs to treat age-related illnesses, potentially increasing the risk of unfavourable health consequences.

5 Modulation of Gut Microbial Composition by Polyphenols

5.1 Prebiotic Effect: Increase in the Abundance of Beneficial Bacteria

Dietary phenolic substances as well as the metabolites exert their influence on the gut microbiota by modulating its composition, leading to the suppression of certain bacterial groups while promoting the growth of beneficial bacteria (Table 1). This modulation of gut bacteria composition by polyphenols can positively affect the gut health and functionality of the gastrointestinal system by reducing the risk of gastrointestinal infections. They help in nutrient processing by breaking down complex carbohydrates, fibre and other indigestible components. These bacteria indirectly contribute in lowering down serum cholesterol levels, stimulation of mucus secretion in the intestines which provides a physical barrier against pathogens. They also promote a balanced immune response by reducing the risk of inflammatory conditions in the gut. In an in vitro study by Rezende et al. (2022), orange albedo showed highest prebiotic activity on the growth of *Lactobacillus acidophilus and Bifidobacterium animalis* in comparison to isolated dietary fibres (resistant starch, pectin, polydextrose). Another experiment by Andrade et al. (2020) showed that jerivá pulp promoted the growth *Bifidobacterium lactis, Lactobacillus casei, and Lactobacillus acidophilus*. Macaúba pulp, jerivá kernel cake, and macaúba kernel cake also increased the growth of probiotic strains. SCFA such as lactic, propionic, butyric, and acetic acid were also produced, showing their potential to enhance health and well-being. According to a study by Fujita et al. (2017), gallic acid and caffeic acid in papaya juice had a positive impact on the proliferation of *bifidobacteria* and *eubacteria.* In a study with Aronia berry (Liu et al. 2021a, b), and another study with 9 common berries namely (red Chinese bayberry, strawberry, raspberry, red goji berry, mulberry, blackberry, black goji berry, blueberry, and white Chinese bayberry) (Chen et al. 2022), anthocyanins showed significant modulation on the gut microbiota, characterised by the reduction of potentially harmful bacteria and a proliferation of SCFA-producing bacteria. The effects of dietary polyphenols, notably those in red wine, on gut flora and health have been the focus of numerous research studies. The research has shown these polyphenols can increase number of specific gut microbial groups, such *as Prevotella, Bacteroides, Eggerthella lenta, Bacteroides uniformis, Bifidobacterium, Enterococcus, and Blautia coccoides–Eubacterium rectale* groups (Ortuño et al. 2012), and decrease the reducing the risk of metabolic disorders associated with obesity (Indias et al. 2015). Moderate red wine consumption may exert a direct effect on the microbiota, enhancing the prevalence of health-promoting species such as *Akkermansia muciniphila*, *Faecalibacterium prausnitzii,* and *Roseburia spp.*, which is primarily attributed to the high wine-polyphenol-metabolizers along with SCFAs formation (Barberan et al. 2016). Among these species, *Faecalibacterium spp.* and *Roseburia spp.* are particularly prevalent and significant bacteria within the gut, playing a major role in creating butyrate, a vital compound for sustaining gut health.

Decaffeinated green and black tea polyphenols supplementation had anti-obesity benefits and altered the composition of the gut microbiota in diet-induced obese mice (Henning et al. 2018). A sufficient amount of green tea polyphenols particularly epigallocatechin gallate, caffeine, and theanine promoted the gut microbiota by increasing the growth of *Bifidobacteria* and *Lactobacillus spp.*, indicating potential prebiotic effects (Jung et al. 2019). Green tea polyphenols reduced the obesity in male mice by improving gut health, strengthening the intestinal barrier, limiting the translocation of endotoxins and eventually reducing the inflammation of adipose (Dey et al. 2019). Effective modulation of gut microbiota was observed due to green tea polyphenols in mice (Wang et al. 2016; Wang et al. 2018a, b) and canines (Li et al. 2020) fed with high-fat diet, thereby suggesting the potential of green tea polyphenols as a dietary intervention for managing obesity and promoting gut health. Sun et al. (2018a, b) observed that polyphenols from oolong tea, green tea, and black tea displayed substantial effected the gut microbiome. These compounds led to an increase in the presence of beneficial bacteria such as *lactobacilli, bifidobacteria,* and *Enterococcus spp.* along with production of short-chain fatty acids (SCFAs).

5.2 Inhibition of Harmful Bacteria

The role of dietary polyphenols and their metabolites in suppressing the proliferation of certain bacteria is evident in the literature, which highlights their potential as antibacterial agents. They possess the ability to attach themselves to bacterial cell membranes, and their effect is directly related to their concentration. By interacting with the membrane, they can significantly alter its functions, leading to the inhibition of bacterial growth. These compounds have been shown to effectively inhibit the growth of harmful and toxin-producing bacteria, which cause gastrointestinal illnesses (Golić et al. 2017). The effect of polyphenols in reducing the prevalence of *Clostridium* pathogenic species was highlighted by Ma and Chen (2020) in which tea polyphenols were found to display the highest inhibitory effect, followed by apple consumption. Studies have shown that antibacterial effect of phenolic compounds present in blueberries against *Listeria monocytogenes, Escherichia coli, S. enteritidis, Enterococcus faecalis, L. innoca, Bacillus cereus, P. aeruginosa, Vibrio parahaemolyticus. and S. aureus* (Silva et al. 2013; Sun et al. 2018a, b; Liu et al. 2021a, b). Chan et al. (2018) tested antimicrobial activity of polyphenolic extracts derived from 6 spices and medicinal herbs (oregano, Pomegranate peel, Japanese knotweed, Padang cassia, Chinese cassia, and clove) against probiotic bacteria and common pathogenic bacteria including *Bacillus cereus, Shigella flexneri, Staphylococcus aureus, E. coli, and Salmonella enterica subsp. enterica serovar typhimurium.* The extracts demonstrated significant antibacterial activity against food-borne pathogens but did not exert antagonistic effects on probiotic LAB.

Table 1 Studies on the effect of polyphenols on gut microbiota modulation

S.No	Polyphenol	Source	Model	Effect on gut health	References
1	Anthocyanins, resveratrol, flavanols and flavonols	Grape polyphenols	Mice	Stimulated the proliferation of *Akkermansia* and *Lactobacillus* bacteria and enhanced the integrity of the colonic barrier	Lu et al. (2021)
2	Resveratrol	Commercial	Mice	Enhanced growth of Bacteroides, *Ruminiclostridium_9, Lachnospiraceae_NK4A136_ group, Blautia, Parabacteroides and Lachnoclostridium* decreased inflammation, altered lipid metabolism, and enhanced intestinal barrier integrity	Wang et al. (2020)
3	Betacyanins	Red pitaya	Mice	Lowered the ratio of Firmicutes while elevating the proportion of Bacteroidetes, encouraged the growth of Akkermansia, and simultaneously mitigated the weight gain and visceral obesity induced by a high-fat diet	Song et al. (2015)
4	Quercetin	Commercial	Wistar rats	Effective slowdown of HFS-diet-induced gut microbiota dysbiosis through: Modulation of microbiota, reduction in the ratio of *Firmicutes/Bacteroidetes* and inhibition of *Eubacterium cylindroides, Erysipelotrichaceae,* and *Bacillus*	Etxeberria et al. (2015)
5	Phenolic acids, flavonoids, anthocyanins,	Cranberry	Mice	Increased the proportion of the *Akkermansia,* reduced *intestinal inflammation and oxidative stress*	Anhe et al. (2014)
6	Hesperetin (HT)	Citrus fruits	Rats	Significant reduction in *Clostridium* subcluster XIVa proportion, increase in short-chain fatty acids (SCFA)	Unno et al. (2018)
7	Resveratrol, catechin, epicatechin, procyanidins	Grape pomace	Lamb	Promoted the proliferation of facultative probiotic bacteria while suppressing the growth of *Enterobacteriaceae* and *E. coli*	Kafantaris et al. (2017)
8	Ellagic acid, quercitrin, and chlorogenic acid	Rosa roxburghii Tratt fruit	Mice	Increase in *Blautia, Bacteroides, Lachnospiraceae_NK4A136_ group, Roseburia,* regulation of metabolites balance	Liu et al. (2023)

(continued)

Table 1 (continued)

S.No	Polyphenol	Source	Model	Effect on gut health	References
9	Phenolic acids and Flavonoids	*Smilax china L.* rhizome	Mice	Increased the concentration of *Akkermansiaceae* in the gut, Inhibit the growth of *Firmicutes* to *Bacteroidetes* and relative abundance of *Desulfovibrionaceae, Lachnospiraceae, Streptococcaceae*	Li et al. (2021a, b)
10	Tea polyphenols	Tea	Mice	Increased the growth of (*Lactobacillus, Akkermansia, Blautia, Roseburia*, and *Eubacterium* and reduced the proportion of genes associated with human disorders	Li et al. (2021a, b)
11	Chlorogenic acid	Commercial	Rats	Myofibrillar protein-chlorogenic acid (MP-CGA) complexes increase in the abundance of probiotics *Bacteroides, Akkermansia*, and *Parabacteroides* while suppressing opportunistic pathogens *Enterococcus* and *Staphylococcus*	Zhou et al. (2023)
Human studies					
12	Catechin	Green tea	Human study	Increased SCFA producing genera, *Firmicutes, Actinobacteria* and *Lachnospiraceae,* reduction of fusobacterium	Yuan et al. (2018)
13	Proanthocyanidins,	Cranberry	Healthy adults	Decrease in growth Firmicutes and a rise in Bacteroidetes abundance	Morató et al. (2018)
14	Flavanones	Orange	Healthy adults	Inhibition of *Blautia coccoides* and *Clostridium leptum*	Cuervo et al. (2014)
15	Anthocyanins	Black currant	Healthy humans	Significant increases in *lactobacilli* and *bifidobacteria* populations, and populations of Clostridium spp. and Bacteroides spp. decreased. The activity of β-glucuronidase was also reduced	Molan et al. (2014)

(continued)

Table 1 (continued)

S.No	Polyphenol	Source	Model	Effect on gut health	References
16	Catechins	Oolong tea	Healthy adults	Altered gut microbial diversity, enrichment of *Bacteroides* and *Prevotella,* decreased *Megamonas* together with Improved gastrointestinal function	Li et al. (2023)
17	Polyphenols	Gnetum *gnemon* var. tenerum leaf powder	Human study	Increased level of *Bacteroides* and *Bifidobacterium*, production of SCFAs	Anisong et al. (2023)

The antibacterial mechanism of action of polyphenols may vary with type of polyphenolic compound and bacterial strain. Interaction of polyphenols with bacterial protein can disrupt their structure and vital cellular processes leading to disturbance in cell survival (Makerewicz et al. 2021). Furthermore, polyphenols can interfere the synthesis of nucleic acids, disrupting replication and transcription process. Flavonoids possess the ability to form hydrogen bonding with nucleic acid bases due to presence of B ring and ultimately affecting nucleic acid synthesis. *p*-coumaric acid found to exhibit bactericidal activity by interfering with nucleic acid synthesis and disruption of bacterial cell membrane (Lou et al. 2012). In case of *Staphylococcus aureus*, flavonoids (isobavachalcone, 4-hydroxylonchocarpin and diprenyleriodictyol) from *Dorstenia* sp. caused cell death through inhibition of DNA, RNA, and proteins synthesis along with disruption electrical potential across the cell membrane (Dzoyem et al. 2013). They can alter the functioning of cytoplasmic membrane leading to increased permeability and ultimately contributed to bacterial vulnerability. Catechins have shown to cause structural damage and destabilization of the bacterial cell by binding to lipid bilayer (Reygaert et al. 2014). Perumal et al. (2017) showed the effectiveness of caffeic acid and ECG against *Psuedomonas aeruginosa* by targeting both cell wall and cytoplasmic membrane which increased the permeability towards hydrophobic antibiotics and leading to nucleotides leakage. Apart from this, polyphenols can also cause energy metabolism inhibition and interference of biofilm formation. EGCG effectively eliminated the biofilm formation from *Streptococcus mutans* (Wu et al. 2018a, b), whereas myricetin and Quercetin demonstrated a targeted inhibition of biofilm formation in *S. aureus* and other *Staphylococcal* species (Cuenca et al. 2020).

Besides these mechanism, antimicrobial activity of polyphenols is also defined by their structural configuration which enable for effective prediction of bioactivity. The number and positions of functional groups that are attached to a molecular structure of polyphenols affect their antibacterial activity. Flavonoids with amphipathic properties, containing both hydrophilic and hydrophobic moieties exhibit significant antibacterial effects (Echeverría et al. 2017). Flavonoids exist as “aglycons,” which are free molecules, or as “glycosides,” where an aglycon is bonded to a sugar moiety.

Flavonoid glycosides are typically found in the diet as O-glycosides, with a prevalence in either ring A or C. Because of substitution in ring A, it exerts a significantly more substantial influence on the overall activity. The effectiveness of a compound's antibacterial properties is significantly impacted by the degree of glycosylation which is determined by the class of flavonoid and the specific site where the sugar component is attached (Wang et al. 2018a, b). DUDA-CHODAK (2012) investigated the antibacterial effects of naringenin, naringin, hesperetin, hesperidin, quercetin, rutin, and catechin on the growth of human intestinal microbiota. It was observed that some polyphenols, notably their aglycones (naringenin, hesperetin), inhibited the growth of the majority of the bacteria, in contrast to their glycosides (naringin and hesperidin), which had no effect. With the exception of kaempferol and quercetin, all flavonoids (flavones, flavonols, and flavanones) evaluated for antibacterial action were effective against 3–4 bacterial species. The study demonstrated that analysed plant components are antibacterial, with a focus on Gram-negative bacteria.

Flavonoids generally exhibit improved antibacterial properties when they contain hydrophobic elements like prenyl groups, alkylamino chains, alkyl chains, or nitrogen or oxygen-containing heterocyclic structures (Xie et al. 2014). In the case of flavanones, the presence of 2′, 4′- or 2′, 6′-dihydroxylation on the B ring and 5, 7-dihydroxylation on the A ring is crucial for anti-Methicillin-resistant *Staphylococcus aureus* activity (Panda et al. 2022). The presence of additional hydroxyl group is thought to be responsible for its inhibitory effect, as these groups possess the ability to damage the structural integrity of cell membranes and resulting in release of cellular contents. It can be seen in case of caffeic acid which exhibited higher antimicrobial activity in comparison to p-coumaric acid attributed to extra hydroxyl group (Kępa et al. 2018).

5.3 Modulation of Gut Microbial Metabolites

Short-chain fatty acids (SCFAs), such as acetate, propionate and butyrate are produced in colon through bacterial fermentation of undigested carbohydrates, fibres and other complex molecules. They are associated in supporting gut health, maintaining intestinal homeostasis, reducing inflammation, and even stimulating metabolic functions. The polyphenols have the potential to alter the formation of total SCFAs by influencing the diversity and, consequently, the functionality of the gut microbiota. Wu et al. (2021) showed that Oral EGCG alleviated colitis induced by Dextran sulfate sodium, influencing gut microbiota composition and metabolites production, with SCFAs-producing bacteria like *Akkermansia* playing a crucial role. Role of *Akkermansia muciniphila* in stimulating the production of propionate and acetate is evident in literature and it also promoted the butyrate production by interacting with butyrate-producing bacteria (Zhai et al. 2019). The increase in the production of short-chain fatty acids (SCFAs) such as butyrate initiated a beneficial response, resulting in reduced intestinal inflammation and improved barrier function. This led to the alleviation of intestinal inflammation and damage. Aronia polyphenols significantly promoted the microbial production of propionate and butyrate during in vitro fermentation in the human intestinal system (Wu et al. 2018a, b). In a study by Kim et al. (2018), mango intake significantly increased beneficial bacteria like *Lactobacillus plantarum* and *Lactococcus lactis* along with butyrate-producing bacteria, resulting in elevated levels of butyrate in DSS-treated colitis mice. Through the modulation of microbiota composition and SCFA production particularly butyrate and valerate, mango beverage contributed in alleviating the inflammation in the DSS-induced colitis model.

Level of SCFA production found to be increased in presence of black tea extract than green tea extract in rats. It was clearly observed that black tea extract can potentially increase the production of SCFA by efficiently facilitating the bacterial utilization of starch (Unno et al. 2018). Administration of hesperetin diet enhanced the levels of major SCFAs (acetic, propionic, and butyric acids) in cecum whereas hesperidin did not show any considerable effect in Wistar rats. It was observed that hesperetin, majorly found in citrus fruits may potentially reduce starch digestion leading to increased microbial fermentation in large intestine (Unno et al. 2015).

5.4 Dietary Polyphenols Affect the Bacterial Cell Membrane

Polyphenols possess the ability to damage the complex and multilayered bacterial cell membrane structure, resulting into disruption of membrane integrity.

Polyphenols have a more pronounced antibacterial impact on gram-positive bacteria compared to gram-negative bacteria. This is attributed to the presence of an outer membrane that envelops the cell wall in gram-negative bacteria, which acts as a protective barrier, preventing the entry of chemicals, whereas gram-positive bacteria lack this outer membrane, rendering them comparatively more susceptible to the antibacterial effects of polyphenols. Gram-negative bacteria possess hydrophilic outer membrane and enzymes in the periplasmic space, making them more resistant to many antibacterial substances. Antibacterial abilities of polyphenols include buildup of hydroxyl groups in lipid bilayers, which causes disruption of the interaction between lipoproteins (Lobiuc et al. 2023). This disruption may enhance the cell membrane's permeability, allowing vital cellular components to flow out and causing damage the bacteria. The role of the cell wall in maintaining the integrity and shape of the cell is crucial, so any damage caused to the bacterial cell wall weakens the ability of the cell to withstand osmotic challenges and ionic imbalances, which leads to a reduction in its resistance. EGCG inhibit the growth of *Staphylococcus* possibly by dissolving its protective outer layer, preventing the biofilm formation and neutralization of harmful toxin produced by bacteria (Marín et al. 2015). Epicatechin gallate (ECG) interact with phospholipid membrane of bacteria leads to weaking of membrane structure which results increased permeability and hampering bacterial survival and growth (Li et al. 2022). Tea polyphenols, particularly catechins, display a remarkable affinity for the lipid bilayers present in cell membranes through the formation of H-bonds with bilayer surface (Sirk et al. 2008; Zhang et al. 2021). It leads to penetration into the surface and exert antimicrobial effects. Through this interaction, tea polyphenols impart the beneficial effects by targeting the structural integrity bacterial cell membranes.

6 Biotransformation of Polyphenols by Gut Microbiota

The gut microbiota has been studied for their significant effect on the metabolism and utilisation of dietary polyphenols, which directly affect the absorption levels of parent polyphenols and their metabolites, ultimately determining their physiological effects. It is important to note that a high polyphenol content in food does not always equate to a high bioavailability, since enormous diversity of chemical structures present in polyphenols greatly alter bioavailability of polyphenols. Furthermore, the bioavailability of polyphenols is subject to the influence of absorption and metabolism, both of which can be modulated by biotransformation facilitated by the gut microbiota. Based on the current available data, polyphenol molecules absorbed from the small intestine are mostly aglycones and some intact glucosides since the majority of polyphenols found in food exist as esters, glycosides, or polymers, which are inherently unabsorbable in their native form.

Metabolic fate of polyphenols in human body must be taken into consideration. Absorption of small percentages of polyphenols with monomeric and dimeric structures occurs in small intestine, where it is substantially impacted by de-glycosylation reactions. Following absorption, less complex polyphenols undergo in enterocytes and hepatocytes. This transformation involves Phase I reactions (oxidation, reduction, and hydrolysis) and notably, Phase II reactions (conjugation). This process results in the production of water-soluble metabolites that are conjugated in nature, such as glucuronide, sulfate, and methyl derivatives. These metabolites can be efficiently transported to various organs via the bloodstream. Eventually, these metabolites are eliminated from the body through urine. About 90–95% of polyphenols which remain unabsorbed due to intricate compositions and substantial molecular sizes in small intestine proceeds into large intestine where resident bacteria metabolize and bio-transform them. Besides these human-related aspects, the bioavailability of polyphenols is significantly affected by polyphenol rich food matrix. This happens during industrial processing, which modifies the availability of certain phenolic chemicals. For instance, in case of almond skin polyphenols whose bioavailability is affected to greater extend due to bleaching (Mandalari et al. 2010). Similarly, the production of orange juice involves a specific process that causes the precipitation of flavanones, making the compound less readily available for absorption (Izquierdo et al. 2001).

Anthocyanins (cyanidin-3-glucoside, cyanidin-3-rutinoside, and delphinidin-3-rutinoside) from mulberry plants were studied for their bacterial-dependent metabolism during a simulation of large intestine conditions. It was observed that cyanidin-3-glucoside and cyanidin-3-rutinoside were metabolised into p-coumaric acids, protocatechuic, 2,4,6-trihydroxybenzaldehyde and vanillic whereas delphinidin-3-rutinoside was converted into gallic acid, 2,4,6-trihydroxybenzaldehyde and syringic acid (Chen et al. 2017). According to research conducted by Ekbatan et al. (2016), bio-transformation of a polyphenol mixture containing chlorogenic acid, caffeic acid, ferulic acid was carried out in a multi-reactor gastrointestinal model, producing phenylpropionic, benzoic, phenylacetic, and cinnamic acids in the colonic compartments. Lin et al. (2016) studied the biotransformation of three subclasses of flavonoids (flavonols, flavones, and flavanones into p-hydroxyphenylacetic acid, proto-catechuic acid, p-hydroxybenzoic acid, vanillic acid, hydrocaffeic acid, coumaric acid, 3-(4- hydroxyphenyl) propionic acid using vitro and vivo models. Bioavailability of ellgic acid was very low due to its hydrophobic nature but they were further metabolised by intestinal microorganisms in large intestine and resulted into formation of urolithins which exerted strong antioxidant and preventive effects against chronic diseases (Rad et al. 2022).

7 Conclusion

Polyphenols, which are abundant in a variety of healthy foods have been related to beneficial outcomes on a variety of disorders due to their direct antioxidant, anti-inflammatory properties and cytoprotective properties. Besides these effects, majority of health benefits of the dietary polyphenols occur via their symbiotic relation with gut microbiota. There is emerging scientific research that strongly supports the beneficial aspects of dietary polyphenols on host health through the interaction with gut microbiota. Dietary polyphenols and their metabolites have been proven to promote a healthy gut by positively influencing gut microbiota. They achieve this by fostering the growth of useful bacteria while also inhibiting the proliferation of harmful pathogens. On the other hand, biotransformation of polyphenols through gut microbiota resulting into higher bioavailability has also been assessed in various studies investigated highlighting the bidirectional and mutually beneficial relationship between phenolics and gut microbiota. However, a comprehensive and in-depth understanding of the interplay between polyphenols and gut microbiota interactions is required, mainly in relation to the metabolic pathway, which will enable for targeted interventions and new therapeutic strategies for gut-related illnesses.

References

Abu Zarin M, Wan HY, Isha A, Armania N (2016) Antioxidant, antimicrobial and cytotoxic potential of condensed tannins from Leucaena leucocephala hybrid-Rendang. Food Sci Hum Wellness 5(2):65–75

Ahmed NA, Radwan NM, Aboul Ezz HS, Salama NA (2017) The antioxidant effect of Green Tea Mega EGCG against electromagnetic radiation-induced oxidative stress in the hippocampus and striatum of rats. Electromagn Biol Med 36(1):63–73

Andrade AC, Marinho JFU, De Souza AC, De Sousa TT, Dias DR, Schwan RF, Nunes CA, Bastos SC (2020) Prebiotic potential of pulp and kernel cake from Jerivá (Syagrus romanzoffiana) and Macaúba palm fruits (Acrocomia aculeata). Food Res Int 136:109595

Anhê FF, Roy D, Pilon G, Dudonné S, Matamoros S, Varin TV, Garofalo C, Moine Q, Desjardins Y, Levy E, Marette A (2015) A polyphenol-rich cranberry extract protects from diet-induced obesity, insulin resistance and intestinal inflammation in association with increased *Akkermansia* spp. Population in the Gut Microbiota of Mice Gut 64(6):872–883

Anisong N, Siripongvutikorn S, Puttarak P, Wichienchot S (2023) Fecal fermentation and gut microbiota modulation of dietary fibre and polyphenols from Gnetum gnemon Linn. Leaves. Bioact Carbohydr Diet Fibr 30:100380

Belščak-Cvitanović A, Durgo K, Huđek A, Bačun-Družina V, Komes D (2018) Overview of polyphenols and their properties. In Charis M Galanakis, (ed) Polyphenols: Properties, recovery, and applications, Woodhead Publishing, 3–44

Bešlo D, Došlić G, Agić D, Rastija V, Šperanda M, Gantner V, Lučić B (2022) Polyphenols in ruminant nutrition and their effects on reproduction. Antiox 11(5):970

Borges A, Ferreira C, Saavedra MJ, Simões M (2013) Antibacterial activity and mode of action of ferulic and gallic acids against pathogenic bacteria. Microb Drug Resist 19(4):256–265

Catalkaya G, Venema K, Lucini L, Rocchetti G, Delmas D, Daglia M, De Filippis A, Xiao H, Quiles JL, Xiao J, Capanoglu E (2020) Interaction of dietary polyphenols and gut microbiota: Microbial metabolism of polyphenols, influence on the gut microbiota, and implications on host health. Food Frontiers 1(2):109–133

Chan CL, Gan RY, Shah NP, Corke H (2018) Polyphenols from selected dietary spices and medicinal herbs differentially affect common food-borne pathogenic bacteria and lactic acid bacteria. Food Control 92:437–443

Chen Y, Li Q, Zhao T, Zhang Z, Mao G, Feng W, Wu X, Yang L (2017) Biotransformation and metabolism of three mulberry anthocyanin monomers by rat gut microflora. Food Chem 237:887–894

Chen J, Shu Y, Chen Y, Ge Z, Zhang C, Cao J, Li X, Wang Y, Sun C (2022) Evaluation of antioxidant capacity and gut microbiota modulatory effects of different kinds of berries. Antiox 11(5):1020

Cho HS, Lee JH, Cho MH, Lee J (2015) Red wines and flavonoids diminish *Staphylococcus aureus* virulence with anti-biofilm and anti-hemolytic activities. Biofouling 31(1):1–11

Cuervo A, Valdés L, Salazar N, De Los Reyes-Gavilán CG, Ruas-Madiedo P, Gueimonde M, González S (2014) Pilot study of diet and microbiota: interactive associations of fibers and polyphenols with human intestinal bacteria. J Agric Food Chem 62(23):5330–5336

Danneskiold-Samsøe NB, De Freitas D, Queiroz Barros H, Santos R, Bicas JL, Cazarin CBB, Madsen L, Kristiansen K, Pastore GM, Brix S, Maróstica Júnior MR (2019) Interplay between food and gut microbiota in health and disease. Food Res Int 115:23–31

Das K, Roychoudhury A (2014) Reactive oxygen species (ROS) and response of antioxidants as ROS-scavengers during environmental stress in plants. Front Environ Sci 2:53

Das T, Chatterjee N, Capanoglu E, Lorenzo JM, Das AK, Dhar P (2023) The synergistic ramification of insoluble dietary fiber and associated non-extractable polyphenols on gut microbial population escorting alleviation of lifestyle diseases. Food Chem X 18:100697

Dey P, Sasaki GY, Wei P, Li J, Wang L, Zhu J, McTigue D, Yu Z, Bruno RS (2019) Green tea extract prevents obesity in male mice by alleviating gut dysbiosis in association with improved intestinal barrier function that limits endotoxin translocation and adipose inflammation. J Nutr Biochem 67:78–89

Di Pietro N, Baldassarre MPA, Cichelli A, Pandolfi A, Formoso G, Pipino C (2020) Role of polyphenols and carotenoids in endothelial dysfunction: an overview from classic to innovative biomarkers. Oxid Med Cell Longev 2020:6381380

Duda-Chodak A (2012) The inhibitory effect of polyphenols on human gut microbiota. J Physiol Pharmacol 63(5):497–503

Dzoyem JP, Hamamoto H, Ngameni B, Ngadjui BT, Sekimizu K (2013) Antimicrobial action mechanism of flavonoids from Dorstenia species. Drug Discov Ther 7(2):66–72

Echeverría J, Opazo J, Mendoza L, Urzúa A, Wilkens M (2017) Structure-activity and lipophilicity relationships of selected antibacterial natural flavones and flavanones of Chilean flora. Molecules 22(4):608

Etxeberria U, Arias N, Boqué N, Macarulla MT, Portillo MP, Martínez JA, Milagro FI (2015) Reshaping faecal gut microbiota composition by the intake of trans-resveratrol and quercetin in high-fat sucrose diet-fed rats. J Nutr Biochem 26(6):651–660

Fujita Y, Tsuno H, Nakayama J (2017) Fermented papaya preparation restores age-related reductions in peripheral blood mononuclear cell cytolytic activity in tube-fed patients. PLoS ONE 12(1):e0169240

Gibiino G, Lopetuso LR, Scaldaferri F, Rizzatti G, Binda C, Gasbarrini A (2018) Exploring Bacteroidetes: Metabolic key points and immunological tricks of our gut commensals. Dig Liver Dis 50(7):635–639

Gil-Izquierdo A, Gil MI, Ferreres F, Tomás-Barberán FA (2001) In vitro availability of flavonoids and other phenolics in orange juice. J Agric Food Chem 49(2):1035–1041

Golić N, Veljović K, Popović N, Djokić J, Strahinić I, Mrvaljević I, Terzić-Vidojević A (2017) In vitro and in vivo antagonistic activity of new probiotic culture against clostridium difficile and clostridium perfringens. BMC Microbiol 17(1):108

Hanasaki Y, Ogawa S, Fukui S (1994) The correlation between active oxygens scavenging and antioxidative effects of flavonoids. Free Radic Biol Med 16(6):845–850

Hasan N, Yang H (2019) Factors affecting the composition of the gut microbiota, and its modulation. PeerJ 7:e7502

Henning SM, Yang J, Hsu M, Lee RP, Grojean EM, Ly A, Tseng CH, Heber D, Li Z (2018) Decaffeinated green and black tea polyphenols decrease weight gain and alter microbiome populations and function in diet-induced obese mice. Eur J Nutr 57(8):2759–2769

Joseph N, Mirelle AFR, Matchawe C, Patrice DN, Josaphat N (2016) Evaluation of the antimicrobial activity of tannin extracted from the barks of *Erythrophleum guineensis* (Caesalpiniaceae). J Pharmacogn Phytochem. 5(4):287

Jung ES, Park JI, Park H, Holzapfel W, Hwang JS, Lee CH (2019) Seven-day green tea supplementation revamps gut microbiome and caecum/skin metabolome in mice from stress. Sci Rep 9(1):18418

Kafantaris I, Kotsampasi B, Christodoulou V, Kokka E, Kouka P, Terzopoulou Z, Gerasopoulos K, Stagos D, Mitsagga C, Giavasis I, Makri S, Petrotos K, Kouretas D (2017) Grape pomace improves antioxidant capacity and faecal microflora of lambs. J Anim Physiol Anim Nutr 101(5):e108–e121

Kasprzak-Drozd K, Oniszczuk T, Stasiak M, Oniszczuk A (2021) Beneficial effects of phenolic compounds on gut microbiota and metabolic syndrome. Int J Mol Sci 22(7):3715

Kępa M, Miklasińska-Majdanik M, Wojtyczka RD, Idzik D, Korzeniowski K, Smoleń-Dzirba J, Wąsik TJ (2018) Antimicrobial potential of caffeic acid against *Staphylococcus aureus* clinical strains. Biomed Res Int 2018:1–9

Kezimana P, Dmitriev AA, Kudryavtseva AV, Romanova EV, Melnikova NV (2018) Secoisolariciresinol diglucoside of flaxseed and its metabolites biosynthesis and potential for nutraceuticals. Front Genet 9:641

Khoo HE, Azlan A, Tang ST, Lim SM (2017) Anthocyanidins and anthocyanins: colored pigments as food, pharmaceutical ingredients, and the potential health benefits. Food Nutr Res 61(1):1361779

Kim H, Krenek KA, Fang C, Minamoto Y, Markel ME, Suchodolski JS, Talcott ST, Mertens-Talcott SU (2018) Polyphenolic derivatives from mango (Mangifera Indica L.) modulate fecal microbiome, short-chain fatty acids production and the HDAC1/AMPK/LC3 axis in rats with DSS-induced colitis. J Funct Foods 48:243–251

Kumar N, Goel N (2019) Phenolic acids: natural versatile molecules with promising therapeutic applications. Biotechnol Rep 24:e00370

Li Y, Rahman SU, Huang Y, Zhang Y, Ming P, Zhu L, Chu X, Li J, Feng S, Wang X, Wu J (2020) Green tea polyphenols decrease weight gain, ameliorate alteration of gut microbiota, and mitigate intestinal inflammation in canines with high-fat-diet-induced obesity. J Nutr Biochem 78:108324

Li J, Chen C, Yang H, Yang X (2021a) Tea polyphenols regulate gut microbiota dysbiosis induced by antibiotic in mice. Food Res Int 141:110153

Li Z, Feng C, Dong H, Jin W, Zhang W, Zhan J, Wang S (2022) Health promoting activities and corresponding mechanism of (–)-epicatechin-3-gallate. Food Sci Hum Wellness 11(3):568–578

Li A, Kou R, Liu H, Chen M, Wang J, Liu Q, Xing X, Zhang B, Dong L, Wang S (2023) Multi-omics analyses reveal relationships among polyphenol-rich oolong tea consumption, gut microbiota, and metabolic profile: a pilot study. Food Chem 426:136653

Li X, Yang L, Xu M, Qiao G, Li C, Lin L, Zheng G (2021) Smilax china L. polyphenols alleviates obesity and inflammation by modulating gut microbiota in high fat/high sucrose diet-fed C57BL/6J mice. J Funct Foods 77:104332

Lin W, Wang W, Yang H, Wang D, Ling W (2016) Influence of Intestinal Microbiota on the Catabolism of flavonoids in mice: microbiotic metabolism of flavonoids in mice. J Food Sci 81(12):H3026–H3034

Liu H, Wu H, Wang Y, Wang F, Liu X, Zhou J (2021a) Enhancement on antioxidant and antibacterial activities of Brightwell blueberry by extraction and purification. Appl Biol Chem 64(1):78

Liu X, Martin DA, Valdez JC, Sudakaran S, Rey F, Bolling BW (2021b) Aronia berry polyphenols have matrix-dependent effects on the gut microbiota. Food Chem 359:129831

Liu Y, Zhang S, Tang L, Zhang M, Wang P, Sun X, Shang L, Wang Q, Zhao Y, Meng D, Luo P, Gao X (2023) Analysis of the effects of Rosa roxburghii Tratt fruit polyphenols on immune function in mice through gut microbiota and metabolomics: an in vivo preclinical trial study. J Funct Foods 102:105464

Lobiuc A, Pavăl NE, Mangalagiu II, Gheorghiță R, Teliban GC, Amăriucăi-Mantu D, Stoleru V (2023) Future antimicrobials: natural and functionalized phenolics. Molecules 28(3):1114

Lou Z, Wang H, Rao S, Sun J, Ma C, Li J (2012) P-Coumaric acid kills bacteria through dual damage mechanisms. Food Control 25(2):550–554

Lu F, Li Y, Wang X, Hu X, Liao X, Zhang Y (2021) Early-life polyphenol intake promotes Akkermansia growth and increase of host goblet cells in association with the potential synergistic effect of Lactobacillus. Food Res Int 149:110648

Ma G, Chen Y (2020) Polyphenol supplementation benefits human health via gut microbiota: a systematic review via meta-analysis. J Funct Foods 66:103829

Maiti P, Dunbar G (2018) Use of curcumin, a natural polyphenol for targeting molecular pathways in treating age-related neurodegenerative diseases. Int J Mol Sci 19(6):1637

Makarewicz M, Drożdż I, Tarko T, Duda-Chodak A (2021) The interactions between polyphenols and microorganisms especially gut microbiota. Antiox 10(2):188

Mandalari G, Tomaino A, Rich GT, Lo Curto R, Arcoraci T, Martorana M, Bisignano C, Saija A, Parker ML, Waldron KW, Wickham MSJ (2010) Polyphenol and nutrient release from skin of almonds during simulated human digestion. Food Chem 122(4):1083–1088

Marín L, Miguélez EM, Villar CJ, Lombó F (2015) Bioavailability of dietary polyphenols and gut microbiota metabolism: antimicrobial properties. BioMed Res Int 2015:1–18

Matilla-Cuenca L, Gil C, Cuesta S, Rapún-Araiz B, Žiemytė M, Mira A, Lasa I, Valle J (2020) Antibiofilm activity of flavonoids on staphylococcal biofilms through targeting BAP amyloids. Sci Rep 10(1):18968

Molan AL, Liu Z, Plimmer G (2014) Evaluation of the effect of blackcurrant products on gut microbiota and on markers of risk for colon cancer in humans: blackcurrant products and gut microbiota. Phytother Res 28(3):416–422

Moreno-Indias I, Sánchez-Alcoholado L, Pérez-Martínez P, Andrés-Lacueva C, Cardona F, Tinahones F, Queipo-Ortuño MI (2016) Red wine polyphenols modulate fecal microbiota and reduce markers of the metabolic syndrome in obese patients. Food & Funct 7(4):1775–1787

Nicholson JK, Holmes E, Kinross J, Burcelin R, Gibson G, Jia W, Pettersson S (2012) Host-gut microbiota metabolic interactions. Science 336(6086):1262–1267

Panda L, Duarte-Sierra A (2022) Recent advancements in enhancing antimicrobial activity of plant-derived polyphenols by biochemical means. Horticulturae 8(5):401

Pandey KB, Rizvi SI (2009) Plant polyphenols as dietary antioxidants in human health and disease. Oxid Med Cell Longev 2(5):270–278

Penders J, Thijs C, Vink C, Stelma FF, Snijders B, Kummeling I, Van Den Brandt PA, Stobberingh E (2006) Factors influencing the composition of the intestinal microbiota in early infancy. Pediatrics 118(2):511–521

Perumal S, Mahmud R, Ismail S (2017) Mechanism of action of isolated caffeic acid and epicatechin 3-gallate from Euphorbia hirta against Pseudomonas aeruginosa. Pharmacogn Mag 13(50):311

Queipo-Ortuño MI, Boto-Ordóñez M, Murri M, Gomez-Zumaquero JM, Clemente-Postigo M, Estruch R, Cardona Diaz F, Andrés-Lacueva C, Tinahones FJ (2012) Influence of red wine polyphenols and ethanol on the gut microbiota ecology and biochemical biomarkers. Am J Clin Nutr 95(6):1323–1334

Ramesh P, Jagadeesan R, Sekaran S, Dhanasekaran A, Vimalraj S (2021) Flavonoids: classification, function, and molecular mechanisms involved in bone remodelling. Front Endocrinol 12:779638

Rao YL, Ganaraja B, Joy T, Pai MM, Ullal SD, Murlimanju BV (2020) Neuroprotective effects of resveratrol in Alzheimer's disease. Front Biosci 12(1):139–149

Reygaert WC (2014) The antimicrobial possibilities of green tea. Front Microbiol 5:434

Rinninella E, Raoul P, Cintoni M, Franceschi F, Miggiano G, Gasbarrini A, Mele M (2019) What is the healthy gut microbiota composition? A changing ecosystem across age, environment, diet, and diseases. Microorg 7(1):14

Rodríguez-Morató J, Matthan NR, Liu J, De La Torre R, Chen CYO (2018) Cranberries attenuate animal-based diet-induced changes in microbiota composition and functionality: a randomized crossover-controlled feeding trial. J Nutr Biochem 62:76–86

Sadeghi Ekbatan S, Sleno L, Sabally K, Khairallah J, Azadi B, Rodes L, Prakash S, Donnelly DJ, Kubow S (2016) Biotransformation of polyphenols in a dynamic multistage gastrointestinal model. Food Chem 204:453–462

Salazar N, Valdés-Varela L, González S, Gueimonde M, De Los Reyes-Gavilán CG (2017) Nutrition and the gut microbiome in the elderly. Gut Microbes 8(2):82–97

Sharifi-Rad J, Quispe C, Castillo CMS, Caroca R, Lazo-Vélez MA, Antonyak H, Polishchuk A, Lysiuk R, Oliinyk P, De Masi L, Bontempo P, Martorell M, Daştan SD, Rigano D, Wink M, Cho WC (2022) Ellagic acid: a review on its natural sources, chemical stability, and therapeutic potential. Oxid Med Cell Longev 2022:1–24

Silva S, Costa EM, Pereira MF, Costa MR, Pintado ME (2013) Evaluation of the antimicrobial activity of aqueous extracts from dry *Vaccinium corymbosum* extracts upon food microorganism. Food Control 34(2):645–650

Singh NA, Mandal AKA, Khan ZA (2015) Potential neuroprotective properties of epigallocatechin-3-gallate (EGCG). Nutr J 15(1):60

Sirk TW, Brown EF, Sum AK, Friedman M (2008) Molecular dynamics study on the biophysical interactions of seven green tea catechins with lipid bilayers of cell membranes. J Agric Food Chem 56(17):7750–7758

Song H, Chu Q, Yan F, Yang Y, Han W, Zheng X (2016) Red pitaya betacyanins protects from diet-induced obesity, liver steatosis and insulin resistance in association with modulation of gut microbiota in mice: the function of red pitaya betacyanins. J Gastroenterol Hepatol 31(8):1462–1469

Sun H, Chen Y, Cheng M, Zhang X, Zheng X, Zhang Z (2018a) The modulatory effect of polyphenols from green tea, oolong tea and black tea on human intestinal microbiota in vitro. J Food Sci Technol 55(1):399–407

Sun X, Zhou T, Wei C, Lan W, Zhao Y, Pan Y, Wu VCH (2018b) Antibacterial effect and mechanism of anthocyanin rich Chinese wild blueberry extract on various foodborne pathogens. Food Control 94:155–161

Takó M, Kerekes EB, Zambrano C, Kotogán A, Papp T, Krisch J, Vágvölgyi C (2020) Plant phenolics and phenolic-enriched extracts as antimicrobial agents against food-contaminating microorganisms. Antioxidants 9(2):165

Thaung Zaw JJ, Howe PRc, Wong RHx, (2021) Long-term effects of resveratrol on cognition, cerebrovascular function and cardio-metabolic markers in postmenopausal women: a 24-month randomised, double-blind, placebo-controlled, crossover study. Clin Nutr 40(3):820–829
Tomás-Barberán FA, Selma MV, Espín JC (2016) Interactions of gut microbiota with dietary polyphenols and consequences to human health. Curr Opin Clin Nutr Metab Care 19(6):471–476
Ulrey RK, Barksdale SM, Zhou W, Van Hoek ML (2014) Cranberry proanthocyanidins have anti-biofilm properties against Pseudomonas aeruginosa. BMC Complement Med 14(1):499
Unno T, Osakabe N (2018) Green tea extract and black tea extract differentially influence cecal levels of short-chain fatty acids in rats. Food Sci Nutr 6(4):728–735
Unno T, Hisada T, Takahashi S (2015) Hesperetin modifies the composition of fecal microbiota and increases cecal levels of short-chain fatty acids in rats. J Agric Food Chem 63(36):7952–7957
Wang L, Zeng B, Zhang X, Liao Z, Gu L, Liu Z, Zhong Q, Wei H, Fang X (2016) The effect of green tea polyphenols on gut microbial diversity and fat deposition in C57BL/6J HFA mice. Food Funct 7(12):4956–4966
Wang L, Zeng B, Liu Z, Liao Z, Zhong Q, Gu L, Wei H, Fang X (2018a) Green tea polyphenols modulate colonic microbiota diversity and lipid metabolism in high-fat diet treated HFA mice. J Food Sci 83(3):864–873
Wang T, Li Q, Bi K (2018b) Bioactive flavonoids in medicinal plants: structure, activity and biological fate. Asian J Pharm Sci 13(1):12–23
Wang P, Li D, Ke W, Liang D, Hu X, Chen F (2020) Resveratrol-induced gut microbiota reduces obesity in high-fat diet-fed mice. Int J Obes 44(1):213–225
Wang Y, Wu S, Li Q, Lang W, Li W, Jiang X, Wan Z, Chen J, Wang H (2022) Epigallocatechin-3-gallate: a phytochemical as a promising drug candidate for the treatment of Parkinson's disease. Front Pharmacol 13:977521
Wu CY, Su TY, Wang MY, Yang SF, Mar K, Hung SL (2018a) Inhibitory effects of tea catechin epigallocatechin-3-gallate against biofilms formed from Streptococcus mutans and a probiotic lactobacillus strain. Arch Oral Biol 94:69–77
Wu T, Grootaert C, Pitart J, Vidovic NK, Kamiloglu S, Possemiers S, Glibetic M, Smagghe G, Raes K, Van De Wiele T, Van Camp J (2018b) Aronia (*Aronia melanocarpa*) polyphenols modulate the microbial community in a simulator of the human intestinal microbial ecosystem (SHIME) and decrease secretion of proinflammatory markers in a Caco-2/endothelial cell coculture model. Mol Nutr Food Res 62(22):1800607
Wu Z, Huang S, Li T, Li N, Han D, Zhang B, Xu ZZ, Zhang S, Pang J, Wang S, Zhang G, Zhao J, Wang J (2021) Gut microbiota from green tea polyphenol-dosed mice improves intestinal epithelial homeostasis and ameliorates experimental colitis. Microbiome 9(1):184
Xie Y, Yang W, Tang F, Chen X, Ren L (2014) Antibacterial activities of flavonoids: structure-activity relationship and mechanism. Curr Med Chem 22(1):132–149
Yahfoufi N, Alsadi N, Jambi M, Matar C (2018) The immunomodulatory and anti-inflammatory role of polyphenols. Nutr 10(11):1618
Yuan X, Long Y, Ji Z, Gao J, Fu T, Yan M, Zhang L, Su H, Zhang W, Wen X, Pu Z, Chen H, Wang Y, Gu X, Yan B, Kaliannan K, Shao Z (2018) Green tea liquid consumption alters the human intestinal and oral microbiome. Mol Nutr Food Res 62(12):1800178
Zhai Q, Feng S, Arjan N, Chen W (2019) A next generation probiotic, *Akkermansia muciniphila.* Crit Rev Food Sci Nutr 59(19):3227–3236
Zhang H, Zhao W (2022) Resveratrol alleviates ischemic brain injury by inhibiting the activation of pro-inflammatory microglia via the CD147/MMP-9 pathway. J Stroke Cerebrovasc Dis 31(4):106307
Zhang L, Gui S, Wang J, Chen Q, Zeng J, Liu A, Chen Z, Lu X (2020) Oral administration of green tea polyphenols (TP) improves ileal injury and intestinal flora disorder in mice with Salmonella typhimurium infection via resisting inflammation, enhancing antioxidant action and preserving tight junction. J Funct Foods 64:103654

Zhang Q, Zhang J, Zhang J, Xu D, Li Y, Liu Y, Zhang X, Zhang R, Wu Z, Weng P (2021) Antimicrobial effect of tea polyphenols against foodborne pathogens: a review. J Food Prot 84(10):1801–1808

Zhao WH, Hu ZQ, Hara Y, Shimamura T (2002) Inhibition of penicillinase by epigallocatechin gallate resulting in restoration of antibacterial activity of penicillin against penicillinase-producing *Staphylococcus aureus.* Antimicrob Agents Chemother 46(7):2266–2268

Zhou L, Wang W, Huang J, Ding Y, Pan Z, Zhao Y, Zhang R, Hu B, Zeng X (2016) In vitro extraction and fermentation of polyphenols from grape seeds (Vitis vinifera) by human intestinal microbiota. Food Funct 7(4):1959–1967

Contribution of Sorghum and Finger Millets for Sustainable Food and Nutritional Security

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1 Introduction

Food security is a critical worldwide issue that encompasses availability, accessibility, and utilisation of safe food for all individuals that is essential for well-being and survival of individuals. It is also closely related to economic growth, social stability, and environmental sustainability (Cole et al. 2018). However, different number of factors, such as climate change, rapid increase in population growth, and economic inequalities, pose multiple food security challenges. There are three main staple cereals—corn, wheat, and rice which are worldwide cultivated and consumed. As we heavily rely on corn, wheat, and rice as staple foods, the emphasis on maximizing their production and introducing different modern and novel technologies leaves limited space for diversification, which is causing burden on food security. Due to this mono-cropping system, the food supply is exposed to disease outbreaks or other environmental factors such as soil erosion, water pollution, and loss of biodiversity (Zamaratskaia et al. 2021; Gregory and George 2011). Additionally, these three cereals are deficit in essential nutrients, which risk diets of general population to be nutrient deficient and reduces the overall resilience of food system, causing an increase in the prevalence of malnourishment (Wakeel et al. 2018). As per reports of the Food and Agriculture Organization United Nations, in 2015, about 10.8% and in 2016, about 11% world population were malnourished (Prosekov and Ivanova 2018). Therefore, it is essential to implement sustainable agricultural practices, encourage equitable resource distribution, and improve access to food for vulnerable populations.

Crop diversification is one such sustainable practice to combat food security challenges. It involves crops that have the tolerance to withstand harsh conditions, require

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fewer agricultural resource inputs, and would overall reduce micronutrient deficiency among the malnourished population. The millets have these combined potentials (i.e., resilient crop and nutritious) and can be termed as "sustainable crops" (Fischer et al. 2016). Millets are a diverse category of crops notable for their small-seeded grains, and they are categorized based on grain size into major millets which are sorghum (*Sorghum bicolor*), Finger millet (*Eleusine coracana*) and pearl millet (Pennisetum glaucum) and minor millets which are, proso millet (Panicum miliaceum), foxtail millet (Setaria italica), and Kodo millet (Paspalum scrobiculatum) (Dekka et al. 2023). Millets and major cereals have similar morphology, still, they are under-utilised in comparison to major cereals, but in recent years interest in use of millets have been increasing due to its sustainable properties.

Sorghum (*Sorghum bicolor*), also known as "Jowar" is a versatile and highly sustainable crop that has been cultivated for thousands of years. Its resilience and ability to thrive in arid and semi-arid regions make it a valuable resource for food security and economic stability in many countries. Sorghum is a food source that can be used for both humans as well as livestock. It has essential nutritional value including dietary fiber, protein, and antioxidants. (Dayakar Rao et al. 2017). Sorghum supports sustainability as it has variety of noteworthy features, for instance, it requires significantly lower level of water for the production compared to different crops helping in water scarcity, as well has the ability to withstand harsh climatic conditions (Hossain et al. 2022).

Finger millet (*Eleusine coracana*), is basically originated from Africa, and now widely grown in in Asia, specifically in India and Nepal regions. In Southern Indian region it is also termed as "Ragi" and has grown major adaptability in the population of particular region. Finger millet is round in shape and small in size but has abundance of essential nutrients such as calcium, iron, niacin, and dietary fiber which makes it a great addition to the nutritious meal for the population (Rathore et al. 2019; Grovermann et al. 2018).

Two prominent millets that can contribute significantly to maintaining long-term food and nutrition security are sorghum and finger millets because of their versatility in agroecologies and resistance in harsh environments (Dekka et al. 2023). These millets have been cultivated and eaten around the globe, specifically in Africa and Asia. As well as these crops have enormous health and nutritional benefits which make them vital sources for addressing the challenges of food insecurity and malnutrition (Dayakar Rao et al. 2017).

The purpose of this chapter is to emphasize the nutritional excellence of sorghum and finger millets and focusing their role in environmental and nutritional security. As well as, summarizing their different applications in food production for generating healthy, sustainable food products that are significant to consumers.

2 Nutrient Significance of Sorghum and Finger Millet

Finger millet is one of the potential millet helpful in ensuring food security as it is packed with the vital nutrients, especially protein, dietary fibre, calcium and other minerals (Thapliyal and Singh 2015; Table 1). It is a staple food for many African south Asian countries. It is a versatile crop as it is suitable for various purposes like porridges, flour, sprouts, etc. In India finger millet is also used by brewing industries, feeding infant calves, and growing animals and is recommended for infants. Finger millet contains 59.4–70.2% of carbohydrates as the main constituent, starch contains 80–85% amylopectin and 15–20% of amylose. As compared to brown varieties, white varieties are higher in protein content (Dayakar Rao et al. 2017). Finger millet contains essential 44.7% amino acids with prolamin being the most prominent of all i.e., 24.6–36.2% of the total protein. It also contains 99.1 mg of soluble proteins per 100 gm (Dayakar Rao et al. 2017). Among millets, finger millets show a better amino acid profile as they contains better amount of lysine, threonine, and valine. The protein fraction of finger millet like globulin and albumin contains a good combination of essential amino acids whereas proline, valine, leucine, phenylalanine, glutamic acid, and isoleucine are higher in prolamin fraction but low in arginine and glycine. The isoleucine and leucine ratio is equal to that of rice and wheat (Thapliyal and Singh 2015).

The range of crude fat content was found to be 1.3–1.8%. the crude fat content may vary from 1.2 to 1.4% in brown and white varieties. In spite of having less fat, finger millet is abundant in polyunsaturated fatty acids. Oleic acid was the most abundant fatty acid in finger millet, followed by palmitic acid and linoleic acid. It also included a trace of linolenic acid. According to the fatty acid profile, saturated fatty acids account for 25.6% of total fatty acids, whereas unsaturated fatty acids account for 74.4% (Thapliyal and Singh 2015).

2.1 Sorghum

Sorghum is a grain that is known to have nutrient potential which has the ability to satisfy the nutritional requirements and can be helpful in preventing and fighting lifestyle diseases. Proteins in sorghum are mostly found in the endosperm (80%), germ (16%), and pericarp (3%). Kafirin, prolamins, and glutelins are the most abundant components in sorghum and are found in the endosperm, whereas albumins and globulins are abundant in the germ (Dayakar Rao et al. 2017). Sorghum protein is more hydrophobic as compared to proteins present in wheat, maize, and rice and this property of its protein molecule reduces its digestibility. This is because α kafirin which is the most hydrophobic protein is surrounded by protease—resistant and hydrophobic β and γ kafirins, thus affecting its digestibility (Hossain et al. 2022).

The main components of carbohydrates found in sorghum are starch, soluble sugar, and fiber. These carbohydrates are divided into two main components i.e., structural

Table 1 Nutritional values of Sorghum and finger millet *Source* Longvah et al. (2017)

Nutrients	Sorghum (per 100 g)	Finger millet (per 100 g)
Calories (Kcal)	334.13	320.75
Protein (g)	9.97	7.16
Carbs (g)	67.68	66.82
Sugar total (g)	1.27	0.34
Fibre (g)	10.22	11.18
Total fat (g)	1.73	1.92
Saturated fatty acids (g)	0.16	0.31
Polyunsaturated fatty acids (g)	0.52	0.43
Mono unsaturated fatty acids (g)	0.31	0.58
Trans fatty acids (g)	0	0
Cholesterol (mg)	0	0
Omega (mg)	16.54	68.58
Calcium (mg)	27.6	364
Iron (mg)	3.95	4.62
Zinc (mg)	1.96	2.53
Magnesium (mg)	133	146
Chloride (mg)	44	44
Chromium (mg)	0.01	0.03
Copper (mg)	0.45	0.67
Iodine (mcg)	0	0
Manganese (mg)	1.19	3.19
Molybdenum (mg)	0.04	0.01
Phosphorus (mg)	274	210
Potassium (mg)	328	443
Selenium (mcg)	26.29	15.3
Sodium (mg)	5.42	4.75
Vitamin A (mcg)	1.38	0.26
Vitamin B1 (mg)	0.35	0.37
Vitamin B2 (mg)	0.14	0.17
Vitamin B3 (mg)	2.1	1.34
Vitamin B5 (mg)	0.27	0.29
Vitamin B6 (mg)	0.28	0.05
Vitamin B7 (mcg)	0.7	0.88
Vitamin B9 (mcg)	23.1	20.38
Vitamin B12 (mcg)	0	0
Vitamin C (mg)	0	0
Vitamin D (mcg)	3.96	41.46

(continued)

Table 1 (continued)

Nutrients	Sorghum (per 100 g)	Finger millet (per 100 g)
Vitamin E (mg)	0.06	0.16
Vitamin K (mcg)	43.82	3
Vitamin D2 (mcg)	3.96	41.46

and non-structural. The structural component comprises of cellulose, hemicellulose, and non-structural component comprises of sugars, starch, and fructosans. Sorghum has a significant proportion of slow digestible starch (SDS), which has the functional virtue of prolonging digestion and carbohydrate absorption in the colon. This SDS is beneficial for nutritional management as well as metabolic illnesses including diabetes and hyperlipidemia. The fiber content of sorghum is high i.e., 9.7–14.3gm (Longvah et al. 2017), which acts as a bulking agent, cholesterol binding agent, increases transit time, and slows the absorption of carbohydrates all of which help to prevent and manage diseases such as constipation, irritable bowel syndrome, and obesity (Rao 2003).

Sorghum contains a minor amount of lipids which are capable of reducing the blood cholesterol level. 83–88% of the lipid is in the form of unsaturated fatty acids and rest is in the monounsaturated fatty acids (MUFA). Oleic acid, palmitic acid, and linolenic acids are some of the fatty acids that are found in sorghum (Hossain et al. 2022). Vitamins and minerals are found in the aleurone layer and germ of the grain. Sorghum contains fair amount of vitamin B but is deficient in B12. Yellow varieties of sorghum contain fair amount of beta-carotene, lutein, and zeaxanthin. However, it may change according to environment and genes. Sorghum is deficient in vitamin-C but can be synthesized with soaking. It can also provide a good supply of potassium and ideal quantity of magnesium, iron, zinc, and copper, but is a poor source of calcium and sodium.

3 Health Benefits of Sorghum and Finger Millet

Finger millet and Sorghum are popularly known as Ragi and Jowar respectively in India (Gangaiah 2008). Both of these millets are highly nutritious and a highly nutritious, functional and gluten-free grains. Where on one hand finger millet is a great source of Calcium on other hand Sorghum is a good source of Iron and dietary fiber (Martino et al. 2012). Both Finger millet and Sorghum have this interesting property of popping (Kaur et al. 2023).

High amount of dietary fiber in millets; finger millet and sorghum lead to a healthy weight loss. High fiber foods develop sense of satiety for longer and hence help in prevention of overeating. Significant amount of fiber in these millets improves overall digestion and helps in preventing constipation and various other complications (Dayakar Rao et al. 2017). As discussed above these millets are great sources of nutrients like calcium, iron, zinc, potassium and phosphorus magnesium, protein, and vitamin D, vitamin B- complex which helps in proper growth and nutrient uptake (Dayakar Rao et al. 2017; Longvah et al. 2017). Finger millet consists of significant amount of calcium and hence helps in improving overall bone quality and helps in preventing and managing bone-related disorders (Maharajan et al. 2021). Both millets are very good sources of Iron, consumed usually in the form of chapati, porridges, pudding, and snacks (Dayakar Rao et al. 2017). Individuals with raised demands of these nutrients; mensurating girls, pregnant women, and anaemic individuals can add these two millets in their diet to manage Iron deficiencies (Anagha 2023).

Millets are extensively known for low Glycemic Index (GI). After studying numerous statistical analysis and meta-analyses it is concluded that GI of sorghum and finger millet is 52.7 ± 10.3 and hence is beneficial in controlling and managing diabetes. Finger millet and Sorghum are high in dietary fiber helps in reducing cholesterol (LDL), and antioxidants, magnesium helps in reducing heart strokes and atherosclerosis, potassium is a vasodilator helps in lowering blood pressure. Hence they helps in enhancing cardiovascular health (Dayakar Rao et al. 2017) (Tables 2 and 3).

Table 2 Health benefits of finger millet

Health benefits	Research finding	References
Obesity-induced oxidative stress	Mice study was done for 12 weeks, results shows that diet supplemented with Finger millet reduces obesity-induced oxidative stress	Murtaza et al. (2014)
Hyperglycaemia	6 noninsulin dependent diabetes mellitus subjects were taken and consumption of finger millet-based diet resulted in significantly lower plasma glucose levels	Lakshmi Kumari and Sumathi (2002)
Iron-deficiency Anaemia	60 Adolescent girls were selected and divided into 2 groups and dietary supplementation of ragi porridge was done plus examined at 45 days and 90 days. A statistically significant increase in hemoglobin was studied in the intervention group after 90 days	Karkada et al. (2019)
Improve bone density	150 women with low BMD and calcium were divided into 2 groups and one was treated with physical activity and figure millet laddu for 3 days per week for 3 months. The results shows that experimental group had improved amount of calcium and BMD	Sahaya Rani et al. (2021)
Serum LDL, cholesterol, VLDL, triglycerides levels	Trial was conducted on 30 individuals, divided into 2 groups. This study was conducted for 60 days. Experimental group was given 200 g of finger millet flour buns, Significant reduction in serum LDL (11.22%) cholesterol (4.41%) triglyceride (5.11%), VLDL (4.74%)	Sahaya Rani et al. (2021)

Table 3 Health benefits of Sorghum millet

Health benefits	Research finding	References
Obesity	88 subjects were taken and divided into 2 groups, control and trial group, trial group people were asked to take a millet-based diet (Sorghum, pearl millet etc.) and 30 min of walk daily and were observed that there BMI dropped significantly from 30.8 to 29.8. (Study period 3 months)	Anushia et al. (2017)
Hyperglycemia and oxidative damage	Diabetic rats were distributed into 6 groups, control group, 12.5,25,50,75 and 100% treated with sorghum diet daily for 8 weeks. Results shows that consumption of sorghum diet protects from hyperglycemia and oxidative damage	Olawole et al. (2018)
Cardiovascular diseases	60 individuals were subjected to millet-based diet (sorghum, pearl millet and finger millet) for 12 weeks. Total cholesterol, VLDL, triglyceride showed a significant decline	Singh et al. (2020)
Celiac Disease	Sorghum derived food products were given to celiac patients for 5 days and no gastrointestinal and non-gastrointestinal symptoms were seen, No alteration in anti-transglutaminase	Ciacci et al. (2007)
Growth and micronutrient status	160 boys and 160 girls (9–12 yrs) divided into 2 groups of 80 each, one control and other experimental. EG was provided 60% sorghum diet and 40% rice diet and Cg was provided 100% rice diet. Results shows that growth rate and hemoglobin, serum ferritin, albumin, retinol binding protein and iron levels were significantly higher in EG	Prasad et al. (2016)

Finger millet and Sorghum are rich in tryptophan, protein, iron, and calcium These nutrients help in increased production of milk in lactating mothers, and bone health as tryptophan regulates calcium. These millets are a good source of a few important essential amino acids, methionine and lysine, and many antioxidants; phenolic acids, and anthocyanins which help in collagen development which improvs skin elasticity (Dayakar Rao et al. 2017; Anagha 2023). The overview of different health benefits of these millets are mentioned in Fig. 1.

3.1 Nutraceutical Potential of Finger Millet and Sorghum

Millets have proved to be the storehouse of nutrients, therefore have the potential to be used as the treatment for undernutrition. Finger millet and Sorghum is regaining popularity as a component in the manufacture of functional foods. They are intended to allow people to eat enriched meals that are similar to their natural condition rather

Fig. 1 Health benefits of Sorghum and finger millets

than taking dietary supplements in liquid or capsule form. Nutrification is the process through which functional foods are supplemented or fortified (Rathore et al. 2019).

Finger millet is also helpful in reducing the severity of asthma, reducing the incidence of migraine attacks as it is high in magnesium. In research it has been found that finger millet has the potential to reduce the risk of atherosclerosis and has anti diabetic effect (Pradhan et al. 2010). It is also helpful in reducing cholesterol levels as it has a good combination of essential amino acids and vitamins A, B and phosphorus. Finger millet contains polyphenols mainly in the outer seed coat of the grain. Ferulic acid, p-coumaric acid and proanthocyanins are the major phenolics present in finger millets (Rathore et al. 2019). Whereas sorghum has antioxidant properties as it has abundant levels of polyphenols, flavonoids, condensed tannins, phenolic acids: gallic, p-hydroxyl benzoic, vanillic, syringic and protocatechuic acids and hydroxycinnamic acids (coumaric, caffeic, ferulic, and sinapinic acids) (Dayakar Rao et al. 2017) (Fig. 2).

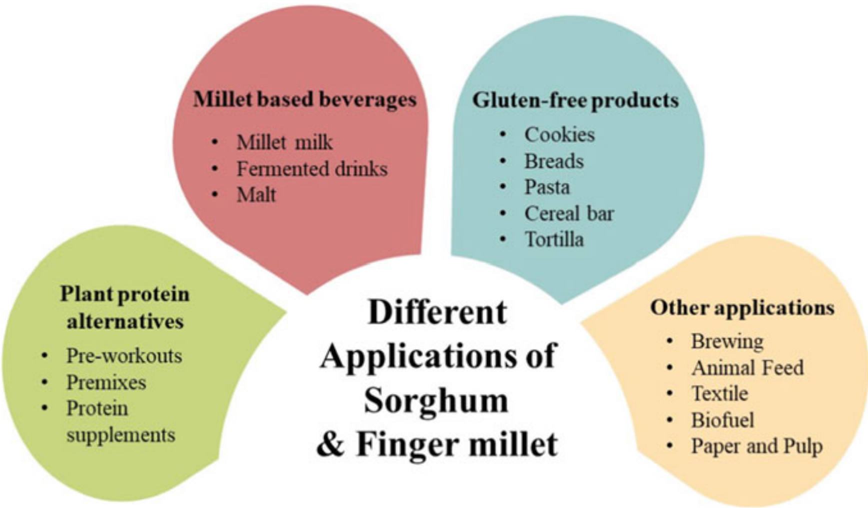

Fig. 2 Different food applications of sorghum and finger millet

4 Applications of Sorghum and Finger Millet in Sustainable Based Food Applications

4.1 Millet Based Beverages (Dairy-Free)

These days there has been a growing trend for the production of healthy foods through the judicious blending of millets with milk or milk products. The idea behind this combination is to obtain an improved product in terms of taste and overall nutrients. Such foods are known as 'Composite Dairy Foods'. These are based on milk and grains that are popular among people of all ages, particularly children. Milk millet-based composite dairy foods have the potential to satisfy the nutritional needs and are cost effective (Prasad 2023).

In today's scenario, 80% of the population is affected by health issues like lactose intolerance and milk allergies, which have led to the change in consumer preferences and replacing milk with plant-based milk beverage. Millets can be utilized for plant-based milk. Ragi and sorghum are sprouted first and then used for making milk (Prasad 2023). Also, the dairy industries are known for the high emission of greenhouse gases therefore the people are now days becoming more aware and are looking for sustainable dietary options (Haas et al. 2019).

In a study (Bembem and Agrahar-Murugkar 2020), a ready-to-drink beverage was developed using sprouted sorghum and finger millet along with other ingredients. This drink was rich in energy, protein, and calcium and have the potential to fulfill one-tenth of recommended daily allowances (RDA). However, these plant-based drinks still face palatability and consumer acceptability issues. Consumers often complain regarding unpleasant taste, earthy or chalky texture and slightly unacceptable mouthfeel. One such suitable way to avoid such organoleptic issues and change the overall appearance of the drink is fermentation. For this purpose, lactic acid bacteria are used. These fermented products promote gut health and enhance protein digestibility and nutrient bioaccessibility, and decrease the level of anti-nutritional factors naturally present in food (Balakrishnan and Schneider 2022).

4.2 Gluten Free Products

Gluten is a storage protein found in many cereals like wheat, barley, oats, spelt and as well as in cross hybrids of these grains in very good amount. Gluten is a linear chain structure but it has the capability to coil and fold itself to form a three-dimensional structure, gliadin is a compact spherical structure and glutenin is an elongated rope like structure. Gluten persists a few very interesting properties; heat stability, moisture retention, viscoelastic property, binding capacity. Water and kneading activate gluten present in the flour, this helps in bread, cookie, sponge, donut, pizza base, brownies and certain other baked items (Tables 3 and 4). Gliadin is a potentially toxic component that can cause certain types of immunological responses and can lead to poor health issues when consumed by people who are gluten sensitive (Biesiekierski 2017). According to FSSAI and FDA, a food product is considered to be "Gluten-Free" only when the amount of gluten present is below 20 ppm, this amount of gluten if consumed by any highly gluten sensitive person, will not show any sort of immunological responses (Cohen et al. 2019).

Finger millet and Sorghum are naturally gluten-free (Jnawali et al. 2016) and highly nutritious in terms of various nutrients. Gluten-sensitive people are usually malnourished because they feed upon basically rice-based food products which leads to malnutrition. Hence Sorghum and finger millet can help these gluten-sensitive people and are a very healthy dietary option for them. Sorghum and finger millet don't alter the level of anti-transglutaminase antibodies even after continuous consumption (Dayakar Rao et al. 2017).

4.3 Millet Based Plant Protein Alternatives

A new emerging field where ancient grains are being used is as vegan meat replacements. Vegan meat replacements are developed especially for flexitarians (those who minimise meat consumption for health/environmental reasons) and vegetarian/vegan consumers to meet their daily protein requirements using plant-based proteins like soyabean, ancient grains and pulses. Most of such products are made with soyabean and cereals which tends to be allergic some of the consumers (Balakrishnan and Schneider 2022).

Table 4 Some gluten free products developed from Sorghum in past are listed below

Product developed	Ingredients	Properties	References
Sorghum cookies	Sorghum flour, Turkish bean flour, gum arabica, Xanthan, Cress seed gum, fenugreek, flaxseed gum, Okra gum (6 variations were developed by different gums)	Gums improved pasting properties, Hardness increased, good protein and fiber content, good taste and texture, rich in minerals, and soluble fibers	Shahzad et al. (2020)
Sorghum Pasta	Sorghum flour, Egg albumen, Egg powder, Xanthan gum, corn starch	Sorghum pasta was better accepted, soft and firm, improved chewiness, high luminosity	Palavecino et al. (2017)
Sorghum Bread	10 different sorghum flours, corn starch, yeast, water salt, sugar	Good color, low loaf height, good crumb formation	Schober et al. (2005)
Sorghum cereal bar	Sorghum, sorghum pop, banana, dates, coconut flakes, buckwheat flakes, almonds, flaxseeds, vanilla. (3 variations of 4,6,8% pop sorghum was prepared)	Improved elasticity, Improved taste and nutritional value, deformation at maximum load	Aleksandrova et al. (2021)
Sorghum tortilla	4 types of sorghum variety were used to develop tortillas	Light color, soft and extensible tortilla, perfect sweetness and grittiness A few varieties of sorghum gave dark color	Winger et al. (2014)
Sorghum papad	Sorghum, finger millet papad in different concentrations of finger millet, 10, 20 30, 40, 50%	Papad with 40% finger millet was best accepted in terms of moisture content, protein, etc	Prabhakar et al. (2017, 2016)

Protein plays a range of functions in foods. Flexibility, solubility, foaming, oil binding, flavour binding, and coagulation are among the functional qualities. High coagulation rate proteins are necessary for the production of meat substitutes. Plant-based proteins, such as millet proteins, are gaining scientific traction in order to meet the growing need for protein-rich diets. Sorghum protein, which has been demonstrated to boost the quantity of protein in the final product, can be used to make a variety of gluten-free products, including pasta, bread, drinks, and premixes. Sorghum protein, which has been demonstrated to boost the quantity of protein in the final product, can be used to make a variety of gluten-free products, including pasta, bread, drinks, and premixes (Madhumitha et al. 2023).

Various critical functions are performed by millet protein in human metabolism. Millet protein can also be a part of infant weaning foods and infant formulas. There are four types of millet protein: glutelin, prolamin, globulin and albumin (Sachdev et al. 2023). Sorghum and finger millet protein is a hypoallergenic protein with a low

Table 5 Some gluten free products developed from finger millet in past are listed below

Products developed	Ingredients	Properties	References
Finger millet cookies	Bajra flour, Buckwheat flour, finger millet flour (4 variations were developed) varying flour proportions	Increased amount of Iron and calcium, High amount of dietary fiber, blend with 20% ragi flour was most acceptable	Bhoite et al. (2018)
Finger millet Pasta	Finger millet, rice, guar gum. (5 variations were developed)	High in Iron and calcium Pasta developed from 40% Finger millet flour and 40% rice and 20% guar gum was highly acceptable in terms of taste and appearance	Singh and Immanuel (2022)
Finger millet cereal bar	Millet flour (Finger millet, pearl millet and sorghum)	Low microbial growth, improved shelf life	Karuppasamy and Latha (2020)
Finger millet flat bread	Rice, sorghum, moong, amaranth, sama, ragi, water chestnut, buckwheat, soy, tamarind kernel, chickpea, black gram and unripe banana flour. (6 variations were developed)	Improved dough making ability, rolling, puffing ability, sensory overall acceptability	Patil et al. (2021)
Finger millet papad	ragi, amaranth, buckwheat, and fava bean flour (Papad biscuit, namakpara, sev were developed)	Protein, calcium and iron content was significantly higher in this flour mix	Yadav (2020)

gluten level that can help avoid celiac disease and is suitable for people of all ages. Millet protein can be tested for compatibility and used to create health-enhancing and promoting food products (Madhumitha et al. 2023).

Using biochemical extraction procedures, underutilised millet seeds could be made commercially available as an alternative protein source in the form of protein concentrate with an acceptable amino acid profile. To meet human protein requirements, the nutritional content of the food can be increased by supplementing with deficient amino acids/complementary proteins.

4.4 Other Food Applications

Sorghum and finger millets have numerous applications in various industries due to their nutritional value and versatile properties. Here are some potential uses of these millets in different sectors:

1. Food and brewing Industry: Millets can be utilized as ingredients in the production of a variety of food items in the food and beverage industry. They can be used to make flour, which can then be used to make bread, cookies, and other bakery goods. It is also possible to create instant mixes, breakfast cereals, and snacks made with millet. Moreover, millets may be fermented to create alcohol-containing drinks such as beer and spirits (Aruna and Visarada 2019).
2. Animal Feed Industry: Millets are an important source of nourishment for cattle in the animal feed industry. They can be used in the formulations of animal feed for animals such as pigs, cattle, and poultry. These millets are rich in essential elements like carbs, proteins, fiber, and minerals, which support general health of animal (Ronda et al. 2019).
3. Textile Industry: millet fibres are utilized by the textile industries to create thin, environmentally friendly materials. Clothing, textiles for the home, and industrial components can all be made with these materials. As a durable, pest-resistant, and moisture-wicking alternative to conventional textile fibres, millet fibres are a fascinating material (Banerjee and Sarkar 2015).
4. Biofuel Production: The Biofuel, bioethanol, and biodiesel can be made from millet. The starches in the grains can be extracted through processing, and after fermentation and distillation, the starches are transformed into ethanol. Millets have the potential to replace fossil fuels as a sustainable and renewable energy source (Stamenković et al. 2020).
5. Pharmaceutical and Cosmetic Industries: Millet extracts offer promise for use in medicinal and cosmetic products. They are beneficial components of skincare, hair care, and dietary supplements due to their anti-inflammatory, antibacterial, and anti-oxidant characteristics (Hasnain et al. 2022).
6. Paper and Pulp Industry: Millet straw can be utilized as a raw material for producing paper and pulp. The straw's high cellulose content makes it suitable for manufacturing biodegradable and recyclable paper products (Belayachi and Delmas 1995).

5 Bioavailability of Sorghum and Finger Millet

Millets are processed using a combination of mechanical and traditional technologies; the mechanical techniques used to process millets include decortication, milling, and sieving; whereas the traditional techniques used to process millets include germination, fermentation, malting, popping, and soaking and cooking; these processes are used to improve the taste, nutritional value, and overall quality of millets (Tharifkhan et al. 2021).

5.1 Mechanical Processing Techniques of Millets

The unwanted components of the harvested millet grains are removed using a variety of mechanical processing procedures. Dehulling, pearling, milling, grinding, and polishing are a few popular processes (Gowda et al. 2022). Dehulling is the process of removing the millet grain's outer shell. This can be accomplished by manually smashing the grains to separate the hulls or by utilising mechanical dehullers. The bran and germ layers are taken off the dehulled grains during the pearling process, which is an additional refinement step. The millet grains' look and texture are enhanced by this treatment.

The process of milling involves turning the dehulled, pearled millet grains into flour. This can accomplish by employing a variety of mills, including roller mills, hammer mills, and stone mills. Milling aids in digestibility improvement and particle size reduction of millet flour, the grains are pounded to remove the hulls (Wang et al. 2022; Jaybhaye et al. 2014).

The millet flour is subsequently broken down into smaller particles using the grinding method. A grinder or a mill can be used for this. Millet flour's smooth and uniform texture can be achieved via grinding. The final step in the mechanical processing of millets is polishing. It entails cleaning the millet grains of any contaminants or other objects that may still be present. Air separation or sieving procedures can be used to accomplish it (Anagha 2023; Kumar et al. 2021).

5.2 Traditional Processing Techniques of Millets

There are various significant processes that have been used for ages when it comes to traditional millet processing. These methods are essential for improving the flavour and nutrition of millets. Here are some tips and guidance from professionals on how to process millets traditionally (Jaybhaye et al. 2014).

- ***Dehulling***: The outer hull that protects millets must be removed before eating. The process of removing this hull is known as dehulling. The millet grains can be manually dehulled by rubbing them between your hands, or mechanically. Millets should be dehulled right before usage in order to preserve their nutritious content (Dinesh Kunkari et al. 2023).
- ***Washing***: After the millets have been dehulled, it's crucial to wash them well to get rid of any contaminants or dust. Rinse the millets many times in clean water until the water is clear. The cleanliness and hygiene of the millets must be ensured by this step (Kumar et al. 2021).
- ***Soaking***: Soaking prior cooking helps to improve the digestion and texture of the millets. Overnight soaking makes the grain tender and reduces the phytic acid content and polyphenolic content due the activation of polyphenol oxidase enzyme. Due to the reduction in these anti nutrients, the protein digestibility is also improved (Yousaf et al. 2021)

- ***Fermentation***: fermented millets are produced in different industries like brewing industries, non-alcoholic beverages, bakery industries etc. It has been found that soluble fiber, protein and fat content improves after fermentation. This may be due to the degradation of cellulose and hemicellulose, synthesis of proteins respectively. However decrease in carbohydrates and crude fiber may be due to enzymatic degradation during fermentation by the microorganisms (Chu et al. 2019)
- ***Malting or germination***: it helps to enhance the functional properties, lowers the antinutrient content and makes the product more digestible. It has been found that the protein and fiber content increases whereas the fat content decreases. Amongst minerals, calcium, iron and vitamin C increases. The carbohydrate content decreases slightly. The reason behind this decrease may be due to the utilization of carbohydrates during sprouting (Chauhan 2018).

These traditional processing techniques of sorghum and finger millets are proven methods to unlock the maximum potential of these nutritious grains. Incorporating these techniques into your cooking will not only improve the taste and texture of millet-based dishes but also ensure that you are getting the most out of their health benefits. Happy cooking with millets (Sarita and Singh 2016; Anagha 2023).

6 Approaches to Improve Sorghum and Finger Millet Consumption

6.1 Effective Promotion of Millets

To combat the problem of adoption of millets in our daily life, several current research initiatives are being conducted. These initiatives aim to raise awareness about the nutritional benefits of finger and sorghum millets, develop innovative and millet-based recipes, and promote their consumption through various platforms (Kumar et al. 2021).

Another strategy is to collaborate with agricultural research organisations to raise millet yields and create high-yielding, disease- and pest-resistant cultivars. This will increase consumers' access to millets and lower their price while also ensuring a consistent supply (Kumar et al. 2021). A comprehensive review showed that different studies project aims to perform studies to emphasise millets' nutritional worth and potential health advantages. In order to comprehend the effects of different millet types on human health, it is necessary to examine the nutrient makeup of those millet varieties. The results of these studies can show millets' potential value in treating a number of health issues and encourage us to include them in our daily diet (Singh et al. 2023).

Furthermore, scientists are investigating novel processing methods to improve the sensory appeal of millet-based goods. To enhance the flavour and texture of millet grains, this entails experimenting with various milling techniques such as pearling and decortication. Additionally, to meet the varied consumer tastes, work is being done to develop value-added millet products such flours, bakery goods, snacks, and ready-to-eat meals (Bhoite et al. 2018; Shahzad et al. 2020).

Research activities are also concentrating on creating advertising campaigns and instructional materials that are aimed at both consumers and members of the food sector in order to raise awareness and promote millets. These advertisements encourage individuals to incorporate millets into their regular diets by highlighting the grains' nutritional advantages, sustainability, and adaptability (King et al. 2017).

6.2 Improvement in the Sensory Attributes of Millet-Based Products

To improve the sensory attributes of millet-based products, there are several research initiatives are worth considering. One approach is to investigate the utilization of different processing techniques such as fermentation, extrusion, and baking, which have been shown to enhance the sensory characteristics of various food products. Additionally, exploring the use of natural additives, such as herbs, spices, and flavoring agents, can help enhance the taste, aroma, and overall sensory experience of millet products. Another avenue to explore is the optimization of formulation and ingredient combinations, ensuring the right balance of texture, flavor, and appearance in millet-based products. Furthermore, sensory evaluation techniques can be employed to gather consumer feedback and preferences, allowing for iterative improvements in product development. Overall, these research initiatives can contribute to enhancing the sensory attributes of millet-based products, making them more appealing to consumers (Bhoite et al. 2018; Mounika et al. 2022).

6.3 Millets Biofortification: A Sustainable Strategy for Nutritional Safety

The process of "biofortifying" millets entails enhancing the nutrient content of millet crops through agricultural methods. Biofortification approaches focus on raising the levels of vital micronutrients, like iron, zinc, and vitamin A, in millet grains to improve the nutritional value of millets. Agronomic practices, genetic engineering, and conventional breeding are just a few of the techniques that can be used to accomplish it (Govindaraj et al. 2020).

Conventional breeding—It's important to select millet cultivars that naturally have higher levels of particular nutrients. By locating and developing millet types with high nutrient contents, this can be accomplished. New types with improved nutritional profiles can be created through careful selection and breeding (Govindaraj et al. 2019).

Genetic engineering—It involves introducing certain genes from other plants that are in charge of nutrient uptake into millet crops. Using this technique, the millet genome may be precisely modified to increase nutrient content. However, it is crucial to make sure that genetically modified millets are safe to eat and do not pose any harm to the ecosystem (Saltzman et al. 2013).

Agronomic practices—The nutrient uptake and accumulation by millet crops can be enhanced by maximizing soil fertility through techniques like balanced fertilization and crop rotation. The increased nutritious content of millet grains can also be attributed to better irrigation practices and appropriate irrigation (Saltzman et al. 2013).

Biofortified Seeds—Increased nutrient content in harvested crops can be achieved by using biofortified seeds, which have been bred or engineered to have higher nutrient levels (Birol et al. 2015).

Overall, millets that have been biofortified provide a useful method for addressing micronutrient deficiencies and enhancing the nutritional status of populations in areas where millet intake is common. To develop millet crops with higher levels of vital micronutrients, it uses advancements in plant breeding, genetic engineering, and agronomic techniques. By encouraging the production and consumption of biofortified millet the problem of malnutrition and community well-being can be improved (Saltzman et al. 2013; Birol et al. 2015).

7 Role of Sorghum and Finger Millet in Food Sustainability

Food sustainability has become worldwide challenge which requires the different innovative approaches to improve the nutritious food supply while minimizing environmental effects. The two ancient millets having climate-resilient properties have gained significant attention in their contribution towards food and nutritional security. They are gluten-free and have various associated health benefits, as they are rich in phytochemicals, protein, dietary fiber, and minerals. Thus, these millets can be ideal components for a nutritious diet for vulnerable population, and helps to improve nutritional diversity (Dayakar Rao et al. 2017).

Climate change has become the serious challenge of food and environmental sustainability (Godfray and Garnett 2014). The International Food Policy Research Institute (IFPRI) projections depicts that yield of major cereals will start decreasing by 5–25% and millets specifically sorghum yield will increase (Ringler et al. 2010). As, both sorghum and finger millet have the ability to sustain harsh weather conditions as well as their roots system give access to water stored in higher depths which enhances resilience to erratic rainfall situations. Thus, Finger millet and sorghum are well suited crop for the feed security (Pontieri et al. 2022; Rurinda et al. 2014).

Sorghum and finger millet has lower production cost and high net income when compared to the major cereals corn, wheat or rice (Staggenborg et al. 2008). In a comparative trial between sorghum and finger millet of water deficit irrigation, it was found out that sorghum is more efficient as it has better surface biomass, yield index and water use than maize. This implies sorghum overall return is higher in water deficit, semi-arid or arid areas (Farré and Faci 2006). A meta-analysis (Zereyesus and Dalton 2017) depicted that sorghum and finger millets research are creating significant producer and consumer advantages for billions of people living in arid or semi-arid regions. Thus, creating high social returns in research investments which averages to 20% per year. As these millets use minimal water, fertilizers and pesticides inputs, this makes them best suited for promoting effective land use by intercropping and agroforestry techniques. Their short growth cycles also enable for more harvesting flexibility, which aids in sustainable management of land. It is apparent that sorghum and finger millets has significant potential of being profitable agricultural system with benefits of with high tolerance to environmental pressures caused by climate change (Kumar et al. 2018).

The reintroduction of sorghum and finger millet agriculture not only helps to ensure food sustainability, as well as empowers local population by maintaining traditional practises and sustaining local businesses. These millets have great cultural value in many communities, and their ongoing cultivation contributes to the preservation of cultural history while also providing a source of food security and a means of subsistence. Incorporation of these millets into meals diversify dietary options and boosts nutrient intake. Their addition can help to alleviate malnutrition and health concerns related to diet by giving alternatives to refined grains (Nagarajan et al. 2007). Both these millets can be processed and modified into different meals such as flours, malt, porridge, and baked products, creating variety of value-added processed food products in the market. Their adaptability in culinary methods makes them amenable to varied traditions and tastes, enhancing their ability to be more important in contemporary diets. Simple processing techniques such as soaking, fermentation, malting or germination can help in combating the protein energy malnutrition, as it improves proteins and mineral bioavailability (Gowda et al. 2022).

The descriptive overview of the contribution of sorghum and finger millets on different sectors of food sustainability is mentioned in Fig. 3. Therefore, Sorghum and finger millet not just ancient crops, they are effective tools in the fight for food sustainability. As they have efficiency of climatic resistance, nutritional value, water efficiency, and economical advantages, they are perhaps more critical parameters of resilient and diverse global food system. Including these millets in regular meals can benefits in healthy, balanced and economic diets As we strive for a more sustainable future, these millets provides crucial means of striking a balance between feeding a rising population and conserving global resources (Gowda et al. 2022; Dayakar Rao et al. 2017).

8 Conclusion

Sorghum and finger millet are two important millet crops with several nutritional benefits. As discussed in the chapter these two millets have now gained a pace for its utilization for various industrial purposes. The important aspect of this chapter

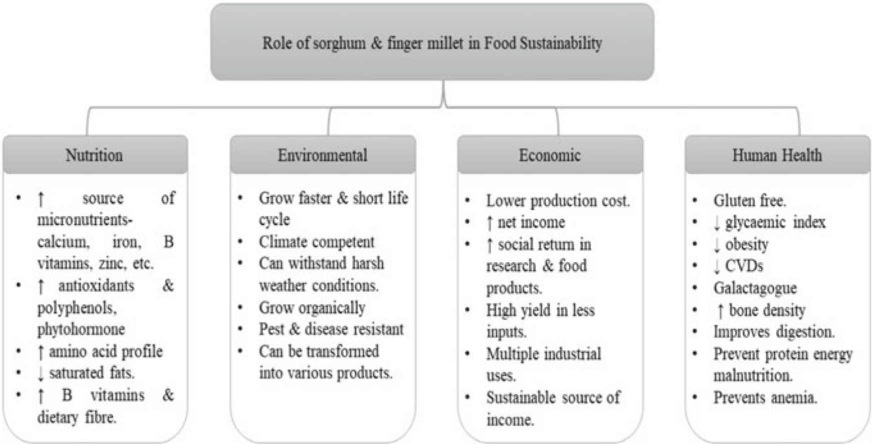

Fig. 3 Role of Sorghum and Finger millet on different sectors of food sustainability

is that these millet-based products have adequate amount of nutrients, vegan and environment friendly. Also, promotion of such products can prove to be helpful for the farmers and cultivators as millets are climate competent crops and shows good productivity in comparatively low agricultural inputs. But still millets are underutilized because of various reasons like lack of awareness, processing prior to cooking and digestibility.

9 Future Scope

Millets, a highly nutritious grain, has gained popularity in recent years due to its health benefits and versatility and potential to address the nutritional security and food sustainability. Millets need to be utilized for the culinary purposes by collaborating with restaurants, food bloggers, chefs and culinary influencers to promote millet as a key ingredient in modern and healthy cuisine. Millets still needs more marketing campaigns to highlight its potential benefits. Also, Development of farming practices that optimize water usage, reduce pesticide use, and improve soil health. Advocate for millet cultivation as an environmentally friendly option for farmers. Identify potential markets and consumer segments abroad where millet consumption is currently low and developing strategies to introduce and promote millet-based products in these markets. Analyse consumer preferences, cultural nuances, and regulatory requirements to ensure successful entry into international markets.

References

Aleksandrova A, Mykolenko S, Tymchak D, Aliieva O (2021) Effect of pop Sorghum on the quality of glutenfree cereal bars. Sci Rise 6:3–10

Anagha K (2023) Millets: nutritional importance, health benefits, and bioavailability: a review. Ener 329(328):361

Anushia K, Uma Mageshwari J, Trueman P, Viswanathan V (2017) The effect of millet supplementation on weight and lipid profile. TAPI J 13(3)

Aruna C, Visarada K (2019) Sorghum grain in food and brewing industry. In: Breeding Sorghum for diverse end uses. Elsevier, pp 209–228

Balakrishnan G, Schneider RG (2022) The role of Amaranth, quinoa, and millets for the development of healthy, sustainable food products—a concise review. Food 11(16):2442

Banerjee A, Sarkar AK (2015) Extraction, characterization, and evaluation of proso millet starch in textile printing. AATCC J Res 2(6):14–19

Belayachi L, Delmas M (1995) Sweet sorghum: a quality raw material for the manufacturing of chemical paper pulp. Biomass Bioen 8(6):411–417

Bembem K, Agrahar-Murugkar D (2020) Development of millet based ready-to-drink beverage for geriatric population. J Food Sci Technol 57(9):3278–3283

Bhoite A, Dere A, Dhangare U (2018) Formulation of finger millet cookies & studies on nutritional and sensory attributes. Int J Adv Res Innov 6(1):1–2

Biesiekierski JR (2017) What is gluten? J Gastroenterol Hepatol 32:78–81

Birol E, Asare-Marfo D, Karandikar B, Roy D, Diressie MT (2015) Investigating demand for biofortified seeds in developing countries: high-iron pearl millet in India. J Agribus Dev Emerg Econ 5(1):24–43

Chauhan ES (2018) Effects of processing (germination and popping) on the nutritional and anti-nutritional properties of finger millet (Eleusine coracana). Curr Res Nutr Food Sci J 6(2):566–572

Chu J, Zhao H, Lu Z, Lu F, Bie X, Zhang C (2019) Improved physicochemical and functional properties of dietary fiber from millet bran fermented by Bacillus natto. Food Chem 294:79–86

Ciacci C, Maiuri L, Caporaso N, Bucci C, Del Giudice L, Massardo DR, Pontieri P, Di Fonzo N, Bean SR, Ioerger B (2007) Celiac disease: in vitro and in vivo safety and palatability of wheat-free sorghum food products. Clin Nutr 26(6):799–805

Cohen IS, Day AS, Shaoul R (2019) Gluten in celiac disease—more or less? Rambam Maimonides Med J 10(1)

Cole MB, Augustin MA, Robertson MJ, Manners JM (2018) The science of food security. NPJ Sci Food 2(1):14

Dayakar Rao B, Bhaskarachary K, Arlene Christina G, Sudha Devi G, Vilas AT (2017) Nutritional and Health benefits of Millets. ICAR_Indian Institute of Millets Research (IIMR) Rajendranagar, Hyderabad. 2)(PDF) Nutr Health Benefits Millets 11

Dekka S, Paul A, Vidyalakshmi R, Mahendran R (2023) Potential processing technologies for utilization of millets: an updated comprehensive review. J Food Proc Engg e14279

Farré I, Faci JM (2006) Comparative response of maize (Zea mays L.) and sorghum (Sorghum bicolor L. Moench) to deficit irrigation in a Mediterranean environment. Agri Water Manag 83(1–2):135–143

Fischer HW, Reddy NN, Rao MS (2016) Can more drought resistant crops promote more climate secure agriculture? Prospects and challenges of millet cultivation in Ananthapur, Andhra Pradesh. World Dev Persp 2:5–10

Gangaiah B (2008) Millets: Sorghum (Jowar), Pearl Millet (Bajra), Finger Millet. In: Agronomy—Kharif Crops. Applied Zoo IARI

Godfray HCJ, Garnett T (2014) Food security and sustainable intensification. Phil Transa Royal Soc b: Biol Sci 369(1639):20120273

Govindaraj M, Rai KN, Cherian B, Pfeiffer WH, Kanatti A, Shivade H (2019) Breeding biofortified pearl millet varieties and hybrids to enhance millet markets for human nutrition. Agri 9(5):106

Govindaraj M, Virk PS, Kanatti A, Cherian B, Rai K, Anderson MS, Pfeiffer WH (2020) Biofortified pearl millet cultivars offer potential solution to tackle malnutrition in India. In: Quantitative genetics, genomics and plant breeding. CABI Wallingford UK, pp 385–396

Gowda NN, Siliveru K, Prasad PV, Bhatt Y, Netravati B, Gurikar C (2022) Modern processing of Indian millets: a perspective on changes in nutritional properties. Foods 11(4):499

Gregory PJ, George TS (2011) Feeding nine billion: the challenge to sustainable crop production. J Exper Bot 62(15):5233–5239

Grovermann C, Umesh K, Quiédeville S, Kumar BG, Moakes S (2018) The economic reality of underutilised crops for climate resilience, food security and nutrition: assessing finger millet productivity in India. Agri 8(9):131

Haas R, Schnepps A, Pichler A, Meixner O (2019) Cow milk versus plant-based milk substitutes: a comparison of product image and motivational structure of consumption. Sustain 11(18):5046

Hasnain A, Naqvi SAH, Ayesha SI, Khalid F, Ellahi M, Iqbal S, Hassan MZ, Abbas A, Adamski R, Markowska D (2022) Plants in vitro propagation with its applications in food, pharmaceuticals and cosmetic industries; current scenario and future approaches. Front Plant Sci 13:1009395

Hossain MS, Islam MN, Rahman MM, Mostofa MG, Khan MAR (2022) Sorghum: a prospective crop for climatic vulnerability, food and nutritional security. J Agri Food Res 8:100300

Jaybhaye R, Pardeshi I, Vengaiah P, Srivastav P (2014) Processing and technology for millet based food products: a review. J Ready Eat Food 1(2):32–48

Jnawali P, Kumar V, Tanwar B (2016) Celiac disease: overview and considerations for development of gluten-free foods. Food Sci Human Well 5(4):169–176

Karkada S, Upadhya S, Upadhya S, Bhat G (2019) Beneficial effects of ragi (finger millet) on hematological parameters, body mass index, and scholastic performance among anemic adolescent high-school girls (AHSG). Comprehen Child Adol Nurs 42(2):141–150

Karuppasamy P, Latha M (2020) Assessment and comparison study of millet bar with farmer practice through on farm trial (2018–19). J Pharmacognosy Phytochem 9(4S):381–384

Kaur H, Oberoi HK, Ganapathy K, Bhardwaj R (2023) Effect of popping and malting processing techniques on physiochemical, antinutrients and antioxidant properties of millets flour. J Food Sci Technol 1–15

King E, Padulosi S, Meldrum G (2017) Millets and markets–need for networking and integration. LEISA-India

Kumar A, Tomer V, Kaur A, Kumar V, Gupta K (2018) Millets: a solution to agrarian and nutritional challenges. Agri Food Secu 7(1):1–15

Kumar A, Tripathi MK, Joshi D, Kumar V (2021) Millets and millet technology, 1st edn. Springer, Singapore

Kunkari D, Lokhande M, Gaikwad ST (2023) Traditional and advance processing technology of millets—a review. J Emerg Technol Inno Res 10(04)

Lakshmi Kumari P, Sumathi S (2002) Effect of consumption of finger millet on hyperglycemia in non-insulin dependent diabetes mellitus (NIDDM) subjects. Plant Foods Human Nutr 57:205–213

Longvah T, Anantan I, Bhaskarachary K, Venkaiah K, Longvah T (2017) Indian food composition tables. National Institute of Nutrition, Indian Council of Medical Research Hyderabad

Madhumitha RVS, Mahendran R (2023) Millet is an alternative source of plant protein. Just Agri vol 3

Maharajan T, Antony Ceasar S, Ajeesh Krishna TP, Ignacimuthu S (2021) Finger millet [Eleusine coracana (L.) Gaertn]: an orphan crop with a potential to alleviate the calcium deficiency in the semi-arid tropics of Asia and Africa. Front Sustain Food Sys 5:684447

Martino HSD, Tomaz PA, Moraes E, Conceição Ld, Oliveira DdS, Queiroz VAV, Rodrigues JAS, Pirozi MR, Pinheiro-Sant'Ana HM, Ribeiro SMR (2012) Chemical characterization and size distribution of sorghum genotypes for human consumption. Rev Inst Adolfo Lutz 71(2):337–344

Mounika D, Sangeetha U, Sireesha G (2022) Estimation of phytochemicals in Millets and selected Millet products. Ind J Appl Pure Bio 37:810–820

Murtaza N, Baboota RK, Jagtap S, Singh DP, Khare P, Sarma SM, Podili K, Alagesan S, Chandra T, Bhutani K (2014) Finger millet bran supplementation alleviates obesity-induced oxidative stress, inflammation and gut microbial derangements in high-fat diet-fed mice. Br J Nutr 112(9):1447–1458

Nagarajan L, Smale M, Glewwe P (2007) Determinants of millet diversity at the household-farm and village-community levels in the drylands of India: the role of local seed systems. Agricult Econ 36(2):157–167

Olawole TD, Okundigie MI, Rotimi SO, Okwumabua O, Afolabi IS (2018) Preadministration of fermented sorghum diet provides protection against hyperglycemia-induced oxidative stress and suppressed glucose utilization in alloxan-induced diabetic rats. Front Nutr 5:16

Palavecino PM, Bustos MC, Heinzmann Alabí MB, Nicolazzi MS, Penci MC, Ribotta PD (2017) Effect of ingredients on the quality of gluten-free sorghum pasta. J Food Sci 82(9):2085–2093

Patil S, Sonawane SK, Arya S (2021) Chemometric approach-based characterization and screening of gluten free flours for development of Indian unleavened flatbread. J Food Sci Technol 58:1829–1838

Pontieri P, Mennini FS, Magni D, Fiano F, Scuotto V, Papa A, Aletta M, Del Giudice L (2022) Sustainable open innovation for the agri-food system: Sorghum as healthy food to deal with environmental challenges. Br Food J 124(9):2649–2672

Prabhakar B, More D, Shivashankar S, Mallesh S, Babu GN (2016) Physico-chemical and sensory evaluation of sorghum-finger millet papad. Int J Food Fermen Technol 6(2):387–395

Prabhakar B, More D, Srilatha P, Fulchand CR (2017) Screening of sorghum varieties for papad preparation. Int J Curr Microbiol App Sci 6(7):1116–1124

Pradhan A, Nag S, Patil S (2010) Dietary management of finger millet (Eleusine coracana L. Gaerth) controls diabetes. Curr Sci 98(6):763–765

Prasad MPR, Benhur D, Kommi K, Madhari R, Rao MV, Patil J (2016) Impact of Sorghum supplementation on growth and micronutrient status of school going children in Southern India—a randomized trial. Ind J Pedia 83:9–14

Prasad S (2023) Application of millets in milk-millet based composite food: a review

Prosekov AY, Ivanova SA (2018) Food security: the challenge of the present. Geoforum 91:73–77

Rao BN (2003) Bioactive phytochemicals in Indian foods and their potential in health promotion and disease prevention. Asia Pacific J Cli Nutr 12(1)

Rathore T, Singh R, Kamble DB, Upadhyay A, Thangalakshmi S (2019) Review on finger millet: processing and value addition. Pharma Inno J 8(4):283–291

Ringler C, Zhu T, Cai X, Koo J, Wang D (2010) Climate change impacts on food security in Sub-Saharan Africa: Insights from comprehensive climate change scenarios. International Food Policy Research Institute (IFPRI)

Ronda V, Aruna C, Visarada K, Bhat BV (2019) Sorghum for animal feed. In: Breeding Sorghum for diverse end uses. Elsevier, pp 229–238

Rurinda J, Mapfumo P, Van Wijk M, Mtambanengwe F, Rufino MC, Chikowo R, Giller KE (2014) Comparative assessment of maize, finger millet and sorghum for household food security in the face of increasing climatic risk. Eur J Agron 55:29–41

Sachdev N, Goomer S, Singh LR, Pathak VM, Aggarwal D, Chowhan RK (2023) Current status of millet seed proteins and its applications: a comprehensive review. Appl Food Res 100288

Sahaya Rani G, Swaminathan A, Vijayaraghavan R (2021) Effectiveness of physical activity and finger millet-based food supplement on biochemical parameters and bone mineral density among premenopausal women. Evid Based Comp Altern Med 2021:1–7

Saltzman A, Birol E, Bouis HE, Boy E, De Moura FF, Islam Y, Pfeiffer WH (2013) Biofortification: progress toward a more nourishing future. Global Food Sec 1:9–17

Sarita ES, Singh E (2016) Potential of millets: nutrients composition and health benefits. J Scien Innov Res 5(2):46–50

Schober TJ, Messerschmidt M, Bean SR, Park SH, Arendt EK (2005) Gluten-free bread from sorghum: quality differences among hybrids. Cereal Chem 82(4):394–404

Shahzad SA, Hussain S, Mohamed AA, Alamri MS, Qasem AAA, Ibraheem MA, Almaiman SAM, El-Din MFS (2020) Gluten-free cookies from sorghum and Turkish beans; effect of some non-conventional and commercial hydrocolloids on their technological and sensory attributes. Food Sci Technol 41:15–24

Singh R, Fedacko J, Mojto V, Isaza A, Dewim M, Watanabe S, Chauhan A, Fatima G, Kartikey K, Sulaeman A (2020) Effects of millet based functional foods rich diet on coronary risk factors among subjects with diabetes mellitus: a single arm real world observation from hospital registry. MOJ Public Health 9(1):18–25

Singh S, Yadav R, Tripathi AK, Kumar M, Kumar M, Yadav S, Kumar D, Kumar S, Yadav R (2023) Current status and promotional strategies of millets: a review. Int J Environ Clim Change 13(9):3088–3095

Singh K, Immanuel G (2022) Physico–chemical, nutritional and sensorial characteristics of ragi pasta enriched with rice and guar gum

Staggenborg SA, Dhuyvetter KC, Gordon W (2008) Grain sorghum and corn comparisons: yield, economic, and environmental responses. Agronomy J 100(6):1600–1604

Stamenković OS, Siliveru K, Veljković VB, Banković-Ilić IB, Tasić MB, Ciampitti IA, Đalović IG, Mitrović PM, Sikora VŠ, Prasad PV (2020) Production of biofuels from sorghum. Renew Sustain Energy Rev 124:109769

Thapliyal V, Singh K (2015) Finger millet: potential millet for food security and power house of nutrients. Intern Res Agri Fores 2(2)

Tharifkhan SA, Perumal AB, Elumalai A, Moses JA, Anandharamakrishnan C (2021) Improvement of nutrient bioavailability in millets: emphasis on the application of enzymes. J Sci Food Agri 101(12):4869–4878

Wakeel A, Farooq M, Bashir K, Ozturk L (2018) Micronutrient malnutrition and biofortification: recent advances and future perspectives. In: Hossain MA, Kamiya T, Burritt DJ, Tran L-SP, Fujiwara T (eds) Plant micronutrient use efficiency. Academic Press, Cambridge, MA, USA, pp 225–243

Wang H, Fu Y, Zhao Q, Hou D, Yang X, Bai S, Diao X, Xue Y, Shen Q (2022) Effect of different processing methods on the millet polyphenols and their anti-diabetic potential. Front Nutr 9:780499

Winger M, Khouryieh H, Aramouni F, Herald T (2014) Sorghum Flour characterization and evaluation in gluten-free flour tortilla. J Food Qual 37(2):95–106

Yadav LYA (2020) Standardization, development and organoleptic evaluation of food products prepared from gluten free flour mix. Pharma Inno J 9(6)

Yousaf L, Hou D, Liaqat H, Shen Q (2021) Millet: a review of its nutritional and functional changes during processing. Food Res Intern 142:110197

Zamaratskaia G, Gerhardt K, Wendin K (2021) Biochemical characteristics and potential applications of ancient cereals—an underexploited opportunity for sustainable production and consumption. Trend Food Sci Technol 107:114–123

Zereyesus YA, Dalton TJ (2017) Rates of return to sorghum and millet research investments: a meta-analysis. PLoS ONE 12(7):e0180414

Conservation and Promotion of Traditional Food Culture

Food Fermentation: A Sustainable Approach to Enrich Water Soluble Vitamins

Mayuri Rastogi, Shivangi Mishra, and Vandana Singh

1 Introduction

Fermentation is one of the major metabolic processes which is responsible for the breakdown of large organic molecular units into smaller organic molecular units (in simplest form). It is an anaerobic pathway that involves unicellular eukaryotes and prokaryotes that shoot up their numbers in millions and billions to get desired results. Though this process also reduced the cooking time of the food. Further talking about the process of fermentation in brief, the process involves the oxidation of glucose partially which leads to the forming of acids and alcohols. For example, in single-cell living organism, glucose oxidized partially to form pyruvic acid then gets converted into ethanol or carbon dioxide and in anaerobic condition lactic acid is produced by reducing pyruvic acid during the process of fermentation in the presence of lactate dehydrogenase enzymes (Fuhrmann 2021).

There are three different types of fermentation-

- Lactic Acid Fermentation
- Acetic Acid Fermentation
- Alcohol Fermentation

1. ***In Lactic acid fermentation***: lactic acid is produced by converting sugar and starch using bacterial strains.
2. ***For Acetic acid fermentation***: starch in grains is fermented into vinegar and condiments.
3. ***In Alcohol fermentation***: after the process of glycolysis, pyruvate acid is formed and then converted into ethanol and carbon dioxide (Fig. 1)

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2 Biochemical Changes During Fermentation

Fermentation is now globally utilized and maneuverer by thousands of food production industries on a bigger scale due to its desirable benefits. Fermented food products give way more benefits to consumers compared to normal unfermented foods, because of the production and increase of several high numbers of antioxidants, peptides, probiotic properties, organoleptic properties, and antimicrobial activity (Xiang et al. 2019a, b). Rollen et al. (2019) reported the Lactic acid fermentation, enhances, protein bioavailability by reducing limiting amino acids, breaking down proteins to small peptides and also increases the accessibility of micronutrients. The fermentation reduces the antinutrients like phytates, tannins and oligosaccharides by 50–90% during the process. Natural food fermentation results in scientifically proven boundless changes in foods, though it is responsible for enhancing flavours, essential amino acids, improving vitamins, proteins, appearance (Colgrave et al. 2021) and shelf life of the fermented food (Kumar et al. 2017).

The process of fermentation is known to decrease the way harmful content of the food, which is toxins and anti-nutrient factors from the raw material, for example, the phytic acid concentration, saponins, and flatulence factors are reduced by the fermentation of soya bean (Liu et al. 2022) and poisonous cyanide content reduction is also seen during the fermentation of cassava (Halake et al. 2017). It is also scientifically proven by Tawakoli et al. (2019) that with decrease in the content of toxins and anti-nutritional factors, the number of antioxidants with their capacity also increases. For instance, curd and yogurt are having higher antioxidant properties in comparison with normal milk, it happens due to the release of biopeptides after proteolysis of milk proteins.

Microbial fermentation and vitamin production, it has been proven that the enhancement and synthesis of growth factors and complex vitamins are held. In general, fermentation result in the synthesis of water-soluble vitamins including, vitamin B complex (riboflavin, niacin, pyridoxine, folate, thiamine, cobalamin, pantothenic acid) and Vitamin C, vitamin K, vitamin E (fat-soluble).

3 Microbes Used for Fermentation

Fermentation is a natural process that has been used by humans for centuries to produce various types of food and beverages. During fermentation, microorganisms like bacteria, yeast, mold, and fungi break down sugars and other organic compounds in food and release enzymes and other byproducts that give the food its characteristic flavor, texture, and nutritional value. In this article, we will explore the different types of microbes that are commonly used for fermentation and their specific roles in producing different types of fermented foods and beverages (Table 1).

Table 1 Microbes used for fermentation and their yield

Microbes used	Vitamin produced	Media used	Yield	Refs.
E. *coli*	Vitamin B1	MM	0.82 mg/L	Cardinale et al. (2017)
	Vitamin B3	LB Media, 2YT Media	519 gm/L	Jaehme et al. (2014)
	Vitamin B6	MM	83–87 gm/L	Hoshino et al. (2004) Richts et al. (2021)
	Vitamin B7	MM, H Media	15 mg/L	Lim et al. (2023); Ledesma et al. (2013)
	Vitamin B12	CM Media		
B. *subtilis*	Vitamin B1	MM	1.30 mg/L	Hassaan et al. (2018)
	Vitamin B2	MM	16 gm/L	Lu et al. (2023)
	Vitamin B5	MM	85–88 gm/L	Hoshino et al. (2004)
	Vitamin B6	MM	70 mg/L	Richts and Commichau (2021)
	Vitamin B7	MM	22 mg/L	Hoshmann et al. (2017)
A. *oryzae*	Vitamin B1	CD-Dex media		Zhang et al. 2015
A. *gossypii*	Vitamin B2	YPD-Plant oil	30 gm/L	Schwechheimer et al. 2018
Candida *famata*	Vitamin B2	YPD-Fluorophenilalanine	1100 mg/L	Dmytruk et al. (2011)
Yeast	Vitamin B3	YPD; Nicotinic acid	10 mg L	Belenky et al. (2011)
C. *glutamicum*	Vitamin B5	MM	900 mg/L	Leonardi and Jackowski (2007)
S. *melilotis*	Vitamin B6	MM	1.40 g/L	Acevedo-Rocha et al (2019)
Agrobacterium	Vitamin B7	MM; Betain	110 mg/L	Streit and Entcheva (2003)
P. *denitrificans*	Vitamin B12	Betain; Beet Molasses	215.25 mg/L	Li et al. (2008)
Propionobactrium shemani	Vitamin B12	YEL, DMBI	208 mg/L	Chamlagain et al. (2018)

(continued)

Table 1 (continued)

Microbes used	Vitamin produced	Media used	Yield	Refs.
Lactobacilus bravis	Vitamin B12, Vitamin B2	YEL, DMBI	9 mg/L	Xie et al. (2019)
L. planatarum	Vitamin B12	MRS Media		Zhang et al. (2023)
K. vulgare	Vitamin C	Glycerol; Bakers Yeast	1.30–1.40 gm/L	Sugisawa et al. (2005); Ma et al. (2019)
B. endophyticus	Vitamin C	D-sorbitol	70–75 gm/L	Ma et al. (2019)
S. cerevisiae	Vitamin C	MM	100 gm/L	Zhou et al. (2021)
G. oxydans		D-Sorbitol	74 gm/L	Pappenberger and Hohmann (2014)

3.1 Bacteria

Foods often contain a variety of bacteria, some of which may be beneficial, such as those preserving foods through products of fermentation, while others may be harmful by resulting in human illness or food spoiling (Ayivi et al. 2020) One of the most significant groups of microbes employed in food fermentations is the lactic acid bacteria, which are mostly found in the genera *Carnobacterium, Enterococcus, Lactobacillus, Lactococcus, Leuconostoc, Oenococcus, Pediococcus, Streptococcus, Tetragenococcus, Vagococcus*, and *Weissella* (Dimidi et al. 2019). Effective carbohydrate fermentation along with substrate-level phosphorylation is the key component of lactic acid bacteria metabolism. This type of fermentation is commonly used to produce dairy products like yogurt, cheese, and sour cream, as well as fermented vegetables like sauerkraut and kimchi.

Other than LAB, other bacteria also have a considerable impact on flavour enhancement and other aspects of fermented products. The most well-known and widely studied Propionibacterium, is used as starter culture in dairy products to develop distinctive eyes and flavour of Swiss cheese. These bacteria can thrive in the acidic environment created by their production of lactic acid, which inhibits the growth of harmful bacteria and preserves the food (Ayivi et al. 2020).

3.2 Fungi

Fungi are a diverse group of organisms that include both molds and yeast. Certain types of fungi are used in fermentation to produce a variety of fermented foods and beverages.

A. oryzae is a type of fungus that is used to ferment soybeans to produce soy sauce and miso, two staple condiments.

3.2.1 Yeast

Yeast is a type of single-celled fungus that is used in fermentation to produce alcoholic beverages like wine, beer, and spirits, as well as non-alcoholic beverages like kombucha. Yeast converts sugars and other carbohydrates into alcohol and carbon dioxide through a process known as alcoholic fermentation (Copetti. 2019). The most common strain of yeast used in fermentation is *Saccharomyces cerevisiae*, also known as brewer's yeast (Cahill et al. 2022). This strain of yeast is used to produce beer, wine, and other alcoholic beverages, as well as bread and other baked goods (Cahill et al. 2022; Nya and Etukudo 2023). Other strains of yeast that are used for fermentation include *Candida*, which is used to produce kefir, a fermented milk drink, and Kombucha, a fermented tea beverage. These yeasts produce a variety of enzymes and other byproducts that give these beverages their unique flavour and nutritional properties (Ashaolu 2019; Nya and Etukudo 2023).

3.2.2 Molds

Molds is a type of fungus that is used in fermentation to produce certain types of fermented foods, like tempeh and certain types of cheese (Copetti . 2019; An et al. 2023). Mold breaks down the protein and other nutrients in food and releases enzymes and other byproducts that give the food its characteristic flavour and texture (Barzee et al. 2021; Alam et al. 2021; An et al. 2023). One common type of mold used in fermentation is *Rhizopus oligosporus*, which is used to produce tempeh, a traditional Indonesian food made from fermented soybeans. The mold helps to break down the protein in the soybeans and create a dense, chewy texture that is rich in protein and other nutrients (Yarlina et al. 2023). Other types of mold used in fermentation include *Penicillium*, which is used to produce blue cheese and Roquefort cheese, and *Aspergillus oryzae*, which is used to ferment soybeans to produce soy sauce and miso (Singh et al. 2021; Alam et al. 2021).

4 Production of Vitamin B Complex

4.1 Fermentation

Vitamin B complex refers to a group of water-soluble vitamins that are essential for various biological processes in the human body. Due to their numerous uses in food, medication, feed, and other industries, B vitamins are in greater demand on a global scale (Rollan et al. 2019) Although the majority of vitamins are produced through chemical synthesis, productive industrial bioprocesses have been devised to produce Vitamin B2 and Vitamin B12. A naturally and economically intriguing method to increase the vitamin content of fermented foods is by microbial vitamin synthesis (Ashaolu et al. 2019). Since microbes also need vitamins for growth, fermentation does not necessarily result in higher vitamin concentrations. Streptococcus thermophilus and Propionibacteria, which produce folate and vitamin B12, respectively, are two well-known microbes for generating vitamins (Wu et al. 2019). Gu et al. (2015) have found the production of vitamin B12(18 μg/100 ml) by using Lactobacillus reuteri. In addition to these various traditional foods have been studied so far for their water-soluble vitamin production during microbial fermentation (Gu et al. 2015; Bishop et al. 2022).

Microbial production of vitamin B complex involves the use of microorganisms such as bacteria, fungi, and yeast, which can synthesize these vitamins (Sharma et al. 2020) The most commonly used microorganisms for the production of vitamin B complex are bacteria, particularly the genus Bacillus, and fungi, such as Aspergillus and Rhizopus.

The production of vitamin B complex by microbial fermentation involves several stages. The first stage involves the selection of the appropriate microorganism, which is capable of producing the desired vitamin. The selected microorganism is then cultured under controlled conditions, such as temperature, pH, and oxygen supply, to optimize the production of the vitamin B complex (Wang et al. 2021).

During the fermentation process, the microorganisms produce vitamin B complex by synthesizing it from precursor molecules, such as amino acids and sugars. The final yield of vitamin B complex depends on various factors, including the strain of the microorganism, the composition of the culture medium, and the fermentation conditions (Calvillo et al. 2022). The production of vitamin B complex by microbial fermentation has several advantages over chemical synthesis and extraction from natural sources. Microbial production is a more sustainable and eco-friendly method, as it reduces the reliance on non-renewable resources and minimizes waste generation (Labuschagne et al. 2021). Moreover, microbial production allows for the production of high-purity vitamins with consistent quality and quantity.

In conclusion, microbial production of vitamin B complex is a promising method for meeting the growing demand for these essential vitamins. The use of microorganisms for the synthesis of vitamin B complex is a sustainable and cost-effective approach that can help to ensure the availability of these vitamins for human health and well-being.

4.2 Metabolic Pathway for Fermentation

Fermentation is a metabolic pathway that operates in the absence of oxygen or with limited oxygen supply, also known as anaerobic respiration. The primary goal of fermentation is to generate ATP by utilizing the energy stored in organic molecules such as glucose (Fuhrmann 2021). In the absence of oxygen, the electron transport chain, which normally operates in the presence of oxygen to generate ATP, cannot function. Instead, fermentation pathways utilize other electron acceptors, such as pyruvate, to generate ATP (Xiang et al. 2019a, b). The production of vitamin B complex in fermentation pathways requires a series of biochemical reactions that involve various enzymes and coenzyme.

The first step in the fermentation pathway for the production of vitamin B complex is the conversion of glucose to pyruvate. This process is known as glycolysis and involves a series of ten enzyme-catalyzed reactions that occur in the cytoplasm of the cell. Glycolysis begins with the phosphorylation of glucose to glucose-6-phosphate and ends with the production of two molecules of pyruvate, two molecules of ATP, and two molecules of NADH (Marie et al. 2016). The next step in the fermentation pathway is the conversion of pyruvate to different end products, depending on the type of microorganism involved in the fermentation process. For example, in alcoholic fermentation, pyruvate is converted to acetaldehyde and then to ethanol, which is the end product (Koubaa et al. 2021). In lactic acid fermentation, pyruvate is directly converted to lactic acid. The conversion of pyruvate to different end products is catalyzed by various enzymes and involves the transfer of electrons from NADH to pyruvate, forming NAD+. Thiamine pyrophosphate (TPP) is required for the synthesis of thiamine (B1) and is synthesized from thiamine by the enzyme thiamine pyrophosphokinase (Fuhrman et al. 2021). Thiamine is a water-soluble vitamin that plays a critical role in energy metabolism and nerve function. Thiamine is essential for the conversion of pyruvate to acetyl-CoA, which is a crucial step in the citric acid cycle. Thiamine deficiency can lead to various health problems such as beriberi, Wernicke-Korsakoff syndrome, and other neurological disorders.

Flavin adenine dinucleotide (FAD) and nicotinamide adenine dinucleotide (NAD+) are required for the synthesis of riboflavin (B2) and niacin (B3), respectively. FAD is synthesized from riboflavin by the enzyme riboflavin kinase, while NAD+ is synthesized from niacin by the enzyme nicotinamide (Fuhrman et al. 2021).

The production of vitamin B complex requires several cofactors and coenzymes, such as thiamine pyrophosphate (TPP), flavin adenine dinucleotide (FAD), nicotinamide adenine dinucleotide (NAD+), and coenzyme A (CoA). These cofactors and coenzymes are involved in various steps of the fermentation pathway and play essential roles in the synthesis of different vitamins (Koubaa et al. 2021).

4.3 Metabolic Pathway for Fermentation in Step by Step Manner

Glycolysis: Glucose is converted to pyruvate through a series of ten enzyme-catalyzed reactions in the cytoplasm of the cell, producing two molecules of ATP and two molecules of NADH (Figs. 2 and 3).

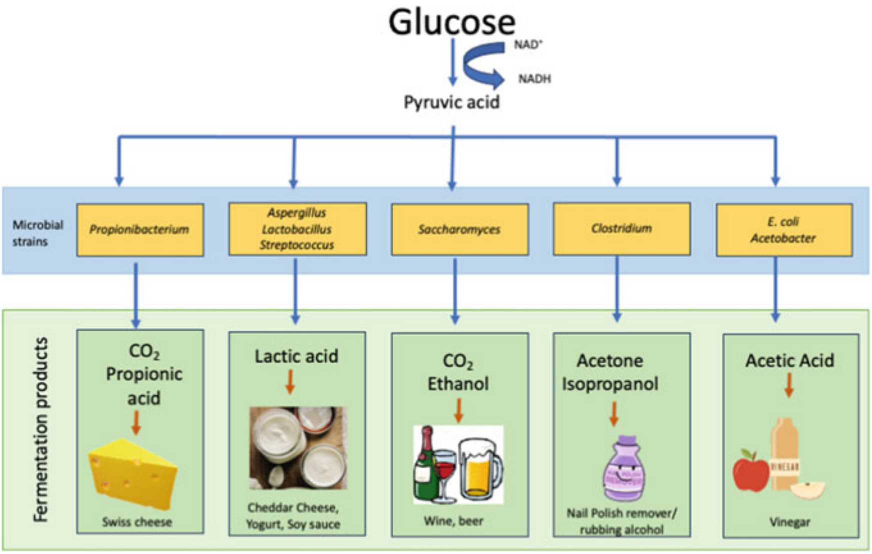

Fig. 1 Different types of Fermentation and their by-products

- ***Pyruvate Conversion***: Depending on the type of microorganism involved in the fermentation process, pyruvate is converted to different end products. In alcoholic fermentation, pyruvate is converted to acetaldehyde and then to ethanol, while in lactic acid fermentation, pyruvate is directly converted to lactic acid.
- ***Thiamine Synthesis***: Thiamine pyrophosphate (TPP), which is required for the synthesis of thiamine (B1), is synthesized from thiamine by the enzyme thiamine pyrophosphokinase. Thiamine plays a critical role in energy metabolism and nerve function.
- ***Riboflavin Synthesis***: Flavin adenine dinucleotide (FAD), which is required for the synthesis of riboflavin (B2), is synthesized from riboflavin by the enzyme riboflavin kinase. In addition to such naturally occurring microbiota, strain enhancement techniques through modification of genes also demonstrated promising results. In an experiment, Burgess et al. (2004), produced riboflavin biosynthetic genes in Lactobacillus lactis strain NZ9000, which transformed the riboflavin-using strain into a factory that produced vitamin B2.
- ***Niacin Synthesis***: Nicotinamide adenine dinucleotide (NAD+), which is required for the synthesis of niacin (B3), is synthesized from niacin by the enzyme nicotinamide adenine dinucleotide synthase. Niacin plays a crucial role in energy metabolism and is involved in various metabolic pathways (Anal et al. 2019; Koubaa et al. 2021)
- ***Pyridoxine Synthesis***: Pyridoxine (B6) is synthesized from pyridoxal through a series of enzyme-catalyzed reactions that involve pyridoxine synthase and pyridoxine 5′-phosphate synthase. Pyridoxine plays a crucial role in amino acid metabolism and neurotransmitter synthesis (Wang et al. 2021)

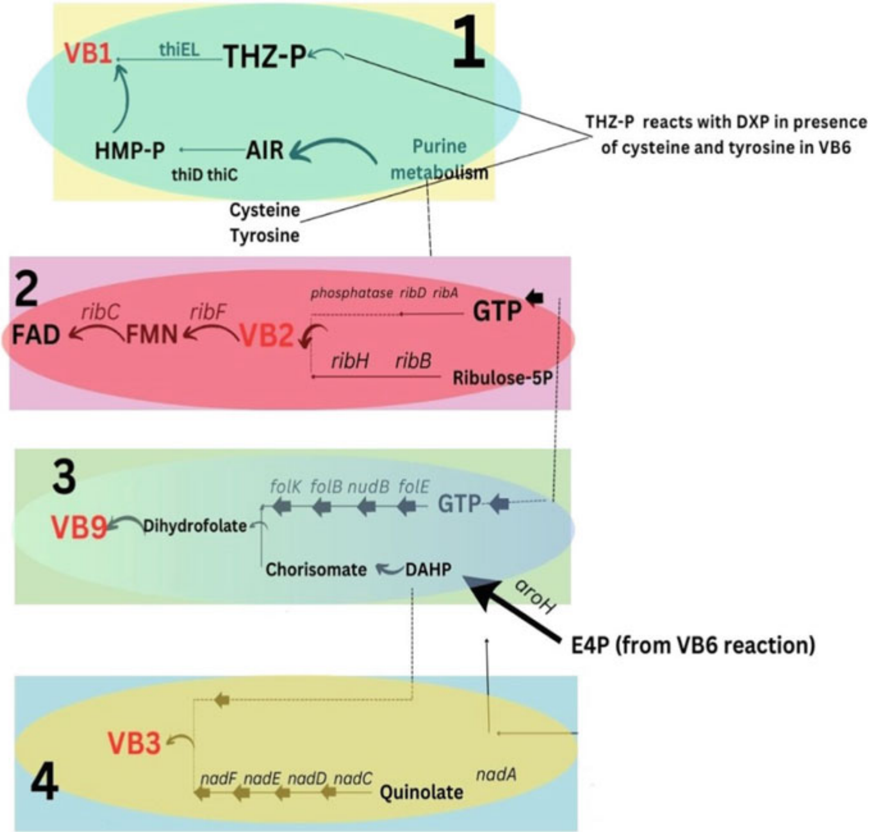

Fig. 2 Production of Vitamin B1 (Thiamine), Vitamin B2 (Riboflavin), Vitamin B3 (Niacin) and Vitamin B9 (Folate)

- ***Cobalamin Synthesis***: Cobalamin (B12) is synthesized by microorganisms through a series of complex enzyme-catalyzed reactions that involve cobalt and various cofactors. Cobalamin plays a crucial role in DNA synthesis and nerve function (Wang et al. 2021)

In conclusion, the metabolic pathway for fermentation for the production of vitamin B complex involves several steps, starting with glycolysis and ending with the synthesis of various vitamins, including thiamine (B1), riboflavin (B2), niacin (B3), pyridoxine (B6), and cobalamin (B12). Each step involves various enzymes, coenzymes, and cofactors, and plays a crucial role in the production of these essential vitamins.

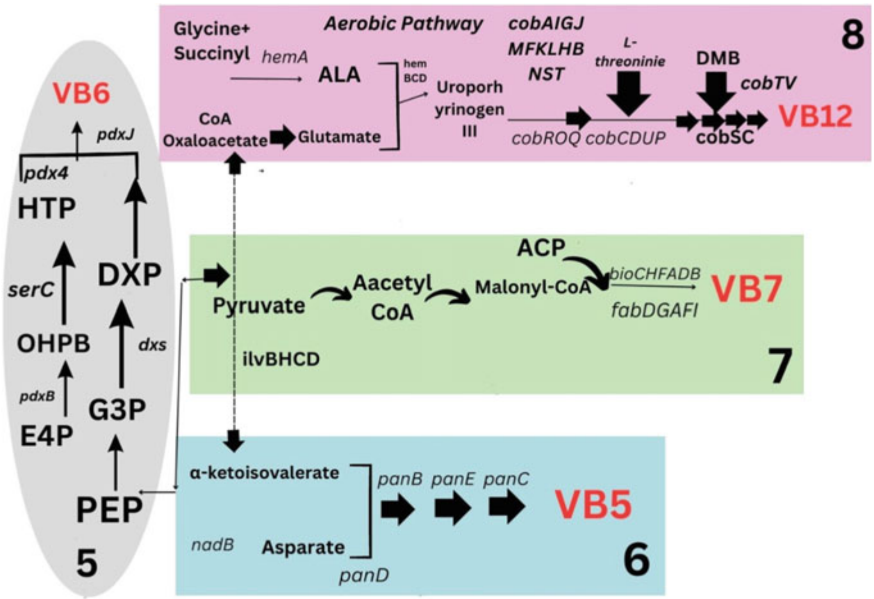

Fig. 3 Production of Vitamin B6 (Pyridoxin), Vitamin B12 (Cobalamin), Vitamin B7 (Biotin) and Vitamin B5 (Pantothenic acid)

4.4 Characterization of Fermented Vitamin B Complex

Fermented vitamin B complex is a group of water-soluble vitamins that are produced by the microbial fermentation of natural substances such as yeast, bacteria, or fungi. The characterization of the fermented vitamin B complex involves the identification and quantification of each individual vitamin present in the complex, as well as the total vitamin B content.

Several analytical techniques are commonly used for the characterization of fermented vitamin B complex, including chromatography, spectrophotometry, and microbiological assays. Each vitamin in the complex has its own unique properties that allow for its identification and quantification.

- ***Thiamine (B1)*** is a yellowish-brown, heat-stable compound that can be detected using ultraviolet–visible spectrophotometry at a wavelength of 265 nm. High-performance liquid chromatography (HPLC) is also commonly used to separate and quantify thiamine from other compounds present in the fermented product (Soares et al. 2021).
- ***Riboflavin (B2)*** is a yellow fluorescent compound that can be detected using fluorescence spectrophotometry at a wavelength of 530 nm. HPLC can also be used to separate and quantify riboflavin from other compounds present in the fermented product (Martynov et al. 2019);

- ***Niacin (B3)*** is a white crystalline compound that can be detected using HPLC or gas chromatography (GC) coupled with mass spectrometry (MS). Microbiological assays, such as the Lactobacillus plantarum test, can also be used to confirm the presence of niacin in the sample (Jang et al. 2022).
- ***Pyridoxine (B6)*** is a white crystalline compound that can be detected using HPLC or GC–MS. Microbiological assays, such as the Micrococcus luteus test, can also be used to confirm the presence of pyridoxine in the sample (Salah et al. 2021)
- ***Cobalamin (B12)*** is a red crystalline compound that can be detected using HPLC or GC–MS. Microbiological assays, such as the Lactobacillus leichmannii test, can also be used to confirm the presence of cobalamin in the sample (Edelmann et al. 2019).

In addition to the individual characterization of each vitamin in the complex, the total vitamin B content can also be determined using microbiological assays, such as the *Lactobacillus fermentum* test, (Farah et al. 2019) which can detect the growth of bacteria in the presence of a known amount of vitamin B complex.

Furthermore, the identification of the microorganisms involved in the fermentation process is also an essential aspect of the characterization of the fermented vitamin B complex. The use of molecular biology techniques, such as polymerase chain reaction (PCR), can be employed to identify the microorganisms present in the fermentation process. This is important because the type of microorganism used in the fermentation process can affect the quality and quantity of the vitamins produced.

Overall, the characterization of the fermented vitamin B complex is crucial for ensuring its quality and efficacy. The use of analytical techniques such as chromatography, spectrophotometry, and microbiological assays, as well as the identification of the microorganisms involved in the fermentation process, can provide valuable information on the composition and potency of the fermented vitamin B complex. This information can be used to optimize the production process and improve the quality of the final product.

5 Production of Vitamin C

5.1 Fermentation

Vitamin C, also known as ascorbic acid, is an essential nutrient that plays a critical role in many physiological processes, including collagen synthesis, wound healing, and immune function (Ahmed et al. 2021; Ustianowski et al. 2023) Humans, unlike most animals, cannot synthesize vitamin C and therefore must obtain it through their diet. However, there are several ways to produce vitamin C, including chemical synthesis, enzymatic synthesis, and microbial fermentation (Verma et al. 2022). In this article, we will focus on the production of vitamin C during microbial fermentation.

Microbial fermentation is a process that involves the use of microorganisms, such as bacteria, fungi, and yeast, to produce various substances. In the case of vitamin

C production, several strains of bacteria are commonly used, including *Acetobacter, Gluconobacter,* and *Corynebacterium.* These bacteria can synthesize vitamin C from glucose, a process that occurs in the cytoplasm of the cell (Melini et al. 2019). The production of vitamin C during microbial fermentation involves several steps. The first step is the selection of a suitable strain of bacteria. The selected strain should have a high vitamin C-producing capacity, be able to grow rapidly and have a low nutritional requirement (Verma et al. 2022). The strain should also be able to tolerate the conditions of the fermentation process, such as pH, temperature, and oxygen concentration.

Once the strain of bacteria has been selected, it is then cultured in a nutrient-rich medium. The medium should contain all the necessary nutrients, including a source of carbon, nitrogen, and minerals, to promote the growth of the bacteria. Glucose is commonly used as the carbon source in the medium, as it is a readily available and inexpensive substrate. The pH of the medium is also carefully controlled, as the production of vitamin C is highly dependent on the pH. A pH range of 5.5–7.5 is typically used for vitamin C production (Xiang et al. 2019a, b).

During the fermentation process, the bacteria consume the glucose in the medium and convert it into vitamin C. The synthesis of vitamin C occurs in the cytoplasm of the cell, where several enzymes are involved in the conversion of glucose to vitamin C. The first enzyme in the pathway is glucose dehydrogenase, which converts glucose to gluconic acid. Gluconic acid is then converted to 2-keto-gluconic acid by the enzyme gluconate 2-dehydrogenase. The final step in the pathway involves the conversion of 2-keto-gluconic acid to vitamin C by the enzyme 2-keto-gluconate reductase.

The production of vitamin C during microbial fermentation can be optimized by controlling several factors. One of the most critical factors is the oxygen concentration in the fermentation medium. Oxygen is essential for the growth of bacteria, but too much oxygen can lead to the production of reactive oxygen species, which can damage the bacteria and reduce the yield of vitamin C (Cagno et al. 2019). Therefore, the oxygen concentration should be carefully controlled throughout the fermentation process.

Another important factor is the temperature of the fermentation process. The optimal temperature for vitamin C production depends on the strain of bacteria used (Wang et al. 2021). However, most strains of bacteria used for vitamin C production grow optimally at temperatures between 25 and 35 °C.

The duration of the fermentation process is also critical for optimizing vitamin C production. The fermentation process typically lasts between 24 and 72 h, depending on the strain of bacteria and the conditions of the fermentation process. Longer fermentation times can lead to higher yields of vitamin C, but they can also lead to the accumulation of unwanted by-products. After the fermentation process is complete, vitamin C is extracted from the fermentation medium. Several methods can be used for vitamin C extraction, including solvent extraction, centrifugation, and filtration. The extracted vitamin C is then purified and dried to produce a pure form of vitamin C.

5.2 Metabolic Pathway for Fermentation

The metabolic pathway of fermentation in the production of vitamin C involves a series of enzymatic reactions that convert glucose to vitamin C. The pathway can be divided into three stages: the oxidation of glucose to gluconic acid, the conversion of gluconic acid to 2-keto-gluconic acid, and the reduction of 2-keto-gluconic acid to vitamin C.

Oxidation of glucose to gluconic acid: The first step in the pathway is the oxidation of glucose to gluconic acid. This reaction is catalyzed by the enzyme glucose dehydrogenase, which removes two hydrogen atoms from glucose and transfers them to an electron acceptor, such as NAD+. The resulting product, gluconic acid, is a six-carbon compound that can be further metabolized (Ma et al. 2019; Soltan et al. 2019; Sharma et al. 2020).

Glucose + NAD+ $\rightarrow$ gluconic acid + NADH + H+

Conversion of gluconic acid to 2-keto-gluconic acid: The second step in the pathway involves the conversion of gluconic acid to 2-keto-gluconic acid. This reaction is catalyzed by the enzyme gluconate 2-dehydrogenase, which removes a hydrogen atom from the C2 carbon of gluconic acid and transfers it to an electron acceptor, such as NAD+. The resulting product, 2-keto-gluconic acid, is a five-carbon compound that can be further metabolized.

Gluconic acid + NAD+ $\rightarrow$ 2-keto-gluconic acid + NADH + H+

Reduction of 2-keto-gluconic acid to vitamin C: The final step in the pathway involves the reduction of 2-keto-gluconic acid to vitamin C. This reaction is catalyzed by the enzyme 2-keto-gluconate reductase, which adds two hydrogen atoms to the C1 and C5 carbons of 2-keto-gluconic acid. The resulting product, L-ascorbic acid, is vitamin C.

2-keto-gluconic acid + NADH+ H+ $\rightarrow$ L-ascorbic acid + NAD+

Overall reaction:

Glucose + 2NAD+ + 2H2O $\rightarrow$ L-ascorbic acid + 2NADH + 2H+

In summary, the metabolic pathway of fermentation in the production of vitamin C involves the oxidation of glucose to gluconic acid, the conversion of gluconic acid to 2-keto-gluconic acid, and the reduction of 2-keto-gluconic acid to vitamin C. These reactions are catalyzed by specific enzymes and result in the conversion of a six-carbon sugar molecule to a five-carbon molecule and then to vitamin C (Ma et al. 2019; Soltan et al. 2019; Sharma et al. 2020).

The pathway is an essential part of the microbial fermentation process and is critical for the production of vitamin C.

5.3 Characterization of Fermented Vitamin C

Fermentation is a process that has been used for centuries to produce a variety of food and beverage products, including fermented vitamin C. Vitamin C is an essential nutrient for humans, and fermentation of vitamin C involves using microorganisms to produce ascorbic acid. The process involves using a substrate, such as glucose or a derivative of glucose, and microorganisms like bacteria, yeast, or fungi. In this article, we will discuss the characterization of fermented vitamin C in microbial fermentation.

Characterization of fermented vitamin C involves analyzing various aspects of the product, such as the ascorbic acid content, microbial composition, and sensory attributes. These parameters are essential to understanding the quality of the product and its suitability for consumption. The following are some of the key parameters used to characterize fermented vitamin C.

- ***Ascorbic Acid Content***

The primary objective of vitamin C fermentation is to produce ascorbic acid, which is a vital nutrient for humans. Therefore, the ascorbic acid content of fermented vitamin C is a critical parameter for its characterization. High-performance liquid chromatography (HPLC) is the most commonly used method for quantifying ascorbic acid in fermented vitamin C. This technique is highly sensitive and can detect ascorbic acid at low concentrations (Faria et al. 2020; Yin et al. 2022). The ascorbic acid content of fermented vitamin C can vary depending on several factors, including the strain of microorganisms used, fermentation conditions, and substrate composition. Studies have shown that fermentation with strains of Gluconobacter produces higher levels of ascorbic acid than other bacterial strains. Additionally, the use of glucose as a substrate has been shown to result in higher ascorbic acid yields than other carbon sources (Li et al.2022).

- ***Microbial Composition***

The microbial composition of fermented vitamin C is also an essential parameter for its characterization. This involves identifying the specific microorganisms present in the product and determining their relative abundance. Several techniques can be used for microbial composition analysis, including 16S rRNA gene sequencing, metagenomic sequencing, and culture-based methods (Duan et al. 2019; Faria et al. 2020). Studies have shown that the microbial composition of fermented vitamin C can vary depending on the fermentation conditions and substrate composition. For example, fermentation with glucose as a substrate has been shown to result in a higher abundance of *Acetobacter* and *Gluconobacter*, while fructose fermentation has been shown to produce a higher abundance of *Leuconostoc* and *Lactobacillus.*

- ***Sensory Attributes***

The sensory attributes of fermented vitamin C are also critical for its characterization. This involves evaluating the product's taste, aroma, texture, and color. Sensory analysis can be conducted using a panel of trained sensory evaluators, who use their senses to evaluate the product's attributes. The sensory attributes of fermented vitamin C can vary depending on several factors, including the strain of microorganisms used, fermentation conditions, and substrate composition. Studies have shown that fermentation with strains of *Acetobacter* produces a vinegar-like taste, while fermentation with *Gluconobacter* produces a milder, fruity taste.

- ***Quality Parameters***

Several other quality parameters can be used to characterize fermented vitamin C, including pH, titratable acidity, and total soluble solids. These parameters provide information on the product's chemical and physical properties and can be used to assess its quality. The pH of fermented vitamin C can vary depending on the microbial composition and fermentation conditions. Studies have shown that fermentation with strains of Acetobacter can result in a pH range of 3.5–4.0, while fermentation with *Gluconobacter* can result in a pH range of 4.0–5.0 (Zhang et al. 2021; Es-sbata et al. 2021).

6 Applications of Water-Soluble Vitamins

Water-soluble vitamin B complex and vitamin C are essential components in the fermentation process, playing a crucial role in various biochemical reactions, growth, and development of microorganisms. Fermentation is the process by which microorganisms such as yeast and bacteria convert organic compounds into useful products such as alcohol, vinegar, and yogurt (Rollán et al. 2019; Koubaa 2021) The application of these vitamins in fermentation is therefore significant as it enhances the growth and metabolic activities of the microorganisms, leading to improved product quality and yield (Fig. 4).

Vitamin B complex is a group of eight water-soluble vitamins that include thiamine, riboflavin, niacin, pantothenic acid, pyridoxine, biotin, folic acid, and

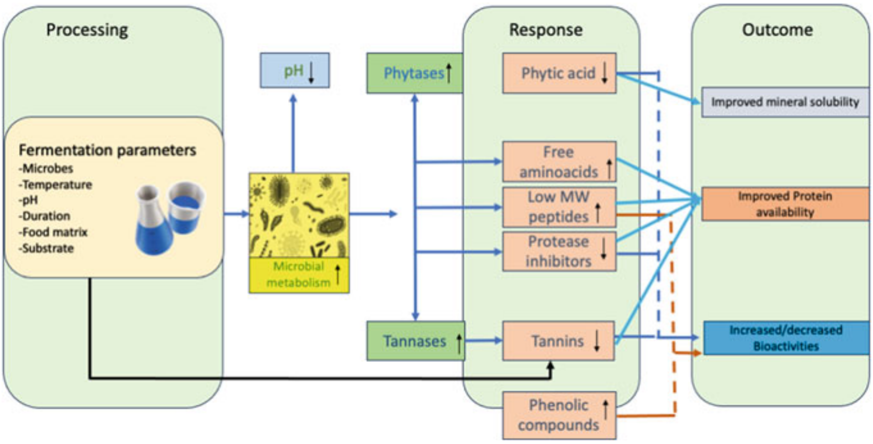

Fig. 4 Applications and outcomes of fermentation

cobalamin. These vitamins are essential in the fermentation process as they act as coenzymes that facilitate the transfer of electrons and protons during metabolic reactions (Labuschagne et al. 2021) For instance, thiamine acts as a coenzyme in the metabolism of carbohydrates, converting them into energy. Riboflavin, on the other hand, is involved in the conversion of amino acids and fatty acids into energy, while niacin is crucial in the production of NADH and NADPH, which are involved in various metabolic processes.

In fermentation, the vitamin B complex enhances the growth of microorganisms and improves their metabolic activities, leading to increased product yield and improved product quality. For instance, in the production of wine, the addition of vitamin B complex to the fermentation process enhances the growth of yeast, leading to increased alcohol production and improved flavour. Similarly, in the production of yogurt, the addition of vitamin B complex enhances the growth of lactic acid bacteria, leading to improved texture and flavour (Koubaa 2021).

Vitamin C, also known as ascorbic acid, is a water-soluble vitamin that is essential in the fermentation process. It acts as an antioxidant, protecting the microorganisms from oxidative stress, which can lead to cell damage and death. In addition, vitamin C is involved in the synthesis of collagen, a structural protein that is essential for the growth and development of microorganisms (Wang et al. 2021).

In fermentation, the application of vitamin C enhances the growth and survival of microorganisms, leading to improved product quality and yield. For instance, in the production of beer, the addition of vitamin C enhances the growth of yeast, leading to increased alcohol production and improved flavour. Similarly, in the production of sauerkraut, the addition of vitamin C enhances the growth of lactic acid bacteria, leading to improved texture and flavour (Xiang et al. 2019).

In conclusion, the application of water-soluble vitamins B complex and vitamin C in fermentation is significant as it enhances the growth and metabolic activities of microorganisms, leading to improved product quality and yield. These vitamins act as coenzymes and antioxidants, facilitating the transfer of electrons and protons during metabolic reactions and protecting the microorganisms from oxidative stress. Their application in fermentation is therefore essential in the production of various useful products such as alcohol, vinegar, and yogurt.

7 Future Aspects

Fermented vitamin B complex and vitamin C are both emerging trends in the food and beverage industry with significant potential in the future. Fermented vitamin B complex is obtained through the fermentation of plant-based sources of vitamin B complex, while fermented vitamin C is obtained through the fermentation of fruit and vegetable sources of vitamin C.

One future aspect of fermented vitamin B complex and vitamin C is their potential as natural alternatives to synthetic vitamin supplements. Synthetic vitamin supplements are widely used to treat vitamin deficiencies, but they often come with side effects and are not well-absorbed by the body (Di Cagno et al. 2019). Fermented vitamin B complex and vitamin C, with their enhanced bioavailability and bioactivity, can provide a more effective and natural alternative to synthetic vitamin supplements. Another future aspect of fermented vitamin B complex and vitamin C is their potential in the prevention and management of chronic diseases (Falah et al. 2019). Vitamin B complex and vitamin C play crucial roles in various metabolic pathways, and their deficiencies have been associated with the development of chronic diseases such as cardiovascular disease, diabetes, and cancer. Fermented vitamin B complex and vitamin C, with their enhanced bioactivity and antioxidant properties, can improve the nutritional status of individuals and reduce the risk of chronic diseases (Dimidi et al. 2019; Rastogi and Marwah 2023).

Fermented vitamin B complex and vitamin C also have the potential to be used as functional food ingredients. Functional foods are foods that provide health benefits beyond their nutritional value, and they are becoming increasingly popular among consumers. Fermented vitamin B complex and vitamin C, with their bioactive compounds, can be used as natural functional food ingredients in the production of various food products such as bread, pasta, and snacks (Dimidi et al. 2019). Furthermore, fermented vitamin B complex and vitamin C can be used in the production of fermented beverages. Fermented beverages such as kombucha and kefir are gaining popularity due to their health benefits and unique flavours. Fermented vitamin B complex and vitamin C can enhance the nutritional value and flavour of these beverages, making them even more appealing to consumers.

In conclusion, fermented vitamin B complex and vitamin C are promising trends in the food and beverage industry with significant potential in the future. Their natural and safe nature, enhanced bioactivity and bioavailability, and potential in the prevention and management of chronic diseases make them attractive alternatives to synthetic vitamin supplements. Their potential as functional food ingredients and in the production of fermented beverages further adds to their value, making them versatile ingredients in the food and beverage industry.

8 Challenges

Despite the many potential benefits of fermented vitamin B complex and vitamin C, there are also some challenges associated with their production, storage, and use in the food and beverage industry. One challenge is the ***variability*** in the production of fermented vitamin B complex and vitamin C. The fermentation process is influenced by several factors such as temperature, pH, and the type and concentration of microorganisms used. The variability in the production process can lead to variations in the composition and bioactivity of the final product, making it difficult to achieve consistent quality (Chilakamarry et al. 2022).

Another challenge is the ***storage stability*** of fermented vitamin B complex and vitamin C. Fermented products are susceptible to spoilage due to the growth of unwanted microorganisms or chemical changes in the product. The storage stability of fermented products can be improved by controlling the storage temperature, pH, and moisture content, but these factors can also affect the bioactivity of the vitamins (Es-sbata et al. 2021; Chilakamarry et al. 2022). The ***bioavailability*** of fermented vitamin B complex and vitamin C is another challenge. While fermentation can enhance the bioavailability of vitamins, it is also influenced by several factors such as the food matrix, the pH of the gastrointestinal tract, and the interactions with other food components. These factors can affect the absorption and utilization of the vitamins by the body, leading to variability in the response to the product (Saranraj et al. 2019).

Regulatory challenges are also associated with the use of fermented vitamin B complex and vitamin C in the food and beverage industry. The production, labelling, and marketing of functional foods and dietary supplements are subject to regulatory oversight by government agencies such as the FDA. The regulatory landscape is complex, and manufacturers need to comply with the relevant regulations to ensure the safety and efficacy of their products (Zhang et al. 2021; Chilakamarry et al. 2022).

Finally, ***consumer acceptance*** is a challenge for fermented vitamin B complex and vitamin C. While the demand for natural and functional foods is increasing, fermented products may not appeal to all consumers due to their strong flavors and textures. Consumer education and marketing efforts are needed to increase awareness and acceptance of fermented products.

In conclusion, while fermented vitamin B complex and vitamin C offer many potential benefits, there are also several challenges associated with their production, storage, and use in the food and beverage industry. Addressing these challenges requires a multidisciplinary approach involving food scientists, microbiologists, regulatory experts, and marketers.

9 Fermentation for Sustainability and Low Environmental Food Print

Fermentation is a sustainable and low environmental footprint process that has been used for centuries to preserve and transform food. The fermentation process relies on natural microorganisms, such as bacteria and yeast, to break down sugars and other nutrients in food, producing lactic acid, alcohol, and other byproducts that enhance flavour, texture, and nutritional value (Rollán et al. 2019). Fermentation has many benefits that make it an attractive option for sustainable and low environmental footprint food production (Singh et al. 2021). One benefit of fermentation is its ability to reduce food waste. Fermentation can transform food that might otherwise go to waste, such as surplus crops, into value-added products that have a longer shelf life. This can help to reduce food waste and save resources. Al-Dhabi et al. (2020) has used *Lactobacillus rhamnosus* AW3 strain to produce lactic acids from food waste and municipal sludge. Fermented foods such as kimchi, sauerkraut, and pickles are examples of how fermentation can transform vegetables into delicious and nutritious products.

Another benefit of fermentation is its ability to enhance food safety. The fermentation process creates an acidic environment that inhibits the growth of harmful bacteria, reducing the risk of foodborne illness. This can reduce the need for chemical preservatives and additives, making fermented products a healthier and more natural option (Dimidi et al. 2019). Fermentation can also enhance the nutritional value of food. The fermentation process can increase the bioavailability of nutrients such as vitamins, minerals, and antioxidants, making them more easily absorbed by the body (Dimidi et al. 2019). For example, fermented dairy products such as yogurt and kefir are rich in probiotics that support gut health, while fermented soy products such as tempeh and miso are high in protein, fiber, and phytochemicals that have been linked to various health benefits. Furthermore, fermentation has a low environmental footprint compared to other food processing methods. The process requires minimal energy and water, and it produces minimal waste. This can help to reduce the environmental impact of food production and support sustainable agriculture practices. In conclusion, fermentation is a sustainable and low environmental footprint process that has many benefits for food production. It can reduce food waste, enhance food safety, and increase the nutritional value of food while minimizing the environmental impact of food production. As consumers become more aware of the environmental impact of their food choices, fermentation is likely to become an increasingly important and attractive option for sustainable and healthy food production.

10 Conclusion

Many different items, including vitamins, have been produced through the process of fermentation. Microorganisms like bacteria and yeast are employed in the fermentation process to transform sugars into a variety of compounds, including water-soluble vitamins like vitamin C and the B complex. The particular microorganisms utilized and the fermentation conditions affect how much B complex vitamin is produced throughout the fermentation process. According to studies, several types of bacteria and yeasts can produce large amounts of B vitamins during fermentation, including thiamin, riboflavin, niacin, pantothenic acid, pyridoxine, and biotin. Similar to this, the type of microorganisms utilized and the conditions of the fermentation affect how much vitamin C is produced. While some studies have reported little to no vitamin C production, some have demonstrated the ability of specific strains of bacteria and yeasts to produce vitamin C during fermentation. Finally, fermentation can be a useful technique for creating water-soluble vitamins like vitamin C and B complex. However, the type of microorganisms utilized and the fermentation process's conditions can have a significant impact on the quantity and caliber of vitamins produced. To optimize fermentation conditions for the synthesis of high-quality vitamins, more study is required.

References

Acevedo-Rocha CG, Gronenberg LS, Mack M, Commichau FM, Genee HJ (2019, Apr 1) Microbial cell factories for the sustainable manufacturing of B vitamins. Curr Opin Biotechnol 56:18–29

Ahmed MH, Hassan A, Molnár J (2021) The role of micronutrients to support immunity for COVID-19 prevention. Rev Brasileira De Farmaco 31(4):361–374

Alam A, Agrawal K, Verma P (2021) Fungi and its by-products in food industry: an unexplored area. Micro Products Health Environ Agricul 103–120.

Al-Dhabi NA, Esmail GA, Valan AM (2020) Co-fermentation of food waste and municipal sludge from the Saudi Arabian environment to improve lactic acid production by *Lactobacillus rhamnosus* AW3 isolated from date processing waste. Sustain 12(17):6899

An F, Wu J, Feng Y, Pan G, Ma Y, Jiang J, Yang X, Xue R, Wu R, Zhao M (2023) A systematic review on the flavor of soy-based fermented foods: core fermentation microbiome, multisensory flavor substances, key enzymes, and metabolic pathways. Compr Rev Food Sci Food Safe Apr 20.

Anal AK (2019) Quality ingredients and safety concerns for traditional fermented foods and beverages from Asia: a review. Ferment 5(1):8

Ashaolu TJ (2019) A review on selection of fermentative microorganisms for functional foods and beverages: the production and future perspectives. Intern J Food Sci Technol 54(8):2511–2519

Ayivi RD, Gyawali R, Krastanov A, Aljaloud SO, Worku M, Tahergorabi R, Silva RC, Ibrahim SA (2020) Lactic acid bacteria: food safety human health applications. Dairy 1(3):202–232

Barzee TJ, Cao L, Pan Z, Zhang R (2021) Fungi for future foods. J Future Foods 1(1):25–37

Belenky P, Stebbins R, Bogan KL, Evans CR, Brenner C (2011, May 11) Nrt1 and Tna1-independent export of NAD+ precursor vitamins promotes NAD+ homeostasis and allows engineering of vitamin production. PloS One 6(5):e19710

Bishop P, Pitts ER, Budner D, Thompson-Witrick KA (2022) Chemical composition of Kombucha. Bever 8(3):45

Burgess C, O'Connell-Motherway M, Sybesma W, Hugenholtz J, Van Sinderen D (2004) Riboflavin production in Lactococcus lactis: potential for in situ production of vitamin-enriched foods. Appl Environl Microbiol 70(10):5769–5777

Cahill JA, Tan K, Kan M (2022) Anaphylaxis to a particular brew of beer due to specific strains of Saccharomyces cerevisiae. Annals Allergy Asthma Immun 128(6):621–623

Calvillo Á, Pellicer T, Carnicer M, Planas A (2022) Bioprocess strategies for Vitamin B12 production by microbial fermentation and its market applications. Bioengg 9(8):365

Carbone D, Faggio C (2016) Importance of prebiotics in aquaculture as immunostimulants. Effects on immune system of Sparus aurata and Dicentrarchus labrax. Fish Shellfish Immunol 54:172–178

Cardinale S, Tueros FG, Sommer MO (2017) Genetic-metabolic coupling for targeted metabolic engineering. Cell Rep 20(5):1029–1037

Chamlagain B, Sugito TA, Deptula P, Edelmann M, Kariluoto S, Varmanen P, Piironen V (2018, Jan) In situ production of active vitamin B12 in cereal matrices using *Propionibacterium freudenreichii*. Food Sci Nutr 6(1):67–76

Chilakamarry CR, Sakinah AM, Zularisam AW, Sirohi R, Khilji IA, Ahmad N, Pandey A (2022) Advances in solid-state fermentation for bioconversion of agricultural wastes to value-added products: opportunities and challenges. Biores Technol 343:126065

Colgrave ML, Dominik S, Tobin AB, Stockmann R, Simon C, Howitt CA, Belobrajdic DP, Paull C, Vanhercke T (2021, Dec 9) Perspectives on future protein production. J Agricult Food Chem 69(50):15076–15083

Copetti MV (2019) Yeasts and molds in fermented food production: an ancient bioprocess. Curr Opinion Food Sci 25:57–61

de Faria LV, Lisboa TP, de Farias DM, Araujo FM, Machado MM, de Sousa RA, Matos MA, Muñoz RA, Matos RC (2020) Direct analysis of ascorbic acid in food beverage samples by flow injection analysis using reduced graphene oxide sensor. Food Chem 319:126509

Di Cagno R, Filannino P, Vincentini O, Cantatore V, Cavoski I, Gobbetti M (2019) Fermented *Portulaca oleracea* L. juice: a novel functional beverage with potential ameliorating effects on the intestinal inflammation and epithelial injury. Nutr 11(2):248

Dimidi E, Cox SR, Rossi M, Whelan K (2019) Fermented foods: definitions and characteristics, impact on the gut microbiota and effects on gastrointestinal health and disease. Nutr 11(8):1806

Dmytruk KV, Yatsyshyn VY, Sybirna NO, Fedorovych DV, Sibirny AA (2011) Metabolic engineering and classic selection of the yeast *Candida famata (Candida flareri)* for construction of strains with enhanced riboflavin production. Metabol Eng 13(1):82–88

Duan R, Zhu S, Wang B, Duan L (2019) Alterations of gut microbiota in patients with irritable bowel syndrome based on 16S rRNA-targeted sequencing: a systematic review. Clin Translat Gastroenterol 10(2)

Edelmann M, Aalto S, Chamlagain B, Kariluoto S, Piironen V (2019) Riboflavin, niacin, folate and vitamin B12 in commercial microalgae powders. J Food Comp Anal 82:103226

Es-sbata I, Lakhlifi T, Yatim M, El-Abid H, Belhaj A, Hafidi M, Zouhair R (2021) Screening and molecular characterization of new thermo-and ethanol-tolerant Acetobacter malorum strains isolated from two biomes Moroccan cactus fruits. Biotechnol App Biochem 68(3):476–485

Falah F, Vasiee A, Behbahani BA, Yazdi FT, Moradi S, Mortazavi SA, Roshanak S (2019) Evaluation of adherence and anti-infective properties of probiotic Lactobacillus fermentum strain 4–17 against Escherichia coli causing urinary tract infection in humans. Microbial Pathogen 131:246–253

Fuhrmann JJ (2021) Microbial metabolism. In: Principles and applications of soil microbiology. Elsevier, pp 57–87

Gu Q, Zhang C, Song D, Li P, Zhu X (2015) Enhancing vitamin B12 content in soy-yogurt by *Lactobacillus reuteri*. Int J Food Microbiol 206:56–59

Halake NH, Chinthapalli B (2020) Fermentation of traditional African Cassava based foods: microorganisms role in nutritional and safety value. J Exper Agr Intern 42(9):56–65

Hassaan MS, Soltan MA, Jarmołowicz S, Abdo HS (2018) Combined effects of dietary malic acid and B acillus subtilis on growth, gut microbiota and blood parameters of N ile tilapia (O reochromis niloticus). Aqua Nutr 24(1):83–93

Hohmann HP, van Dijl JM, Krishnappa L, Prágai Z (2017) Host organisms: bacillus subtilis. Ind Biotechnol Microorg 1:221–297

Hoshino T, Ichikawa K, Tazoe M (2004) Recombinant microorganism for the production. Washington, DC, U.S. Patent and Trademark Office. U.S. Patent No EP 1 543 139 B1

Jaehme M, Guskov A, Slotboom DJ (2014) Crystal structure of the vitamin B3 transporter PnuC, a full-length SWEET homolog. Nature Stru Mol Biol 21(11):1013–1015

Jang Y, Jeon J, Lee SH, Choi YM, Choung MG (2022) Evaluation of the thiamine, riboflavin, and niacin contents in fermented soybean processed foods in various Korean Provinces, pp 688–696

Koubaa M, Barba FJ, Roohinejad S (2021) Fermentation processes. John Wiley & Sons, Incorporated

Kumar P, Chatli MK, Verma AK, Mehta N, Malav OP, Kumar D, Sharma N (2017) Quality, functionality, and shelf life of fermented meat and meat products: a review. Cri Rev Food Sci Nutr 57(13):2844–2456

Labuschagne PW, Divol B (2021) Thiamine: a key nutrient for yeasts during wine alcoholic fermentation. Appl Microbiol Biotechnol 105:953–973

Laureys D, Britton SJ, De Clippeleer J (2020) Kombucha tea fermentation: a review. J Am Soc Brew Chem 78(3):165–174

Ledesma-Amaro R, Santos MA, Jiménez A, Revuelta JL (2013) Microbial production of vitamins. In: Microbial production of food ingredients, enzymes and nutraceuticals. Woodhead Publishing, pp 571–594

Leonardi R, Jackowski S (2007) Biosynthesis of pantothenic acid and coenzyme A. EcoSal Plus 2(2):10–128

Li D, Liu L, Qin Z, Yu S, Zhou J (2022) Combined evolutionary and metabolic engineering improve 2-keto-L-gulonic acid production in Gluconobacter oxydans WSH-004. Biores Technol 354:127107

Li KT, Liu DH, Li YL, Chu J, Wang YH, Zhuang YP, Zhang SL (2008) Improved large-scale production of vitamin B12 by *Pseudomonas denitrificans* with betaine feeding. Bioresour Technol 99(17):8516–8520

Lim SH, Chin NL, Sulaiman A, Tay CH, Wong TH (2023) Microbiological, physicochemical and nutritional properties of fresh cow milk treated with industrial High-Pressure Processing (HPP) during storage. Food 12(3):592

Liu X, Ju Y, Huang L, Liu M, Bo J, Zhou T, Zhang Y, Liu C, Feng M, Zhang S, Yan Y (2022) Effects of a new fermented soya bean meal on growth performance, serum biochemistry profile, intestinal immune status and digestive enzyme activities in piglets. J Animal Physiol Animal Nutr 106(5):1046–1059

Lu L, Wang X, Zhou L, Liu Q, Zhang G, Xue B, Hu C, Shen X, Sun X, Yan Y, Wang J (2023) Establishing biosynthetic pathway for the production of p-hydroxyacetophenone and its glucoside in Escherichia coli. Metabol Engg 76:110–119

Ma Q, Bi YH, Wang EX, Zhai BB, Dong XT, Qiao B, Yuan YJ (2019) Integrated proteomic and metabolomic analysis of a reconstructed three-species microbial consortium for one-step fermentation of 2-keto-L-gulonic acid, the precursor of vitamin C. J Indust Microbiol Biotechnol 46(1):21–31

Marie Sych J, Lacroix C, Stevens MJ (2016) Vitamin B12–physiology, production and application. Indust Biotechnol Vit Biopig Antiox 129–159

Martynov AV, Bomko TV, Farber BS, Nosalskaya TN, Kleyn I (2019) Synthesis of dynamic riboflavin derivatives and the study of their ability to urease photoinactivation. Annals Mechnikov Inst 3:44–49

Melini F, Melini V, Luziatelli F, Ficca AG, Ruzzi M (2019) Health-promoting components in fermented foods: an up-to-date systematic review. Nutr 11(5):1189

Nya E, Etukudo O (2023) Industrial potentials of saccharomyces cerevisiae. Br J Multidis Adv Stud 4(2):23–46

Pappenberger G, Hohmann HP (2014) Industrial production of L-ascorbic acid (vitamin C) and D-isoascorbic acid. Biotechnol Food Feed Add 143–188

Rastogi M, Marwah H (2023) Nutritional assessment of Anemic individuals and its causative factors: an outcome based study. Eur J Mol Clin Med 9(8):3096–3111

Richts B, Commichau FM (2021) Underground metabolism facilitates the evolution of novel pathways for vitamin B6 biosynthesis. Appl Microbiol Biotechnol 105:2297–3305

Rollán GC, Gerez CL, LeBlanc JG (2019) Lactic fermentation as a strategy to improve the nutritional and functional values of pseudocereals. Front Nutr 3(6):98

Saleh O, Mohamed M, El-Galil A, Abd El-Aziz M, El-Kamed A, Sayed H (2021) Isolation and characterization of micrococcus luteus from Oreochromis niloticus in Egypt. J Curr Vet Res 3(2):16–23

Saranraj P, Behera SS, Ray RC (2019) Traditional foods from tropical root and tuber crops: Innovations and challenges. In Innovations in traditional foods. Woodhead Publishing, pp 159–191

Schwechheimer SK, Becker J, Peyriga L, Portais JC, Sauer D, Müller R, Hoff B, Haefner S, Schröder H, Zelder O, Wittmann C (2018) Improved riboflavin production with Ashbya gossypii from vegetable oil based on 13C metabolic network analysis with combined labeling analysis by GC/ MS, LC/MS, 1D, and 2D NMR. Metabolic engineering.1;47:357–373

Sharma R, Garg P, Kumar P, Bhatia SK, Kulshrestha S (2020) Microbial fermentation and its role in quality improvement of fermented foods. Ferment 6(4):106

Singh A, Misra M, Mishra S, Sachan SG (2021) Fungal production of food supplements. Fungi Sustain Food Prod 129–142

Soares Mateus AR, Barros S, Pena A, Sanches Silva A. (2021) Mycotoxins in pistachios (pistacia vera L.): methods for determination, occurrence, decontamination. Tox 13(10):682

Soltan M, Elsamadony M, Mostafa A, Awad H, Tawfik A (2019) Nutrients balance for hydrogen potential upgrading from fruit and vegetable peels via fermentation process. J Environ Manag 242:384–393

Streit WR, Entcheva P (2003) Biotin in microbes, the genes involved in its biosynthesis, its biochemical role and perspectives for biotechnological production. Appl Microbiol Biotechnol 61:21–31

Sugisawa T, Miyazaki T, Hoshino T (2005) Microbial production of L-ascorbic acid from D-sorbitol, L-sorbose, L-gulose, and L-sorbosone by Ketogulonicigenium vulgare DSM 4025. Biosci Biotechnol Biochem 69(3):659–662

Tavakoli M, Najafi MB, Mohebbi M (2019) Effect of the milk fat content and starter culture selection on proteolysis and antioxidant activity of probiotic yogurt. Heliy 5(2):e01204

Teniola OD, Holzapfel WH, Odunfa SA (2023) Selection, use and the influence of starter cultures in the nutrition and processing improvement of ogi. J Food Sci Nutr Res 6(3):61–70

Ustianowski Ł, Ustianowska K, Gurazda K, Rusiński M, Ostrowski P, Pawlik A (2023) The role of vitamin c and vitamin d in the pathogenesis and therapy of periodontitis—narrative review. Int J Mol Sci 24(7):6774

Verma DK, Al-Sahlany ST, Niamah AK, Thakur M, Shah N, Singh S, Baranwal D, Patel AR, Utama GL, Aguilar CN (2022) Recent trends in microbial flavour Compounds: a review on chemistry, synthesis mechanism and their application in food. Saudi J Biol Sci 29(3):1565–1576

Verni M, Rizzello CG, Coda R (2019) Fermentation biotechnology applied to cereal industry by-products: nutritional and functional insights. Front Nutr 6:42

Wang Y, Liu L, Jin Z, Zhang D (2021) Microbial cell factories for green production of vitamins. Front Bioengg Biotechnol 9:661562

Wu W, Zhang B (2019) Lactic acid bacteria and b vitamins. In: Lactic acid bacteria. Bioengineering and Industrial Applications, pp 43–60

Xiang H, Sun-Waterhouse D, Waterhouse GI, Cui C, Ruan Z (2019, Sep 1) Fermentation-enabled wellness foods: a fresh perspective. Food Sci Human Wellness 8(3):203–243

Xiang H, Sun-Waterhouse D, Waterhouse GI, Cui C, Ruan Z (2019a) Fermentation-enabled wellness foods: a fresh perspective. Food Sci Hum Wellness 8(3):203–243

Xiang H, Sun-Waterhouse D, Waterhouse GIN, Cui C, Ruan Z (2019b) Fermentation-enabled wellness foods: a fresh perspective. Food Sci Hum Well 8(3):203–243

Xie C, Coda R, Chamlagain B, Varmanen P, Piironen V, Katina K (2019) Co-fermentation of *Propionibacterium freudenreichii* and *Lactobacillus brevis* in Wheat Bran for in situ Production of Vitamin B12. Front Microbiol 5(10):1541

Yarlina VP, Astuti DI, Djali M, Andoyo R, Lani MN (2023) Effects of combined pure cultures of *Rhizopus* sp.(*Rhizopus oryzae, Rhizopus oligosporus*, and *Rhizopus stolonifer*) on tempeh extract yogurt as a functional food. Curr Nutr Food Sci 19(3):307–316

Yin X, Chen K, Cheng H, Chen X, Feng S, Song Y, Liang L (2022) Chemical stability of ascorbic acid integrated into commercial products: a review on bioactivity and delivery technology. Antiox 11(1):153

Zhang P, You Y, Song Y, Wang Y, Zhang L (2015) First record of Aspergillus oryzae (Eurotiales: Trichocomaceae) as an entomopathogenic fungus of the locust, *Locusta migratoria* (Orthoptera: Acrididae). Biocon Sci Technol 25(11):1285–1298

Zhang Q, Wang L, Liu S, Li Y (2021) Establishment of successive co-fermentation by Bacillus subtilis and acetobacter pasteurianus for extracting chitin from shrimp shells. Carbohy Poly 258:117720

Zhang Y, Momoisea P, Lin Q, Liang J, Burrow K, Serventi L (2023) Evaluation of sensory and physicochemical characteristics of vitamin B12 enriched whole-meal sourdough bread fermented with Propionibacterium freudenreichii. Sustain 15(10):8157

Zhou M, Bi Y, Ding M, Yuan Y (2021) One-step biosynthesis of vitamin C in Saccharomyces cerevisiae. Front Microbiol 12:643472

Processing and Functional Properties of Edible Insects: Risk and Benefits Associate with Its Consumption

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1 Introduction

Entomophagy is an act of eating insects and it is becoming popular globally since insects are expected to be the future food. As the earth's population is set to reach 9 billion by 2050 experts are worried about the production of edible protein to feed all of us (Gahukar 2016). Globally, sustainability is becoming more and more important (Jantzen da Silva Lucas et al. 2020). Therefore there is a need for alternative food sources to replace traditional and less sustainable ingredients. Evidence suggests that more farming and consumption of limited natural resources will not be enough, so could edible insects help? According to nutritional value, cricket provides good quality of protein which are high in essential amino acids. Crickets are rich in protein than chicken, pork beef, and the like's edamame beans. Livestock rearing especially beef gives of large volumes of greenhouse gases such as methane whereas nearly 3000 times fewer greenhouse gases are emitted from insect protein production. Around 2 billion of the world's population is already consuming insects as a part of their diet. The use of proteins, lipids, and fibres from edible insects can be a possible alternative (Jantzen da Silva Lucas et al. 2020).

Insects have been used as food for humans for millions of years (Baiano 2020). 30,000 to 9000 years ago, during the Old Stone Age to Middle Stone Age. There are more than 2,000 edible insect species in the globe. The nutritional makeup of different

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insects varies. When compared to animal production, the industrial production of insects offers more benefits for the environment because it produces fewer greenhouse gases, uses less dry land, and has a higher feed conversion efficiency (Mishyna et al. 2021). The ability to grow insects on food waste makes small-scale insect agriculture more advantageous for the environment and economically sound (Mishyna et al. 2021). Despite this, there is still little practice in the large-scale production of insects. It might be because of the insufficient understanding of industrial insect production, processing, and rearing (Mishyna et al. 2021). Because gathering in tropical zones is more easier than in temperature zones, eating insects is currently a prevalent habit in tropical nations (Huis 2017). Beetles (31%), caterpillars (17%), wasps, bees, and ants (15%), crickets, grasshoppers, and locusts (14%), and real bugs (11%), are the insects that are most commonly consumed. Termites, dragonflies, flies, and other insects are consumed to a lesser amount (Huis 2017).

Insect proteins are more advantageous because they may be more ecologically friendly because they support an atmosphere that is more eco-friendly because there is less emission of greenhouse gases and ammonia. Lao People's Democratic Republic and Nigeria are two examples of tropical nations where eating insects is most popular (Huis 2017). Insects are becoming more accepted as viable sources of protein for food and feed, however because of their look, there is a danger that they won't be accepted by contemporary civilization (Liceaga 2021). Commercial processing techniques that extract food-grade protein while preserving the food's safety, nutritional value, and sensory quality are necessary for the improvement of the insect production sector (Liceaga 2021).

Even though insects have a lot of positive qualities, their usefulness is currently being assessed. With a rise in global population, there will be a severe problem with food security in both undeveloped and emerging nations. Two main food issues that affect people's health and are related to industrialized nations are food safety and the environmental sustainability of food and production (Petkova 2019). The potential of insect protein as a highly valuable functional ingredient in food formulation is the main topic of this review. It also discusses the many difficulties and chances in the study of edible insect proteins.

2 Nutritional Value

Insects are primarily consumed by humans due to their high protein content. The nutritional value of food products can be increased by include edible insects. Insects are abundant in high-value protein sources with high-quality food composition and components that are good for your health. Because there are so many different types of edible insects, their nutritional value is quite varied. Depending on an insect's stage of metamorphosis, where it came from, and what it eats, nutritional values within a group of insects might vary substantially. Numerous variables, including gender, stage of growth, and food, affect nutritional value. Numerous environmental aspects, like the temperature, length of the day, humidity, light intensity, and spectral makeup, can also be taken into account. Insects are typically regarded as a high source of protein (35–61% of total protein), fat (13–33% of total fat), vitamins, and a sizable quantity of "animal" fiber in the form of insoluble chitins. The species has a significant impact on the protein content. Raw insects have protein contents per 100 g of fresh weight that range from 7 to 48 g. For example, edible species of the order Coleoptera have an average protein content of 40.69%, and the species within this order have protein contents ranging from 8.85% to 71.10% (Alrifai and Marcone 2019). Many insect species from a wide range of orders have been examined for their protein content.

Insects have nutritional value, and according to the WHO and FAO, they are an acceptable source of protein for people who are starving. The second-largest part of an insect's nutritional makeup is fat. For instance, Orthoptera, which includes grasshoppers, locusts, and crickets, has an average fat level of 13.41%, Lepidoptera, which includes caterpillars, has a fat content of 27.66%, and Isoptera, which includes termites, has a fat content of 32.74% (Ojha et al. 2021). In insects, there are primarily two types of carbohydrates: chitin and glycogen (Ojha et al. 2021). According to Ojha et al. 2021, the average amount of carbohydrates in edible insects ranges from 6.71% (stink bug) to 15.98% (cicada). Some insects, such crickets, grasshoppers, mealworms, and termites, are also high in iron, zinc, calcium, copper, phosphorus, magnesium, and manganese in addition to the macronutrients. Although the iron content of most edible insects is comparable to that of meat, nothing is known about how readily insects absorb minerals.

3 Farming of Edible Insects

In nature, there are many different species of edible insects that are rich in nutrients and other components that support life. All around the world, people have historically eaten these delectable insects. Approximately 92% of the various species of edible insects, according to Yen (2015a, b), are collected from wild forests, aquatic ecosystems, and agricultural fields; however, these edible insects are not always present in the wild due to various environmental conditions (Baiano 2020). It is impossible to ensure the caliber and safety of insects that are taken from the wild. Taking insects out of the wild could lead to the extinction of certain species as red agave worm (*Comadia redtembacheri* or *Xyleutes redtembacheri*) used in mezcal, the Navajo reservation ant (*Liometopum apiculatum*), and the agave weevil (*Scyphophoru sacupunctures*) (Yen 2015a, b). Hence, continuous farming of edible insects became necessary. There are many insects species that are more often seasonally available. They appear after the first rain of the dry season. For example, insects such as termites and ants often the reproductives (winged ones) are eaten and some of them like caterpillars are depended upon host plants. Some of the insects like the giant water bug*, Lethocerus indicus* (Hemiptera: Belostomatidae) are the kind of aquatic species present in south-east Asia (Huis and Dunkel 2017).

For various edible insect species, different agricultural methods are employed (Huis 2017). Not all types of distinct species of insects can be raised exclusively in laboratory settings. By manually removing pests of edible insects that threaten crops from agricultural crops, we can reduce the need for insecticides and other chemicals while also protecting crops from these pests. For use as food and as animal feed, edible insects are raised and then bred. For farming, two methods are typically used. First, an insect can be completely domesticated and raised in captivity using a straightforward procedure. As an alternative, an insect can be partially raised in captivity by enhancing its habitat and providing it with sustainable circumstances so that it can increase its production without being separated from its wild population (Baiano 2020). As a result, the first method was used to raise mealworms, cockroaches, and a few beetles, whereas the second method was used to raise wasps, bamboo caterpillars, palm weevil larvae, and dragonflies. Each insect species is harvested differently based on three key variables: the stage of development (eggs, caterpillars, larvae, or adults), the season (rainy or dry), and the location (desert or agricultural field). Prior to this strategy, adults who are skilled at harvesting a range of edible insects would gather all edible insects (Huis 2017).

4 Processing of Edible Insects

As is well known, edible insects include a variety of nutrients necessary for a long and healthy existence. We need to process edible insects, such as roasting, frying, and boiling them, in order to get their nutrients and benefits. Traditionally, edible insects were eaten whole right away after harvesting until processing methods were developed. However, after processing methods were developed, people now prefer to eat processed insects. For instance, to enhance the flavor and palatability of edible insects, waste material and non-edible sections are peeled off and then changed into various forms. Their shelf life is also increased by processing (Santiago et al. 2020). Additionally, whole edible insects are ingested after being killed using processing methods like freezing, drying, boiling, and sun-drying. The most popular way among all of these is roasting, which is followed by boiling and then frying. Sun and oven drying are used to create the normally dried product. For the floor and powder of insects, however, freeze-drying and oven drying are more common (Baiano 2020). New techniques like extrusion, marination, supercritical fluid hydrolysis, and fermentation are being used to maintain the quality parameters.

It has been seen that some customers avoid consuming edible insects directly. This is likely owing to the associated unpleasantness. For those who advocate for the eating of edible insects, this is a serious matter. The consumption of edible insects can be increased by processing them into a paste or powder. Paste or powder that has been prepared can be added to other food items, such as bread, spaghetti, crunchy foods, or similar items, to enhance their flavor. In order to maximize their benefits, edible insects are typically turned into powder. The content of protein, fat, and fiber in edible insects was affected by standard techniques such thermal treatment such as boiling, drying, roasting, toasting, and smoking as well as microwave-assisted, microwave, vacuum, and conventional hot drying on rotating rack.. It is also responsible for decreasing energy value, water-soluble vitamins, nutrient content and bioactive compounds of edible insects (Santiago et al. 2020).

5 Functional Properties of Edible Insect

5.1 Solubility

An intriguing replacement for traditional proteins is insects. Protein solubility is the percentage of proteins that are in a soluble state under particular circumstances. As the functional features like forming, gelling, and emulsions depend on it, it is one of the most crucial characteristics in food systems (Gravel and Doyen 2020). It is one of the most desired properties both for protein applications and for digestion (Mishyna et al. 2021). Protein that is soluble depends on a number of variables, including intrinsic and extrinsic ones (Table 1). Insect protein solubility is pH-dependent (Mishyna et al., 2021). The kind of processing treatment used and how intense it is has a significant impact on how soluble insect proteins are. As an illustration, the protein solubility of yellow mealworms dried in a fluidized bed, microwave, and rack oven decreased from 12.65 to 19.25%.It is 40.65% compared to freeze-drying, 49.70 compared to vacuum-drying, and 53.24% compared to fresh mealworms. According to Mishyna et al. (2021), mealworms and crickets both have relatively lower solubility's when roasted and pulverized, 28.2 and 23.2%, respectively. Protein denaturation unfolding and exposition of internal hydrophobic groups are the main cause of a decrease in insect protein solubility. Solubilization of grasshopper proteins at alkaline pH and precipitation at the isoelectric point without thermal treatment caused to increase in protein suitability (Mishyna et al. 2021). After protein extraction and defatting of yellow mealworm in comparison with full-fat flour, the increase in solubility was observed whereas solubility was not changed by defatting of mealworm larvae and silkworm pupae. It has been shown that blanching and fermentation of mealworms with meat starter cultures led to a significant decrease in protein solubility and also shifted the isoelectric point from pH 4 to pH 6. If the given study is perused, it is seen that African cricket (*Gryllida*e) also shows low solubility at pH 3 and 4. The insect proteins, however in both pH values were not enzymatically hydrolyzed. Hence, the study suggests that the isoelectric point of cricket (*Grillades sigillatus*) protein is at or near pH 3.0 (Jantzen da Silva Lucas et al. 2020). Protein solubility depends on intrinsic factors such as amino acid composition and structure, protein size, and three-dimensional structure, as well as extrinsic factors such as ionic length, pH and temperature. The presence of negatively charged and polar amino acids at a protein surface increases solubility while non-polar amino acids decrease solubility (Gravel and Doyen 2020). Extrinsic factors such as temperature can also change the value of protein solubility. Generally, temperature improves protein solubility up to the point where the protein is denatured. Now if we consider ionic length, at lower ionic length ions act as a shield protecting proteins from each other attractive forces and promoting solubility and at high ionic length. The fierce competition between salt and protein for water molecules makes the proteins less soluble (Gravel and Doyen 2020). Protein solubility could be an important concern in improving the functional and rheological properties of edible proteins.

Table 1 Outcomes of functional properties of edible insects with their parameters

Functional Properties	Edible insect		Processing conditions	Outcome	References
Solubility	Scientific name	Common name			
	Tenebrio. M Olitor	Yellow mealworm	Drying [using a microwave and rack oven]	Protein solubility depressed to 12.65–19.25%	Kroncke et al. (2018)
	Gryllus bim aculatus, and B. mori	Two-spotted cricket, and silkworm	Enzymatic hydrolysis [using commercial enzymes like Flavourzyme and Alcalase]	Solubility of protein increases	Sungwon Yoon, Nathan A. K. Wong (2019)
Emulsifying property	Chondracris Roscapbrunner	Large grasshopper	Flour, concentration	Demonstrated greater cmulsifying property	Chatsuwan et al. (2018)
Foaming property	Protactia. br evitarsisseulensis	White-spotted flower chafer beetle	Pressur-treatment, concentration	The foaming capacity of pressure-treated P. breviaries selenosis is high	Kim (2020)
Gelling property	Acheta domesticus	House cricket	Heating, defatted concentration	Gel formation takes place at pH 7	Mishyna et al. (2021)
Oil holding capacity	Acanthoplus discoidalis	Armored bush cricket	Oven drying, flour	Oven-dried sample have higher oil holding capacity compared to sundried samples	Mugova A. and R2 (2021)
Water holding capacity	Tenebrio. M olitor	Yellow Mealworms	Roasting, grinding, and Fermentation	The water holding capacity increased	Mishyna et al. (2021)

5.2 Emulsifying Property

Emulsification is known as the homogenous mixture of two immiscible liquids, whether it be a droplet of oil in water or a droplet of water in oil. Methods for determining emulsifying property given by Wu et al. (2009). Overall, the surface action on the oil–water interface is determined by the amphiphilic character of the protein, similar to the air–water interface, but scattering interactions often accelerate protein absorption in the oil–water interface. The amphiphilic properties of proteins allow them to form and stabilize food emulsions by reducing surface tension at the oil–water interface (Mishyna et al. 2021). The emulsifying activity of proteins is affected by their molecular weight, hydrophobicity, conformation stability, surface charge, and their physicochemical properties, such as pH, ionic strength, and temperature (Zhao et al. 2012). Emulsification is also influenced by intrinsic and extrinsic factors. In particular, protein shapes affect emulsion formation and stability (Gravel and Doyen 2020). Smaller proteins are conducive to diffusion and generally show better emulsion capacity, but lower emulsion stability. Whereas, larger proteins have lower diffusion rates, which increases emulsion stability after the formation of a layer around the oil–water interface.

Unlike solubility, which is crucial for oil absorption, the presence of hydrophobic amino acids on the surface of proteins enhances emulsification capabilities. External elements that affect emulsion, like extremely low ionic strengths, severe pH values, and partial hydrolysis, also enhance the ability of proteins to emulsify (Lam et al. 2018). Due to their emulsifying qualities, traditional proteins including milk, eggs, and soy are frequently employed as additions. There are various studies on the emulsifying abilities of insects in the literature that can be used as a benchmark. High emulsifying activity index (EAI) values indicate a small number of oil droplets dispersed in the oil–water interface and high absorption capacity of proteins (Pacheco-Aguilar, Mazorra-Manzano, and Ramírez-Suárez 2008). Hall et al. (2018) verified that the treatments that showed the highest emulsion capacity (27–32 m^2/g) were Tests 1 and 2 (0.5% E/S for 30 and 60 min, respectively) and Test 8 (3% E/S, 60 min.). Tests, 5–7 and 9 (1.5% E/S, 30–90 min and 3% E/S, 90 min, respectively), showed lower EAI compared to other treatments, and unhydrolyzed protein values were significantly different ($p < 0.05$) in emulsions stabilized by crickets (*Grillods singultus*)—CPH hydrolysates. The highest functional properties became apparent when hexane was used as a solvent, followed by ethanol. Overall, the emulsifying properties are affected by protein processing as well as foaming properties (Mishyna et al. 2021).This emulsion property has many useful applications, for example in baked goods, mayonnaise, salad dressing, frozen desserts, and comminute meats (Kinsella 1976).

5.3 Foaming Property

Different insect species that are treated with the same methods typically have different foaming qualities. A continuous aqueous phase and a dispersed gas phase combine to form foams, which constitute a two-phase colloidal system. The movement, penetration, and rearrangement of molecules control foam formation at the air–water interface. Mealworm powder that has been roasted and crushed is renowned for its lack of foaming. In comparison to fava beans (62%) and yellow peas (49%) cricket powder has superior foaming stability (86%) (Mishyna et al. 2021). In order to form like other functional features that depend on many aspects like protein structure, foams are formed by air bubbles caught in the liquid and stabilized by proteins in the air–liquid interface. Foam formation means protein unfolding to ensure better absorption in the air–water interface. Globular and compact proteins are usually less effective at forming foam than their more fibrous and elastic counterparts. Rapid air bubble formation does not always imply foam stability. Strongly related and closely packed globular proteins from a more resistant film, which makes them better at foaming and forming a deformation-resistant foam than elastic proteins (Kinsella 1981).

Generally higher foaming capacity was noted in the protein preparation. The foam stability ranged from 19.33% to 34.67% for the whole insect and from 6.17% to 99% for the protein preparation. The highest value of 92.0% and 34.67% protein preparation and foam capacity is found in whole pest's *G. singultus*, respectively. The lowest value of foam capacity and protein preparation was reported in *S. gregoria* i.e. 6.17% and 19.33%, respectively. These results are not consistent with most hydrophobic amino acid content in the proteins of species studied, but in the case of *G. sigiltus*, they may depend on the location of the hydrophobic amino acid residue on the surface of the protein.

5.4 Gelling Property

Disulfide bonds and hydrophobic interactions are the key factors in gel formation, which is measured by a protein's gel-forming capability (Villaseor et al. 2021). The most important functional characteristic of animal proteins in emulsion products is their ability to gel. Gel-forming ability is influenced by protein content, pH, ionic strength, processing, and protein denaturation. Gelation is dependent on a number of internal elements, such as electrostatic interaction, and external factors, such as temperature, which is the most important factor, much like every other functional feature we have previously explored. According to Kim et al. (2020), the gel can be understood as a structured protein network capable of holding huge amounts of water without exhibiting laminar flow in a fixed area. Animal products' heat stability and animal proteins' gel stability are crucial in various procedures. Heat supply is crucial for gel formation because it speeds up protein production and breakdown, which leads to gradual rearrangement and accumulation and the development of the ideal gel during the cooling phase (Kim et al. 2020). Due to the protein pH being close by, acid circumstances were unsuitable for gel formation. In these circumstances, weak electrostatic interactions between proteins cause aggregates to develop during denaturation changes. On the other hand, low protein concentrations make it simple to produce gases in an alkaline pH. The gel in *Locusta. migratoria* contains between 4 and 20% protein concentrate when the pH is 7.2 (Villase-Or et al. 2021).

5.5 Water Holding Capacity

The ability of proteins to hold or bind water molecules and thus prevent their release is called water holding capacity (Mishyna et al. 2021). Water-holding capacity (WHC), water-binding capacity (WBC), and water absorption capacity (WAC) are all terms associated with the ability of protein matrix to retain as much water as possible per gram of sample material, against gravity whether it can be bound or physically entrapped water (Gravel and Doyen 2020).Water holding capacity is highly correlated with gelation properties. It is associated with improved texture and moisture, which is of great importance in food formulation (Mishyna et al. 2021). Cricket powder of 66% of protein (dry weight) and approx 16% lipids showed a water holding capacity of 1.76 g/g. These types of commercial powders were obtained by roasting the whole insects at 107 °C and then grinding them into powder. Whole yellow mealworm powder obtained through freeze-drying and grinding showed a water holding capacity of 1.29 g/g (Mishyna et al. 2021).

5.6 Oil Holding Capacity

Oil holding capacity, oil absorption capacity, and oil holding capacity are all terms used to describe a protein's ability to absorb and keep onto fat (Mishyna 2021). All refer to how many lipids a specific volume of protein powder may absorb (Gravel and Doyen 2020). This characteristic and emulsifying properties are connected. Taste and texture are connected to oil absorption potential. For cricket powder with 66% protein (dry weight) and 16% lipids, the measured value range is between 1 and 4 g/g OHC, with an OHC of 1.42 g/g. The complete insects were roasted at 107 °C and then ground into powder to create these commercial powders.

6 Food Safety and Environmental Effect

Cooking, drying, and acidification by lactic fermentation are a few methods that can be used to prevent entero-bacterial and bacterial spore-related contamination of insects. Edible insects should be regarded as regular food, and food safety procedures should be followed, to ensure food safety. A popular technique for preventing physical–chemical and biological contamination throughout the food production processes is the HACCP (hazard analysis and critical control points) system (Huis 2017).

The first factor contributing to global warming is greenhouse gas (GHG) emissions from human activity. Studies show that the average global temperature has risen by 1.4°F over the past century, and it is expected to keep rising, which will have serious adverse effects. Climate change will have a significant impact on crop productivity, which is already declining, rainfall, and ambient temperature. Because of intensive farming practices using synthetic fertilizers and pesticides, soil fertility is fast declining and the environment is being severely harmed. To protect food and feed crops from damage, chemical pesticides are employed against pests, weeds, and plant diseases (Gahukar 2016). According to FAO (2014), the production of meat contributes significantly to the present 15–24% global warming emissions. The settings under which insects or animals are raised have an impact on the rate of emission of these gases. Given the rising demand for meat, it is expected that by 2050, emissions would rise by 39% and biomass use will rise by 21%. In contrast to conventional livestock (pigs and beef cattle), insects emit substantially less GHG per kilogram of meat (Gahukar 2016). There is a very visible accompanying drop in the amount of land resources available to produce this amount of food as a result of the ongoing increase in human population, which in turn leads to a large demand for food. Currently, global warming poses a risk to utilizing all of the accessible land area (Premalatha et al. 2011). Insect farming is far more advantageous from an environmental standpoint than conventional cattle farming since it produces fewer greenhouse gas emissions, uses less water and land, costs much less money, and has a higher feed conversion rate. For instance, 1 kg of insect protein may be produced from various kinds of crickets and mealworms using just 40 L of water. Insects are also observed to have a rapid rate of reproduction and a broad geographic range. However, if the research of the UN and FAO are examined, it is thought that insects offer a potential answer to any potential food insecurity.

From the viewpoint of environmentally clean farming, insects are more suitable as compared to the livestock for the following reasons:

- ***Their farming on organic side streams is possible;***
- ***They emit less GHGs and little ammonia;***
- ***High feed conversion efficiency is possible;***
- ***Compared to mammals and birds, insects pose less risk of transmitting zoonoticm infections to humans, livestock, and wildlife; and***
- ***An increase in animal production will require additional cropland and feed and it may also trigger deforestation of land used for grazing.***

It can be understood better with this example, forest land in the Amazon basin would be reduced in the future nearly by 70% when used for pasture or feed crops (Gahukar 2016). In addition to the above advantages, the largest advantage of edible insects in comparison to conventional livestock is that several species can successfully be grown on organic side-streams, converting low-value organic by-products into high-value proteins. This particular conversion is extremely significant considering that one-third of all our agricultural produce and food is wasted, which is, globally1.3 billion tons each year annually (FAO 2011) costing US$750 billion (Economist 2014). Ramos-Elorduy et al. (2002) demonstrated the usefulness of edible insects in waste management by using waste fruits and vegetables for mealworms (Huis and Dunkel 2017). If developed and poor countries are compared globally, developed countries consume more protein per person per day (approximately 96 g), but a significantly higher percentage (65%) of this comes from meat. According to Alan (2009), protein consumption in underdeveloped nations is significantly lower (approximately 56 g/person/day), and only 15% of that is made up of animal protein. Livestock raising, In addition, it should be remembered that among the 6 billion people that inhabit the planet, one in every six die from starvation and malnutrition (Premalatha et al. 2011). Given the aforementioned situation, it is crucial to stop ignoring the potential of insects as human food, especially to offer the much required protein for the world's growing population. While insects farming is economical as well as beneficial in many aspects, insect consumption can be risky as well as beneficial. Hence, it is necessary to pursue the same.

7 Risk and Benefits of Consuming Insects

7.1 Benefits

Insects are consumed globally as it has nutritional values. With over 1900 species of edible insects, nutritional values are highly variable, and would be rather difficult to generalize their nutritional composition. However, it must be noted that Nutritional values of edible insects can vary depending on their metamorphic stage, an environment they are in, their diet, preparation, method of processing (i.e., baking, frying, boiling), and storage before consumption (Gravel and Doyen 2020). Though these variations can be significant, Rumpold and Schlüter (2013) compiled data on nutrient compositions of 236 edible insects (based on the dry matter) found in the literature which shows promise of edible insects providing satisfactory amounts of energy and protein for humans, both MUFAs and PUFAs, including essential linoleic and a-linolenic and several vitamins and minerals (calcium, iron, zinc) (Alrifai and Marcone 2019). Some of the major application and benefits of edible insects are shown in given Fig. 1.

Fig. 1 Major Application and benefits of edible insects

- On a fresh weight basis, the protein and calorie contents of insects are generally comparable to those of beef, fish, and chicken, while they include more PUFAs and minerals like iron and zinc.
- In addition, Onore (1997) contends that insects are a healthy meal. For instance, 100 g of dried termites have considerable levels of phosphorus, salt, iron, and potassium as well as about 53% protein, 15% fat, and 3.5% carbs (Alrifai and Marcone 2019).
- Consuming insects, such as termites and crickets, can also help strengthen our immune systems and stimulate metabolic processes because they contain vital vitamins.

7.2 Risk

There may be dangers associated with eating insects that need to be considered. The EFSA recently issued a risk profile connected to insect ingestion (Kouimská and Adámková 2016).

- Eating an insect at the wrong stage of development poses the greatest risk when eating edible insects. In addition, improper handling and preparation of food might increase the danger of ingesting insects. According to a study (Kouimská

and Adámková 2016), eating grasshoppers and locusts without first removing their feet can result in intestinal blockage, which may be fatal.
- Some insects have a chitin-based, stiff outer shell for their bodies that makes it challenging for humans to ingest and digest. Additionally, ingesting insects has been linked to allergies.
- It is also important to mention that some insect species that have come into touch with the incest to be consumed pose a serious risk of transmitting infectious diseases. Insects' gut microbiome may provide a favourable environment for the development of harmful pathogens.
- Insects have a very diverse microbiota in both their digestive system and on the outside of their bodies; these microbial communities are moulded by the insect's upbringing and living circumstances as well as by the processing involved in turning it into food (Mishyna et al. 2021).

In addition to this, insects act as carriers of pathogenic germs. It is crucial to ensure the microbiological safety of edible insects since the total microbial load of a product affects both food safety and its shelf life.

8 Conclusion

The new source of animal protein is insects that can be eaten. It is impractical to distribute food to everyone because of the increasing global population. This problem will primarily be solved by entomophagy, which is a particularly nutrient-dense source of food and feed for animals. Numerous edible insects include key amino acids that humans need and have a well-balanced nutritional profile. The creation of protein hydrolysates will be useful in preventing various illnesses, including diabetes, hypertension, and cardiac arrest. A large portion of the population is put off by eating edible insects because they are disgusting, but habits of doing so continue since they are rich in nutrients, proteins, and other components that support life. Producing and raising food insects is more environmentally friendly than raising conventional livestock. Comparatively speaking to more traditional animals (such as cattle, chickens, goats, etc.), insects needed a lot less space to flourish. Additionally, they don't need a lot of food or water. Because of this, there is an increased need for edible insects as a source of diverse proteins, minerals, and vitamins. This review article explains how various processing procedures are used on edible insects to get the varied functional qualities. This review article explains how various processing procedures are used on edible insects to get the varied functional qualities. As a result, edible insects are utilized for a variety of purposes, including food, medicine, and vitamin supplements for particular diets, such as those for athletes.

Reference:s

Baiano A (2020) Edible insects: an overview on nutritional characteristics, safety, farming, production technologies, regulatory framework, and socio-economic and ethical implications. Trends Food Sci Technol 100:35–50. https://doi.org/10.1016/j.tifs.2020.03.040

da Silva Lucas, Andressa, Lauren Menegon de Oliveira, Meritaine da Rocha, and Carlos Prentice. (2020) Edible Insects: An Alternative of Nutritional, Functional and Bioactive Compounds. Food Chem 311: 126022. https://doi.org/10.1016/j.foodchem.2019.126022

Gahukar RT (2016) Edible insects farming : efficiency and impact on family livelihood. Food Secur Environ Com Livest Crop. 85–111

Gravel A, Doyen A (2020) The use of edible insect proteins in food: challenges and issues related to their functional properties. Innov Food Sci Emerg Technol 59:102272. https://doi.org/10.1016/j.ifset.2019.102272

Hall Felicia, Philip E Johnson, Andrea Liceaga, Philip E Johnson (2018). Food chemistry department of food science , purdue university , 745 Agriculture Mall Dr., West Lafayette, IN Department of Food Science and Technology-Food Allergy Research & Resource Program, Authors Email Addresses. https://doi.org/10.1016/j.foodchem.2018.04.058.

Huis A Van (2017). New sources of animal proteins : Edible Insects. 443–61

Huis A Van, Dunkel FV (2016). Edible insects: A neglected and promising food source. In Nadathur SR, Wanasundara JPD, Scanlin L (Eds.), Sustain Protein Sources (pp 341–355). Elsevier. https://doi.org/10.1016/B978-0-12-802778-3.00021-4

Kim TK, Lee MH, Yu MH, Yong HI, Jang HW, Jung S (2020) Thermal stability and rheological properties of heat-induced gels prepared using edible insect proteins in a model system. LWT-Food Sci Technol 134:110270. https://doi.org/10.1016/j.lwt.2020.110270

Kinsella JE (1976) Functional properties of proteins in foods: a survey. Critical Rev Food Sci Nutr 7(3):219–280

Kinsella JE (1981) Functional properties of proteins: possible relationships between structure and function in foams. Food Chem 7(4):273–288

Kouřimská Lenka, Anna Adámková (2016) Nutritional and sensory quality of edible insects NFS J 22–26

Lam ACY, Can Karaca AC, Tyler RT, Nickerson MT (2018) Pea protein isolates: structure, extraction, and functionality. Food Rev Intern 34(2): 126–47

Liceaga, Andrea M (2021) Processing insects for use in the food and feed industry. 1–12

Ma P (2019) Edible Insects and Related Products. 2100:139–165

Mishyna M, Julia K, Keppler CJ (2021) Techno-Functional properties of edible insect proteins and effects of processing. Current Opin Colloid Inter Sci 56:1–24

Oday A, Marcone MF (2019) Human use of insects as Food—Food security. Comprehen Biotechnol 4:618–628

Ojha S, Alaa El-Din B, Tilman G, Oliver KS (2021) Bioavailability of nutrients from edible insects. Current Opin Food Sci 41:240–248

Onore G (1997) A brief note on edible insects in ecuador. Ecol Food Nutr 36(2–4):277–285

Pacheco-Aguilar R, Mazorra-Manzano MA, Ramírez-Suárez JC (2008) Functional properties of fish protein hydrolysates from pacific whiting (Merluccius Productus) muscle produced by a commercial protease. Food Chem 109(4):782–789

Premalatha M, Abbasi T, Abbasi T, Abbasi SA (2011) Energy-Efficient Food Production to Reduce Global Warming and Ecodegradation : the Use of Edible Insects. 15:4357–4360

Qiang Z et al (2012) Comparison of functional and structural properties of native and industrial Process-Modified proteins from Long-Grain indica rice. J Cereal Sci 56(3):568–575

Rumpold BA, Schlüter OK (2013) Nutritional composition and safety aspects of edible insects. Molr Nutr Food Res 57(5):802–823

Santiago-l L, Belinda Vallejo-cordoba, Cecilia Castro-l (2020) An insight to fermented edible insects : a global perspective and prospective Adri A. 137

Villaseñor, Víctor M, Enriquez-Vara JN, Urías-Silva JE, Mojica L (2021) Edible insects: techno-functional properties food and feed applications and biological potential. Food Rev Intern 1–27
Wu Haiwen, Qiang W, Tiezheng M, Jiajia R (2009) Comparative studies on the functional properties of various protein concentrate preparations of peanut protein. Food Res Intern 42(3): 343–48
Yen AL (2015a) Insects as food and feed in the asia pacific region: current perspectives and future directions. J Insects Food Feed 1(1):33–55
Yen AL (2009) Edible insects: traditional knowledge or western phobia? Entomol Res 39(5):289–298
Yen AL (2015b) Conservation of lepidoptera used as human food and medicine. Curr Opinn Insect Sci 12:102–108

Food Processing Techniques to Conserve Millet-Based Ethnic Food Products of India

Shruti Mishra and Shivangi Mishra

1 Introduction

Food is an essential part of human life. It is not only a means of sustenance but also a powerful expression of cultural identity and heritage. Food production, processing and consumption are all intimately related to humans and their culture. It not only represents diversity and human adaptations but also encompasses a wide range of geographical, cultural, and lifestyle perspectives (Reddy and van Dam 2020). Thus, any alterations in food production and consumption patterns have an impact on ecosystems and human diets (Kearney 2010; Aleksandrowicz et al. 2019). This is supported by the Food and Agricultural Organization's (FAO) findings, which revealed that 3.1 billion impoverished individuals suffer from hunger and malnutrition, while approximately two billion experience undernutrition and micronutrient deficiencies. Simultaneously, around two billion people are overweight or obese and it is estimated to rise continuously at a global scale (FAO et al. 2022).

The current food practices involving production, processing, supply, and consumption do not adequately meet the present and future needs of the human (Béné et al. 2019). This system is heavily influenced by the global economic sector, emphasizing the industrialized production, intensive food processing, hostile food distribution, and advertising. Unfortunately, these practices are often prioritized over local cultural heritage and environmentally sustainable approaches (Lairon 2012). Therefore, there is a dire need to introduce a fresh approach that promotes and encourages the concept and idea, and acceptance of sustainable diets in both developed and

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developing country. This will be crucial in ensuring food safety and maintaining high quality foods standards. This can be achieved by combining new processing techniques with the knowledge of traditional and ethnic food cultures (Sarkar et al. 2019). Traditional or ethnic food is closely tied to the inheritance and customs of an ethnic community, incorporating locally sourced ingredients from plants and/or animals into their cuisine. The definition of ethnic or traditional cuisines encompasses the idea of food originating from a specific ethnic group's heritage and cultural practices, utilizing their knowledge of local ingredients; besides social and cultural acceptance by the consumers outside of that particular group (Kwon 2015). It is worth noting that traditional foods not only act as cultural vehicles but also often known for various health benefits, as they typically prioritize palatable and nutritious options. Ethnic food culture incorporates the culinary traditions, ingredients, and cooking techniques that have been passed down through generations, preserving the unique flavours and aromas of different regions around the world (Almansour et al. 2022). Ethnic food cultures are closely associated with various factors like cultural diversity, farming practices, diversity in food, traditional processing techniques that lead to minimized food waste (Fig. 1). Ethnic food culture also has important sustainability implications, considering factors such as food miles, carbon emissions, economic considerations related to compositional changes, food security, and community relationships (Drewnowski et al. 2020). Thus, it becomes important to preserve the ethnic food culture as it not only conserves cultural heritage and diversity but also contributes to a sustainable food system, food security, and resilience.

As highlighted earlier, the growing population exerts pressure to ensure access to high quality food, which poses a challenge in finding viable solutions to meet the increasing demand of food (Li and Siddique 2020). One viable option is to explore underutilized crops like millet, which can effectively address the food demand while reducing malnutrition (Revoredo-Giha et al. 2022; Regmi et al. 2023). Millets also

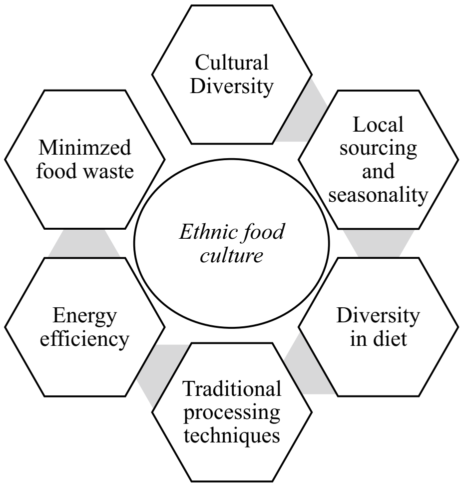


Fig. 1 Highlights of ethnic food culture

known as "miracle crop" or "resilient crop" or "super food", possess durable characteristics such as resistant to drought and pests, minimal use of fertilizers (Pradhan et al. 2021), high levels of nutrients and minerals to combat malnutrition and potential prebiotic properties that offer various health benefits (Gowda et al. 2022). Considering these attributes millets hold the potential to become important food crop globally to meet the future demand of super foods and functional foods. Seeing its importance, 2018 celebrated as millet year in India while United Nations (UN) observed 2023 as the "International Year of Millet". Millets have the potential to substantially contribute to accomplishing several SDGs, such as Zero Hunger, climate actions and Sustainable Consumption & Production. Generally, millet-based food products are being prepare using the traditional processing techniques. But by implementing improved processing and utilizing techniques, it is possible to create value added products that is widely accepted. However, limited research has been conducted in this area, making it a potential area of interest. Exploring ethnic food and commercializing it, opens up opportunities for these unique cuisines to gain recognition and for people worldwide to experience their richness and distinct nutritional benefits.

1.1 Millet-Based Ethnic Products of India

Millets have historically been overlooked in the food preferences of Americans and Europeans (Sathya 2018). However, due to their remarkable attributes such as versatile multigrain options and their gluten-free nature, millets have been gaining attention in recent times. Indian populations have long history to utilized millets into their diets either in the form of beverage, porridge and staple food. Some of the millet-based products are as follows.

1.2 Millet Flour

In the tradition practice, *chapattis/rotis* are prepared from different types of millets either alone or in combination (multigrain roti). For the preparation of rotis or chapattis a dough is prepared by mixing millet flour with the help of water that act as a binding agent. It can be either be made on flat pan to prepare roti or deep fried to prepare *puri*.

1.3 Millet Porridge

Different types of millet-based porridges are known depending on the region. For instance, in Uttarakhand, *Baadi* is popular among the Kumaon tribe. Buckwheat flour is cooked in boiling water followed by addition of clarified butter (ghee) and constant stirring. Similarly, sweet porridge is made by boiling barnyard millet (*Jhangora*) milk, thereafter addition of sugar, cashews and other nuts (Kala and Nautiyal 2022).

In southern part of India, "*Samaipayasam*" is prepared by using powdered roasted groundnuts, fennel seeds, and jaggery. Little millet is boiled in water with continuous stirring, thereafter added with the powdered mixture (Kumar et al. 2018).

1.4 Apalu

It is a traditional snack prepared by combining pearl millet flour and Bengal gram flour. The dough is prepared by incorporating spices such as carom and sesame seeds, chilli powder and salt. The resultant dough is divided into small portions, which are then shaped into round discs and deep-fried until golden brown and served hot.

1.5 Korramurukulu

It is a famous South Indian crispy snack prepared from foxtail millet flour and Bengal gram flour. To enhance the flavour, spices, salt etc. are added to the flour, thereafter water is added to make a stiff dough. The dough is then loaded into a hand extruder to make a spiral-shaped snack "Murukus". These murukus are deep fried until golden brown colour (Kumar et al. 2018).

1.6 Chhachh-Indu

It is a millet-based beverage of Uttarakhand. For its preparation, Barnyard millet is cooked by boiling in buttermilk. Salt and condiments like chilli and turmeric powder are added to it making it more flavourful (Kala and Nautiyal 2022).

1.7 Beverages

Different types of millets are used for the preparation of alcoholic beverages. These beverages are known by various names depending on the type of millet used and the regionality. For instance, *Sur*: a finger millet beverage is prepared in different regions of Himachal Pradesh, India. The recipe of *Sur*, involve uses roasted barley and dhaeli inoculum. A dough of millet flour prepared and kept for one week for spontaneous fermentation. Further the fermented dough used for the preparation of roti finally prepared rotis cut into pieces mix with dhaeli, jaggery and water, kept for fermentation in earthen pot for around 8–10 days. Once the fermentation complete, liquid is filtered as stored for further consumption (Joshi et al. 2015).

- ***Madua***: Similarly, in Arunachala Pradesh, a fermented drink called *Madua* is widely consumed by local community. The major ingredient of this beverage is Ragi also known as finger millet. The preparation of this beverage is very simple that includes roasting followed by cooking and fermentation. Fermentation of this beverage takes place in a perforated basket covered with Ekam leaves for a period of 4–7 days (Kumar et al. 2018).
- ***Koozh***: It is another traditional fermented beverage popularly consumed in Tamil Nadu, India. It is made from finger millet flour and rice. It involves two stages of fermentation: grinding millet into flour, mixing with water, and fermenting overnight. In this mixture cooked broken rice is added and make a thick porridge called noyee. This mixture further kept for fermentation, after 24 h, the resulting mixture is obtained known as kali, and this is used to prepare koozh by addition of water and salt (Ilango and Antony 2014).
- ***Raggi muddle***: It is another traditional food of Karnataka. It is made from finger millet fermentation (Selladurai et al. 2023). Similarly, in north-east India especially Sikkim and Darjeeling, Kodo-ko-jaanr is the finger millet based mild alcoholic beverage that is sweet in taste (Thapa and Tamang 2004).
- ***Ambali***: is a fermented semi-liquid product made from finger millet popular in Karnataka and Tamil Nadu. It is prepared by making a thick batter of finger millet flour in water, followed by boiling and fermentation.
- ***Rabdi***: Another millet product is Rabdi which is a popular recipe in India's north-western region. It is a pearl millet-based lactic acid-fermented milk product. Pearl millet has a lower glycemic index than other cereals, which aids in the management of non-insulin-dependent diabetes mellitus, the primary cause of which cause a slowdown in carbohydrate metabolism (Modha and Pal 2011).

In addition to the aforementioned products, Millets are also used as a value-addition in the preexisting cuisine that are prepared from the major cereal grain such as wheat and rice. In recent years many studies have been done on the developed of dishes such as dosa, flecks, uttapam, upama, vada etc.

2 Millet-Based Processed Products

The emerging research trends in the arena of processed food products, millets are gaining popularity for the production of various value-added products that may be either the improvisions in the ethnic products or production of processed foods. Innovative advancements in the field of food science have led to the creation of millet-based beverages and weaning foods utilizing diverse base ingredients, such as milk, malted beverages, snacks or instant mixes.

2.1 Cookies/Biscuits

Millet based biscuits/cookies are gluten-free and are generally seen as an alternative for refined flour biscuits. Shadang and Jaganathan (2014) prepared the millet biscuits by using the combination of four millets along with wheat flour in different ratios. In this study, millet namely, foxtail, finger millet, pearl and proso millets were used. Finding of this studies reveled that all different ratios of millets and wheat flour based cookies was acceptable based on sensory scores. Similarly, Rai et al. (2014), used on rice, maize, sorghum, and pearl millet. The cookies prepared with pearl millet & sorghum flour shown highest nutritional properties and received the highest sensory acceptability. Biscuits made with up to 30% pearl millet & 5% soy flour, as well as biscuits with up to 10% pearled sorghum flour and 5% defatted soy flour, also demonstrated favorable sensory acceptability. Similarly, cookies prepared by using 45% millet flour (foxtail and barnyard) and 55% refined wheat flour exhibited higher nutritional value and low glycemic index (50.8 and 68 respectively). Furthermore Biscuits/cookies prepared by using composite flour that is the mixture of finger millet (60–70 w/w) and wheat flour (30–40 w/w) also had better texture profile than wheat biscuits (Saha et al. 2011) Although the nutritional profile of millet-based cookies are better than refined wheat profile, but the former biscuits exhibit higher levels of anti-nutrients (Sehgal and Kwatra 2007).

2.2 Noodles/Pasta

Noodles are a very popular and consider as the convenient meal among the people due to their ease of preparation, cost effectiveness, and longer shelf life. Pasta dishes like vermicelli, noodles, and macaroni are widely enjoyed by today's generation, as well as people of all age groups, due to their delicious taste, affordability, and ease of preparation. In past few years various efforts are made to incorporate underutilized crops like millets. In order to compete the small millets with other essential cereal foods, it is essential to develop preprocessed or alternative millet-based foods. To achieve this, vermicelli, noodles, and macaroni were prepared using refined wheat flour and blended with small millets at an incorporation level of 30% (Shukla and Srivastava 2014). Instant noodles made from foxtail millet are found to have high protein content, minerals, protein efficiency ratio, biological value as well as sensory attributes (Meherunnahar et al. 2023).

2.3 Bread

The making of breads using the millet flours present challenges due to the variability in sensory attributes. Consequently, experts often recommend combining millet flour with other cereal grains to maintain the overall quality of baked goods and enhance their nutritional value (Selladurai et al. 2023). Millet breads are prepared by substituting different portion of wheat flour with millets. Replacing about 50% of wheat flour with foxtail millet does not have substantial impact on flavour and overall acceptability of the bread, though compromising with the texture, colour, and appearance as compared with control wheat bread (Ballolli et al. 2014). Use of processed millet for instance, hydrothermally-treated (HTT) finger millet, for preparing bread have also been studied (Onyango et al. 2020). Bread prepared from composite flour (wheat flour and HTT finger millet flour) displayed a lower crumb firmness and chewiness, and higher specific volume when compared with the bread made from only wheat. These characteristics were due to high water absorption capacity and high α-amylase activity of the HTT finger millet. In terms of nutritional composition, HTT bread contained higher levels of dietary fiber, phytic acid, and polyphenols while maintaining the protein and starch digestibility same as white bread.

2.4 Snacks

Cereal popped products and flakes are well-liked breakfast options, with corn being the primary ingredient used in their production. However, through appropriate processing techniques, it may be possible to create popped or puffed foods and flakes from different types of millets. These Ready-To-Eat (RTE) products have gained popularity due to their crisp and friable texture. Millets are found to be more suitable for producing popped or flaked products due to their relatively small size and high hydration properties. Researchers have successfully flaked and popped small millets and developed various recipes using these processed millet products (Rao et al. 2016). Some of the value-added products include kitchidi, uppma, masala flakes, sweet balls, boli, etc. using small millet flakes, and uppma, bhelpoori, masala corn, and cheeian using popped small millets. Dhumal et al. (2014) devised oil-free, microwave-puffed ready-to-eat fasting foods using potato and barnyard millet. They prepared mixtures of barnyard millet flour and potato by mashing in different proportions (50:50, 55:45, and 60:40) and steamed them for varying durations (10, 15, and 20 min). Time variations exhibited different colour of the puffs. For instance, cold extrudates after steaming in a kitchen pressure cooker for 15 min, exhibited a white color, while the extrudates steamed for 20 min showed a brown color. In another study by Jaybhaye and Srivastav (2015), Barnyard millet-based snack food was developed using combination of potato mash, millet & tapioca powder in the ratio of 37:60:3. High temperature short time (HTST) puffing techniques was used to prepare this snack.

2.5 Ready-To-Eat (RTE) Mixes

In today's fast-paced life, where time is of great value to individuals, "Instant Foods" have become crucial in everyday routines. The term 'instant food' refers to quick, easy-to-prepare, and convenient food options that are not only hygienic and free from microbial contamination but also convenient to consume. As part of this trend, various traditional breakfast foods, such as adai, pittu, idiyapam, kali, roti etc. have been formulated as RTE mixes. Standardized instant mixes of these traditional dishes were developed, incorporating small millets to meet the demands of modern lifestyles like pulav mix, soup mix (Tulasi et al. 2020), weaning mix (Prasanna et al. 2020) and various other pre-mixes.

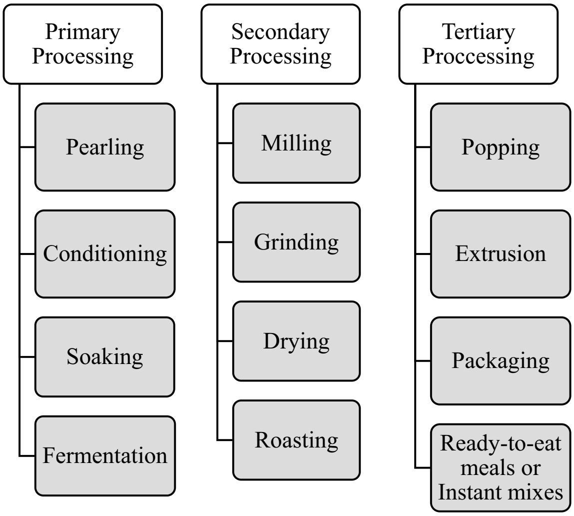
2.6 Ice-Creams

Millets are now seen alternative to dairy fats in the frozen dessert industry. Study shows that octenyl succinyl anhydride esterified from esterified pearl millet starch are effective fat replacer in ice cream (Sharma et al. 2017). In fact, inclusion of finger millets in the ice cream, reduced the need for stabilizers and also enriched the nutritional value of the product (Patel et al. 2015).

3 Food Processing of Millet-Based Products

Food processing is a crucial aspect of the food industry, encompassing a wide range of techniques and technologies that transform raw agricultural products into safe, convenient, and palatable food items. This process plays a vital role in enhancing food safety, extending shelf life, increasing nutritional value, and meeting the demands of a growing global population. Food processing can be divided into several stages, starting from harvesting or sourcing raw materials to the final product that reaches consumers' plates. The primary objectives of food processing are preservation, enhancement, and value addition. Different food materials undergo various types of food processing techniques to produce the desirable product. Generally, there are three stages of food processing: Primary, Secondary and Tertiary. *Primary food processing* refers to the initial stage of converting raw agricultural commodities into perishable food items. In certain cases, the processed food becomes suitable for immediate consumption after primary processing. Alternatively, immediate processing can transform the agricultural product into an ingredient that will subsequently become an edible food, as seen in the processing of grains to produce flour. *Secondary processing* involves using ingredients derived from primary food processing to create ready-to-eat foods. An illustration of this is utilizing flour as an ingredient to prepare dough and subsequently baking it to produce bread. While

Fig. 2 Processing of millet



tertiary food processing encompasses a broad range of ready-to-eat foods, such as packaged snacks. The term "processed food" generally describes the food items produced through the tertiary food processing. Some foods may undergo multiple types of processing before reaching they are ready to be consumed. Figure 2 gives a general overview of processing involved in millet and millet-based products.

3.1 Soaking

Soaking is the centuries old processing techniques that has been used as pre-treatment for preparing various types millet based traditional food products in India. Millets are rich source of polyphenolic compounds, which been identified as the most common antioxidant source in our food. However, these polyphenols also bond to minerals such as phosphorus, iron, rendering them inaccessible to our bodies (Bindra 2019). Soaking reduces antinutrients like tannins and phytic acid and polyphenols, thereby making essential nutrients and minerals like zinc, iron, calcium etc. bioavailable for the absorption by the body. Soaking stimulates the enzyme known as polyphenol oxidase, a process resulting in polyphenol breakdown and loss, and this loss may occur as a result of these substances releasing onto the immersing medium from the seed coat due to their ability to dissolve in water.

3.2 Pulverization or Grinding

Grinding is the process of crushing particles/ingredients against hard surfaces in order to reduce their sizes and enhance their surface area leading to proper extraction of essential compounds (Rani et al. 2018). The grains of millet are often processed manually using the mortar and pestle or by milling machines, to generate the millet flours. Milling reduces the phytic acid and polyphenol content of flour and same effect can be seen on millet chapati (bread) due to the removal of the bran, that contain major antinutrient (Yousaf et al. 2021). With the advancement of technology, nowadays electric mixer-grinder are available that not only crush and grind the ingredients but also combine them into a homogeneous consistency. Pulverization is the major part of prcosssing of any cuisine like millet bread/chappati, millet laddu, millet based dosa and idli.

3.3 Roasting

Roasting is a method of cooking a raw or semi-prepared item over an open flame in order to develop taste and semi-cook the material before its final processing. Roasting is sometimes used as the last phase; it is a better alternative to frying or sautéing because the use of oils is minimal or entirely eliminated in this process. Roasting reduces the load of bacteria in raw ingredients, gelatinizes starch, and denatures proteins, allowing the meal to be ingested immediately. Roasted foods have distinct flavour characteristics that result from the breakdown of carbs and proteins during heat treatment, which is appealing to customers. Most of the millets are roasted to enhance the flavours as well as for the reduction of antinutrient (Pradeep and Guha 2011). Some of the roasted cuisines include sunga pitha (East Indian breakfast dish), akki roti (South Indian breakfast item).

3.4 Fermentation

Fermentation is the process that involve chemical changes in organic compounds through the activity of enzymes. This involves fermenting the substrate under natural conditions or under regulated environment (spontaneous fermentation) to acquire certain flavour, aroma, taste, flavour or texture qualities (Mohapatra et al. 2019). Fermentation not only improves taste but also introduces helpful bacteria into the digestive system, which is good for human health. Fermentation promotes phytate hydrolysis via microbial phytase enzymes, lowering inositol phosphates. This is critical for the absorption of zinc and nonheme iron. In millets, fermentation can remove 90% or more of the phytate (Adebiyi et al. 2017). The fermentation process lowers the leucine-to-lysine proportion while increasing thiamin, riboflavin, and tryptophan concentrations and mineral bioavailability (Jaybhaye et al. 2014).

3.5 Popping

The popping process involves exposing the seed or grain to an elevated temperature for a short-time, which produces a highly heated vapour from the moisture contained inside the grain by immediate strong heating, which cooks the grain and swells the endosperm (Mishra et al. 2014). Popping is a basic heat-treatment-based processing technique. This is because of the small size of the finger millet that leads to difficulty in the de-bran. Moreover, popping increases overall nutritional content in the finished product (Saibhawani et al. 2020). For example, in *ragi hurihittu* which is a flour made from popped finger millet, high fibre and mineral content have been reported. The flour is used to make RTE malts (weaning meals). The abundance of a reducing sugars and amylase activity in finger millet is the primary explanation for the substantial nutritional value of the Ragi hurihittu. Ragi hurihittu contains slow cell wall disintegration components that can be used to make fiber-rich foods. To increase the nutrient content of hurihittu, the finger millet is germinated, that boosts iron and zinc absorption (Saibhawani et al. 2020).

3.6 Germination/Malting

Through de novo production or activation of intrinsic phytase, germination enhances endogenous phytase activity in cereals, legumes, and oil seeds. Endogenous phytase activity is lower in tropical grains such as maize and sorghum. In porridges for infant and early child feeding, a combination of germinated and ungerminated cereal flours increases phytate hydrolysis. During germination, a-Amylase activity increases, lowering viscosity and increasing energy and nutrient densities (Hassan et al. 2006). Some of the traditional foods are prepared by germination and malting, for example, Ragi java, sometimes called the ragi malt, is a thick, hot beverage prevalent in southern India. Cooking crushed ragi or with water or milk produces this dish. Ragi java is a very nutritious drink because of the ragi nutritional profile, which contains a lot of mineral and vitamins (Rathore et al. 2016).

3.7 Extrusion

Extrusion involves forcing a mixture of food ingredients through a die under high pressure and temperature, resulting in the desired shape and texture. Innovative techniques such as extrusion are employed to create a range of millet-based products, including puffed snacks and noodles. Hot extrusion and cold extrusion methods are utilized for producing these snacks and noodle-like products, respectively. By blending semolina derived from various minor millets (such as finger millet and foxtail millet) with refined wheat, vermicelli, noodles, and pasta products can be crafted. These innovative millet-based products exhibit promising market potential due to their high dietary fiber and mineral content. Various institutes like ICAR-CIPHET, CSIR-CFTRI has played a pivotal role in developing a variety of ready-to-eat millet-based products using extrusion techniques (Kotwaliwale et al. 2023). For instance, they have successfully created ready-to-eat puffed products from pearl millet and sorghum, which are fortified with legumes. Blended extrudates combining millets (such as finger millet and pearl millet) with soy have also been developed. In the realm of pasta products, notable innovations include pearl millet-based composite pasta made with barley and pearl millet flour, along with whey protein concentrate (WPC), hydrocolloids, and vegetable blends. These developments in millet-based extruded products showcase the innovative strides being made in incorporating millets into convenient and nutritious food options, offering consumers a diverse range of choices.

3.8 Ultrasonication

Ultrasonication is the advanced processing technique used for treating thermal sensitive food products. Based on the intensity of the waves, ultrasound (US) treatment can be used for activating or deactivating the enzymes, homogenization, preservation, emulsification etc. Lately US treatment has been applied and its effects on millet beverage and its subsequent fermentation process, as well as the characteristics of the fermented product has been studied (Meena et al. 2023). The findings revealed that US treatment had significant impacts on the overall process. Firstly, the US treatment was found to enhance the growth of the probiotic microbes and expedite the fermentation time. This indicates that the application of US treatment positively influenced the development of microorganisms during the fermentation process. The sonicated samples exhibited increased levels of polyphenols, flavonoids and antioxidant activity. Simultaneously, the sugar content in the samples decreased. Moreover, the particle size of the sonicated samples was significantly reduced, which may have contributed to the enhanced microbial growth observed. These findings hold substantial potential of US treatment in the fermentation industry, by effectively reducing the time taken during fermentation times and also enhancing the production efficiency.

4 Challenges in Transforming Ethnic Products for Commercialization

Following the call for local to global, it is important to promote the ethnic or traditional food culture at a large scale. However, there are various challenges to commercialize such products. Some of them are discussed below.

4.1 Availability of the Raw Materials

Raw materials are the basic requirements for any processed food products. Hence a thorough understanding and knowledge of the production, processing and procurement of the raw materials/ingredients that is used in the manufacturing of the food product is essential. This necessitates a detailed examination of the materials accessible in the country, as well as their chemical composition and the way it affects product quality. Availability of quality raw material is necessary for the large-scale production of the millet-based products. Raw material not only impacts the economy but also the quality of the food products. In addition, it also reduces the food loss and minimize food waste or its utilization (Filimonau and Ermolaev 2021).

4.2 Advanced Processing Techniques

Advanced processing techniques are essential for the development and/or improvements of ethnic food products at the commercial level. Equipment layout and efficiency of the machine necessitates the provision of complicated engineering inputs. Emerging processing technologies like 3D printing, nanotechnology, enzyme technology, pulse electric field, sonication etc. have been facilitating the development of various types of food products (Koutchma and Ezzatpanah 2021). However, its application in the traditional millet products is not completely explored. These techniques are used to achieve the optimal product quality and shelf life.

4.3 Product Development/Improvement

Commercialization of ethnic food products at a global scale is effective only when the product is optimized for the specific and unique taste and flavour. This can be achieved using advanced and technological methods without compromising the identity, authenticity and sustainability of the traditional food. To avoid the fluctuations of the food quality within the batches, the product must be standardized. As a result, raw materials to be used and other product specifications must be defined. The use of technology to increase operational economics or improve the product must be evaluated. In a culture where health is becoming more important, changes in the nutritional content of large-scale processed meals must also be considered. Similarly, safety concerns arise frequently and must be addressed appropriately that may indirectly lead to improving the product quality and also increase the shelf life of the products (Muhialdin et al. 2022).

4.4 Packaging and Marketing

Packaging is critical in protecting food from physical, chemical, and environmental variables that could contaminate the food if not properly wrapped. Packaging indirectly plays role in extending the shelf life of the product (Muhialdin et al. 2022). Appealing packaging may also lead to the promotion of the product by attracting the consumer. Besides, use of advanced packaging techniques like active packaging, vacuum packaging, modified atmospheric packaging etc. Promotional activities i.e., marketing of the traditional food products or other value-added millet-based products are essential to increase the sales of the products. This should be analyzed from economic perspective as well (Florek and Gazda 2021). Making traditional cuisine appealing to certain target demographics, such as adolescents and teenagers, is a challenging issue. To counter these, it is required to have proper marketing strategies, and other policies.

All of this necessitates the dissemination of a large amount of scientific knowledge through research. Overcoming with these challenges not only help in the health and nutrition perspective but also economy of the country.

5 Sustainable Approach of Processing of Millet-Products

Sustainable food processing techniques refer to practices that minimize environmental impact, conserve resources, and promote long-term ecological balance in the production and processing of food. These include: minimal processing i.e., minimize the use of processing steps that require excessive energy, water, or additives. Opting for minimal processing techniques retains the nutritional integrity of the food while reducing resource consumption. In addition, using energy-efficient machinery and technologies during food processing, such as high-efficiency motors, heat recovery systems, and energy-saving technologies like induction heating or microwave processing also helps in achieving the goal of sustainable processing. These modern food processing techniques that are employed to enhance the safety, quality, and convenience of food products while meeting consumer demands for nutritious and sustainable options.

6 Conclusion

Commercialization of traditional millet-based products is essential for the outreach of the ethnic food culture at the global scale. To increase the nutritional, shelf life and sensory qualities of food products or even to maintain the authenticity of the product, various methods either traditional or modern/mechanical can be applied. Traditional processing methods like techniques such as germination, roasting, fermentation, malting, puffing/popping, soaking etc., play a vital role in improving the overall quality of millet food products. Additionally, modern technologies like milling, extrusion, baking, and fortification, also contribute to improvement in nutritional quality and storage attributes. By adopting these sustainable food processing techniques, food producers can reduce their environmental footprint, conserve resources, and contribute to the development of a more sustainable and resilient food system.

Further Reading Rao D, Vishala B, Christina A, Tonapi VA (2016). Technologies of millet value added products. Centre of Excellence on Sorghum, ICAR-Indian institute of Millets Research, India.

References

Adebiyi JA, Obadina AO, Adebo OA, Kayitesi E (2017) Comparison of nutritional quality and sensory acceptability of biscuits obtained from native, fermented, and malted pearl millet (Pennisetum glaucum) flour. Food Chem 232:210–217

Aleksandrowicz L, Green R, Joy E, Harris F, Hillier J, Vetter S, Smith P, Kulkarni B, Dangour A, Haines A (2019) Environmental impacts of dietary shifts in India: a modelling study using nationally-representative data. Environ Intern 126:207–215. https://doi.org/10.1016/j.envint.2019.02.004

Almansouri M, Verkerk R, Fogliano V, Luning PA (2022) The heritage food concept and its authenticity risk factors-validation by culinary professionals. Intern J Gastron Food Sci 28:100523. https://doi.org/10.1016/j.ijgfs.2022.100523

Ballolli U, Malagi U, Yenagi NB, Orsat V, Gariepy Y (2014) Development and quality evaluation of foxtail millet (*Setaria italica* (L.)) incorporated breads. Karnataka J Agri Sci 27.

Béné C, Oosterveer P, Lamotte L, Brouwer ID, de Haan S, Prager SD, Talsma EF, Khoury CK (2019) When food systems meet sustainability–current narratives and implications for actions. World Develop 113:116–130. https://doi.org/10.1016/j.worlddev.2018.08.011

Bindra D (2019) Whole grains and millets as raw ingredients for recipes in diabetes mellitus. Intern J Home Sci 5(3):214–219

Dhumal C, Pardeshi I, Sutar P, Jaybhaye R (2014) Development of potato and barnyard millet based ready to eat (RTE) fasting food. J Ready Eat Foods 1:11–17

Drewnowski A, Finley J, Hess JM, Ingram J, Miller G, Peters C (2020) Toward healthy diets from sustainable food systems. Current Develop Nutr 4(6):083. https://doi.org/10.1093/cdn/nzaa083

FAO, IFAD, UNICEF, WFP, WHO (2022) The state of food security and nutrition in the world 2022. Repurposing food and agricultural policies to make healthy diets more affordable. Rome, FAO. https://doi.org/10.4060/cc0639en

Filimonau V, Ermolaev VA (2021) Mitigation of food loss and waste in primary production of a transition economy via stakeholder collaboration: a perspective of independent farmers in Russia. Sustain Prod Consump 28:359–370

Florek M, Gazda J (2021) Traditional food products—between place marketing, economic importance and sustainable development. Sustainability 13(3):1277. https://doi.org/10.3390/su13031277

Gowda NAN, Siliveru K, Prasad PVV, Bhatt Y, Netravati BP, Gurikar C (2022) Modern processing of Indian millets: a perspective on changes in nutritional properties. Foods 11(4):499. https://doi.org/10.3390/foods11040499

Hassan AB, Ahmed IAM, Osman NM, Eltayeb MM, Osman GA, Babiker EE (2006) Effect of processing treatments followed by fermentation on protein content and digestibility of pearl millet (*Pennisetum typhoideum*) cultivars. Pakistan J Nutr 5(1):86–89

Ilango S, Antony U (2014) Assessment of the microbiological quality of koozh, a fermented millet beverage. Afr J Microbiol Res 8:308–312. https://doi.org/10.5897/AJMR2013.6482

Jaybhaye RV, Srivastav PP (2015) Development of barnyard millet ready-to-eat snack food: part II. Food Sci Res J 6(2):285–291

Jaybhaye RV, Pardeshi IL, Vengaiah PC, Srivastav PP (2014) Processing and technology for millet-based food products: a review. J Ready Eat Food 1(2):32–48

Joshi VK, Kumar A, Thakur NS (2015) Technology of preparation and consumption pattern of traditional alcoholic beverage 'Sur' of Himachal Pradesh. J Food Fermen Technol 5(1):75–82

Kala CP, Nautiyal S (2022) Traditional food knowledge of local people and its sustainability in mountains of Uttarakhand State of India. J Soc Econ Develop 1–20. https://doi.org/10.1007/s40847-022-00222-z

Kearney J (2010) Food consumption trends and drivers. Philosophical transactions of the Royal Society of London. Biol Sci 365(1554):2793–2807. https://doi.org/10.1098/rstb.2010.0149

Kotwaliwale N, Gowswmi D, Yadav DN (2023) Millet processing: innovative technologies. Agricult Engg Today 47(1):36–40. https://pub.isae.in/index.php/aet/article/download/1399/1220#:~:text=Millet%20popping%20and%20puffing%20are,desirable%20aroma%20to%20the%20snacks

Koutchma T, Ezzatpanah H (2021) Frontiers: current challenges in food process design and engineering. Front Food Sci Technol 1:780013. https://doi.org/10.3389/frfst.2021.780013

Kumar A, Tomer V, Kaur A, Kumar V, Gupta K (2018) Millets: a solution to agrarian and nutritional challenges. Agri Food Sec 7(1):1–15. https://doi.org/10.1186/s40066-018-0183-3

Kwon D (2015) What is ethnic food? J Ethnic Foods 2(1). https://doi.org/10.1016/j.jef.2015.02.001

Lairon D (2012) Biodiversity and sustainable nutrition with a food-based approach. Sustainable diets and biodiversity.

Li X, Siddique KHM (2020) Future smart food: harnessing the potential of neglected and underutilized species for zero hunger. Maternal Child Nutr 16(S3). https://doi.org/10.1111/mcn.13008

Meena L, Buvaneswaran M, Byresh T, Sunil C, Rawson A, Venkatachalapathy N (2023) Effect of ultrasound treatment on white finger millet-based probiotic beverage. Meas Food 10:100090. https://doi.org/10.1016/j.meafoo.2023.100090

Meherunnahar MST, Ahmed T, Chowdhury RS, Miah MAS, Sridhar K, Inbaraj BS, Hoque MdM, Sharma M (2023) Development of novel foxtail millet-based nutri-rich instant noodles: chemical and quality characteristics. Foods 12(4):819. https://doi.org/10.3390/foods12040819

Mishra G, Joshi DC, Panda BK (2014) Popping and puffing of cereal grains: a review. J Grain Process Storage 1(2):34–46

Modha H, Pal D (2011) Optimization of rabadi-like fermented milk beverage using pearl millet. J Food Sci Technol 48:190–196

Mohapatra D, Patel AS, Kar A, Deshpande SS, Tripathi MK (2019) Effect of different processing conditions on proximate composition, anti-oxidants, anti-nutrients and amino acid profile of grain sorghum. Food Chem 271:129–135

Muhialdin BJ, Filimonau V, Qasem JM, Ibrahim SA, Algboory HL (2022) Traditional fermented foods and beverages in Iraq and their potential for large-scale commercialization. J Ethnic Foods 9(1):1–17

Onyango C, Luvitaa SK, Unbehend G, Haase N (2020) Physico-chemical properties of flour, dough and bread from wheat and hydrothermally-treated finger millet. J Cereal Sci 93:102954. https://doi.org/10.1016/j.jcs.2020.102954

Patel IJ, Dharaiya CN, Pinto SV (2015) Development of technology for manufacture of ragi ice cream. J Food Sci Technol 52:4015–4028

Pradeep SR, Guha M (2011) Effect of processing methods on the nutraceutical and antioxidant properties of little millet (*Panicum sumatrense*) extracts. Food Chem 126(4):1643–1647

Pradhan A, Rane J, Pathak H (2021) Alternative crops for augmenting farmers' income in abiotic stress regions. Tech bull no. 29. ICAR-National Institute of Abiotic Stress Management, Baramati, Pune, Maharashtra. https://niasm.icar.gov.in/sites/default/files/pdfs/Technical%20bulletin%20alternative%20crops.pdf

Prasanna MS, Sowjanya VS, Jaya E, Rajender G (2020) Development of millet based instant weaning mix. J Pharma Phytochem 9(4):1908–1913

Rai S, Kaur A, Singh B (2014) Quality characteristics of gluten free cookies prepared from different flour combinations. J Food Sci Technol 51:785–789

Rani S, Singh R, Sehrawat R, Kaur BP, Upadhyay A (2018) Pearl millet processing: a review. Nutr Food Sci 48(1):30–44

Rathore S, Singh K, Kuma V (2016) Millet grain processing, utilization and its role in health promotion: a review. Intern J Nutr Food Sci 5(5):318–329

Reddy G, van Dam RM (2020) Food, culture, and identity in multicultural societies: Insights from Singapore. Appetite 149:104633. https://doi.org/10.1016/j.appet.2020.104633

Regmi B, Kunwar S, Acharya TD, Gyawali P (2023) Potential of underutilized grain crops in the western mountains of Nepal for food and nutrient security. Agriculture 13(7):1360. https://doi.org/10.3390/agriculture13071360

Revoredo-Giha C, Toma L, Akaichi F, Dawson I (2022) Exploring the effects of increasing underutilized crops on consumers' diets: the case of millet in Uganda. Agricult Food Eon 10(1):1–21. https://doi.org/10.1186/s40100-021-00206-3

Saha S, Gupta A, Singh S, Bharti N, Singh K, Mahajan V, Gupta H (2011) Compositional and varietal influence of finger millet flour on rheological properties of dough and quality of biscuit. LWT-Food Sci Technol 44(3):616–621. https://doi.org/10.1016/j.lwt.2010.08.009

Saibhavani G, Kamalaja T, Srilekha K, Rani RN (2020) Role of traditional foods for immunity boosting. Advan Nutr 121:66–77

Sarkar D, Walker-Swaney J, Shetty K (2019) Food Diversity and indigenous food systems to combat diet-linked chronic diseases. Curr Develop Nutr 4(1):3–11. https://doi.org/10.1093/cdn/nzz099

Sathya A (2018) Role for value addition in processing foods of traditional varieties of grains. Food Processr Incr Qual Consump 423–454. https://doi.org/10.1016/b978-0-12-811447-6.00014-x

Sehgal A, Kawatra A (2007) Use of pearl millet and green gram flours in biscuits and their sensory and nutritional quality. J Food Sci Technol 44(5)

Selladurai M, Pulivarthi MK, Raj AS, Iftikhar M, Prasad PV, Siliveru K (2023) Considerations for gluten free foods-pearl and finger millet processing and market demand. Grain Oil Sci Technol. https://doi.org/10.1016/j.gaost.2022.11.003

Shadang C, Jaganathan D (2014) Development and standardisation of formulated baked products using millets. Int J Res Appl Nat Soc Sci 2(9):75–78

Sharma M, Singh AK, Yadav DN (2017) Rheological properties of reduced fat ice cream mix containing octenyl succinylated pearl millet starch. J Food Sci Technol 54:1638–1645

Shukla K, Srivastava S (2014) Evaluation of finger millet incorporated noodles for nutritive value and glycemic index. J Food Sci Technol 51(3):527–534. https://doi.org/10.1007/s13197-011-0530-x

Thapa S, Tamang J (2004) Product characterization of kodo ko jaanr: fermented finger millet beverage of the Himalayas. Food Microbiol 21:617–622. https://doi.org/10.1016/j.fm.2004.01.004

Tulasi G, Deepika U, Venkateshwarlu P, Santhosh V, Srilatha P (2020) Development of millet based instant soup mix and pulav mix. Intern J Chem Stud 8:832–835. https://doi.org/10.22271/chemi.2020.v8.i5l.10400.

Yousaf L, Hou D, Liaqat H, Shen Q (2021) Millet: a review of its nutritional and functional changes during processing. Food Res Int 142:110197. https://doi.org/10.1016/j.foodres.2021.110197

Sustainable Food Practices from Traditional Indian Culture

Sunayan Sharma

1 Introduction

Indian ancestors have given deep thought to traditional food culture, reflecting different aspects of individual lives inclusive of food habits. Indian cuisine varies with geography, climate, and region. Indian food habits have played pivotal role in rise and fall of civilizations. Traditionally, Indian cultural texts have laid importance between "diet and body, diet and mind, diet and attitude of mind". Indian mythological scripture the book of Bhagavad Gita which is estimated to be at least 5000–6000 years old. In the 17th chapter of the Gits, shlokas 8, 9 and 10 stated the results that appear due to our diet on individual's life. As per Hindu mythology there are three types of nature- *sattvic, rajasic* and *tamasic* (Pole 2023). In recent times, most Indian families, eating food using fingers has been replaced by spoons, forks or the type of dish of specific region. The knowledge of sustainability implies that one should benefit resources only to such extent that it does not damage the future consumption. Hotel or restaurant chefs and even consumers need to be mindful of practicing sustainable culinary techniques to upkeep the environment and for the welfare of the society and future generation at large (Gupta 2023). Eating food using hands provides both physical and mental health gratification in comparison to eating with spoons and forks, are germ-free and beneficial, nevertheless certain individuals does not understand the reason behind the consuming food using fingers and hands (Chayapati 2020). Several families in India especially residing in southern part of India use different leaves like banana leaf, jerk teak leaf, etc. while serving the food extracting from nature reserve. This idea has been well appreciated that enhance the senses of taste, smell, sight, and touch.

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1.1 Hands and Comestible

In Ayurveda, an ancient medicine in India demonstrates how-to live-in harmony with nature explaining it is not only hygienic but also beneficial for senses and digestion. In Ayurveda each finger represents one of the five elements: space (thumb), air (index finger), fire (middle finger), water (ring finger), and earth (little finger). So, eating food with fingers helps the food is well digested, it sends signals to the brain which construct the body to release digestive juices and enzymes (Mehrotra 2023). Moreover, eating using fingers and hand controls the proportions of eating and hence overeating can be avoided. A case-controlled study demonstrated relationship between eating faster increased the risk of type 2 diabetes mellitus in comparison to eating with hands slowly (Radzeviciene and Ostrauskas 2013). Figure 1 shows the relationship between fingers and five elements:

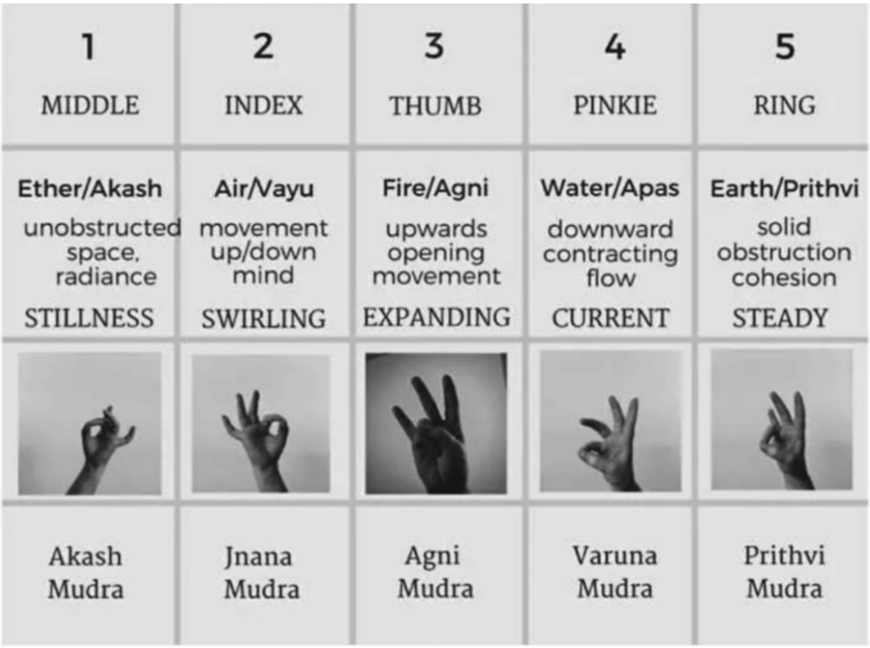

Fig. 1 Relationship between fingers and five elements (*Source* http://www.meditonfornonmediator.com/secret-life-body-mudras.day7/)

2 Meals on the Floor

Nowadays, people consume food while sitting on dining table or they slouch on couch with their meals. The ancient tradition having their roots in ayurveda, and yoga stated that eating food while sitting in Sukh asana/half padmasana or cross-legged position. There is considerable number of muscles are involved as compared to when one sit on seat. While sitting in this position single feet is underneath the heart (as in a position when on a seat), the blood flow gets directed towards the feet leading to better dissemination of heart. The gluteus muscles open, producing the renal pelvis and legs become furthermore flexible. Within this posture central muscles are reinforced, and the lower legs get extended. This leads to is constant back and forth movement activating the abdominal muscles, leading to secretion of stomach acids which inwards led to better digestion (Brit 2012). The Vagus nerve (the principal nerve that helps in transmitting signals from stomach to the cerebrum) start sending signals to the brain when one eats, while sitting on the floor, these nerve executes better and transmit the signals more efficiently and inwardly the stomach and cerebrum send the signal of feeling full (Hedge 2018). Furthermore, constant bending of knees, ankles and hip joints helps the individual to remain free to diseases and keep them flexible and with flexibility brings better lubrication between the joints making it much easier to sit on the floor (Venkateshwara 1989).

3 Using Leaves for Serving Food and Packaging Material

Consuming food on leaves is ingenious and clearing the mess after eating. The use of certain plant leaves as cutlery has been considered sterilised in comparison to using wooden utensils. Plants and variety of tree leaves belonging to plant kingdom had been used as single leaf plates, stitched dining leaf plates, food wraps and packing materials. In comparison with plastic plates, leaf plates propose many benefits such as renewability, biodegradability, non-toxicity (Kora 2019). The leaves contain substantial amount of antibacterial and antifungal properties against several bacteria and fungi shielding natural environment and food borne pathogens (Sahu and Padhy 2013). Certain leaves like banana leaves are inexhaustible, huge thick and not easily punctured. Banana leaves are comprised contain a polyphenol, a characteristics cancer preventing agent one of the richest source of antioxidants. As the Acharya Charaka, the leaves are enormously discreet and while eating food with hands on leaf-on-leaf plate, the touch of the fingers associates all the sense organs with mind. This is apt for managing gastritis and obesity (Hedge et al. 2018). The plastic disposable utensils for banana leave are eco-friendly, as they not only decompose in very short span but also saves extra time and efforts that would have otherwise wasted while washing the dishes. Moreover, chemical-based dishwashing solution further enter the groundwater and pollute water more adversely. Table 1 exhibits the leaves and their benefits (Suri 1956).

Table 1 Leaves and their benefits

Leaves name	Advantages
Plantain tree leaf	Aphrodisiacal, boosting, improves taste, accelerates the digestive fire, effective in the management of toxicity, fatigue, and gout
Bastard teak leaf	Bastard teak leaf eases vata and kappa, treats ascites and stomach tumour, treats dyspnoea, improves taste, and promotes health
Ricinus communis leaf	Relieves kapha, destroys worms, and handles fever
Calotropis leaf	Cures abdominal tumour, pain, poisoning, dyspnoea, anaemia, and skin diseases but aggravates pitta
Castor leaf	Greatly beneficial for eyes and light to digest. Stimulates the digestive fire and alleviates vata
Secrete milk sap leaf	Helps to overcome thirst, burning sensation, and bleeding disorder
Lotus leaf	Aphrodisiac, removes weariness, and is recommended for travellers
Tahitian screw pine leaf	Treats all types of glandular swellings and is beneficial to the eyes

4 Food Preservation Without Refrigeration to Reduce Energy

In ancient time, when the invention of refrigeration technology was not discovered, the storing the perishable food item, the method involved sun drying technique or sometimes storing the food in salt/sugar/lemon solution or oil. The method of pickling includes preserving the plant-based food with lactobacillus bacteria that grown while supressing the development of any other bacteria causing spoilage and diseases. Sugar is metabolized in the vegetable. Through producing lactic acid and other antibacterial substances the plant's nutritional substances for example fiber and vitamin C remained intact. The process is called Lactic Acid fermentation, which provides fermented pickles their qualities tartness (Ketki 2021). With the use of salt as preservation techniques, they bind with water molecules which act as dehydrating agents. Food that are preserved using salt are stored in air-tight jars and left out in sun. The halophilic or salt-tolerant bacteria which is naturally present on the surface, digest the sucrose present in the fruit or vegetable which produces byproducts such as carbon dioxide, acetic acid, and lactic acid (Ketki 2021).

4.1 Vessels

In India, vessels also known as *paatra,* which means the object that is used for storing, protecting the food from spilling (Chayapathi 2020). In olden times, variety of vessels were used such as aluminium, copper, valuable stones, clay, and accordingly on

Table 2 Vessels used in Indian traditional food practices

Vessels	Benefits
Brass	Helps to alleviate Kapha and eliminates worms but it does lead to increase in Vata
Wooden	Improvise appetite and aggravates Kaphs
Gold	Advances Vision and yields wholesome to whole body but alleviates doshas
Silver	Enhance sight and alleviates doshas
Bell metal	Improves intellect, upgrades appetite, and helps in purifying blood
Iron	Treats Anaemia and swelling, imparts strength and successful for Jaundice
Crystal	Pure and cooling

having advantaged of their own. As per Ayurveda, ghee must be kept within iron vessel, silver containers came in to use to storing fruits and other eatables (snacks), pradigdha (broiled meat sodden in milk), acerbic food products (pastes, cooked buttermilk, etc.) in containers finished with stones; and raga, sadava, and sattaka in pots made up of gems and other precious stones, water in copper vessel. The soapstone storage and cookware are known as *rathi chippa*, *kal chatti* and *makal chatti* extensively used in Southern states of India for cooking, serving, and storing the food items. They are carved easily into massive form which are talc rich, non-porous and soft rocks (Baron et al. 2016; Damick and Woodworth 2015). Table 2 illustrates the benefits of different vessels for storing and cooking food items.

5 Conclusion

Eating food by using fingers, sitting on floor with crossed legs are one of the old traditional methods which was widely used in ancient India. Various activities associated with eating have been derived from different hand positions that are part of yoga techniques, reflection of Indian traditional ways. This has been believed that these five components not only nourish the food individual eat, inwardly it purifies the negative energies (Kamatha 2014). These five components are thus, activated when finger touches the food which activates the brain to send signal that helps in secreting the digestive juices. Though, one needs to be cautious about the temperature of the food, the amount to be taken and how one must hold the food within the fingers. The biodegradable leaf used as dining plates has vast potential in international market. Also, adhere many advantages such as renewability, non-toxicity, and antioxidant abundance with respect to religious, medicinal, and economical importance. With recent technological advancement, there is vast scope in leaf plate technology in terms of raw material quality, design improvement, product range, production process marketing. For example, design of popcorn buckets and leak proof soft drinks glasses (Singh 2018). Governmental agencies including forest development, rural development, tribal development, banking, small scale industries like handicraft, textile can coordinate with the stakeholders of the leaf trade which can expands the local, national, and international markets. Every vessel has its own advantage while cooking or storing the food. One of the oldest traditions of storing the water in copper vessel overnight and then consuming it the next morning aids the digestion. According to Ayurveda, ghee should not be stored in bronze vessel for over 10 days. If it exceeds 10 days, it becomes toxic.

References

Baron A, Burke L, Gratuze B, Chapdelaine C (2016) Characterization and origin of steatite beads made by Northern Iroquoians in the St. Lawrence Valley during the 15th and 16th centuries. J Archaeol Sci Rep 8:323–334. https://doi.org/10.1016/j.jasrep.2016.06.011

Brito B, Pauszek SJ, Hartwig EJ, Smoliga GR, Vu LT, Dong PV, Stenfeldt C, Rodriguez LL, King DP, Knowled NJ, Bankowska KB, Long NT, Dung DH, Arzt J (2020) A traditional evolutionary history if foot-and0mouth disease viruses in Southeast Aisa chanllenged by analyses of non-structural protein coding sequences. Scientific Reports 8:6472

Chayapathi V (2020) Ahara-Arogya-Adhyatma. Astanga Yoga Vijnana Mandiram Publication (AYVM), pp 129–134

Damick A, Woodworth M (2015) Steatite beads from tell Fadous-Kfarabida: a case study in early bronze age technology in northern Coastal Lebanon. J Archaeol Sci Rep 3:603–614. https://doi.org/10.1016/j.jasrep.2015.08.028

Gupta SB (2023) Sustainable and inspirational culinary practices in India. https://www.slurrp.com/article/sustainable-and-inspirational-culinary-practices-in-india-1673413475352. Accessed May 2023

Hedge S, Nair LP, Chandran H, Irshad H (2018) Traditional Indian way of eating—an overview. J Ethnic Foods 5:20–23

Kamatha MV, Belavady B (2014) Unavilable carbohydrates of commonly consumed Indian foods. J Sci Food Agri 31:194–202

Ketki (2021) Sustainable food practices from traditional Indian culture. https://curiositysavestheplanet.com/traditional-india-practices-sustainable-food/. Accessed April 2021

Kora AJ (2019) Leaves as dining plates, food wraps and food packing material: importance of renewable resources in Indian culture. Bulletin National Res Cen 43:205. https://doi.org/10.1186/s42269-019-0231-6

Mehrotra R (2023). Decoding science and stigma behind the art of eating with hands. https://www.theweek.in/health/more/2023/04/28/the-experience-benefits-and-stigma-of-eating-with-hands.html. Accessed 12 April 2022

Pole P (2023) Indian ancient food culture: where nutrition and sustainability go together. Indian ancient food culture: where nutrition and sustainability go together (organiser.org). Accessed April 2023

Radazeviviene L, Ostraukas R (2013) Fast eating and the risk of type 2 diabetes mellitus: a case-control study. Clin Nutr 32(2):232–235. https://doi.org/10.1016/j.clnu.2012.06.013

Sahu MC, Padhy RN (2013) *In Vitro* antibacterial potency of *Butea Monosperma* lam. Against 12 clinically isolated multidrug resistant bacteria. Asian Pacific J Trop Dis 3:217–226

Singh TA, Sarangi PK, Singh NJ (2018) Traditional process food of the ethnic tribes of western hills of Manipur, India. Inter J Current Microbiol Appl Sci 7(10):1100–1110

Suri R (1956) Bhojanakuthalam. Institute of Ayurveda and Integrative Medicine (I-AIM), FRLHT, Bangalore

Venkateshwaran PS (1989) Yogic exercise: techniques, benefits, caution. Yoga for healing. Jaico Publishing House, pp 45–87

Climate Change and Sustainable Food Production

Agronomic Biofortification: An Ideal Option for Ensuring Nutritional Security

Rajni Sharma and Hari Ram

1 Biofortification and Its Need

The health of global population relies upon the balance and quality of nutrition in their diets. Malnutrition is defined as the imbalance and deficiency of the dietary intake of nutrients and/or energy by the humans. It is a global crisis of the present-day scenario. More than two billion of the global populations particularly women and children are undernourished resulting from unbalanced dietary intake of necessary micronutrients vital for their growth and development (Huang et al. 2020). The impact of micronutrient deficiencies or 'hidden hunger' are critical for human population mostly women and children under less than five years of age, by weakening their immune systems, increasing susceptibility to diseases and health threats like COVID-19 and ultimately death. Poor and deficit diet along with restricted access to nutritious and healthy foods are among the main reasons of micronutrient deficiencies viz., iron, zinc, folic acid, vitamin A and iodine in human body.

According to "Global Nutrition Report 2020", about eighty-eight countries are predicted to fail in meeting the global nutritional goals by the year 2025 and India is among one of these countries. Furthermore, protein-energy malnutrition (PEM) is a common childhood disorder which is mainly caused by insufficient intake of energy, protein and micronutrients. The State of Food Security and Nutrition in the World, 2020' report also reported, malnutrition as the primary reason behind 69% deaths of children under less than five years of age and 14% of total Indian population is malnourished. As per the Global Hunger Index (GHI), India placed on 94th among 107 countries across the globe. This displayed that India is in a 'serious' category of under nutrition and hunger with score of 27.2 whereas, Bangladesh ranked 75, Myanmar and Pakistan 78th and 88th respectively GHI Report (2022). One of the reasons of inadequate nutrients or insufficiency of nutrients in human diet is

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the negative nutrient balance and deficiency of micronutrients in soil due to non-judicious management of fertilizers as nitrogen, phosphorus and potassium, lesser utilization of green manures and bio-fertilizers and poor on-farm management of crop residues and exhaustive cropping system. Besides this, our agricultural production system has targeted only to increase the productivity and yield of crops rather than to enhance its quality and nutritional value of food products that promotes human health. This strategy has resulted in a rapid increase in various macro- and micro-nutrient deficiencies in food grains, and cumulative nutrient malnutrition among consumers. Currently agriculture and food production are experiencing a paradigm shift from increased production of staple food crops to produce nutrient enrich cultivars of crops consumed by majority of masses and that too in sufficient amounts. This would be quite beneficial to prevent micronutrient deficiency and under nutrition exclusively in developing world, where staple foods are deficit in micronutrients and poor masses had limited access to nutritious and healthy food because of their low purchasing power and lack of awareness. Nevertheless, biofortification of various staple crop varieties gives a long-lasting sustainable solution in providing micronutrients enriches staple crop to the poor and undernourished people. Additionally, biofortified food crops possessing higher bioavailable amounts of essential and necessary micronutrients provides a viable way of fighting malnutrition in poor and lower economic status groups that have restricted or very less access to diversified and nutritious foods.

Biofortification also differs from conventional fortification techniques as fortification practices targets only to increase the nutrient concentration of food products during their processing. The most common examples are, iodized salt, vitamin-D and calcium fortified milk and milk products, etc., whereas biofortification increases the nutrient concentration in food crops during the crop growth (Huang et al. 2020). Thus, it presents a way to reach poor masses where supplementation and conventional fortification practices find it difficult to reach. Biofortification or biological fortification is an easy, cost effective and sustainable approach against micronutrient deficiencies or 'hidden hunger', as only one-time investment is involved in biofortification and no cost is involved in purchase and addition of fortificants to the food every time during their processing. Thus, provides a long-term, cost-effective sustainable strategy in fighting micronutrient deficiencies.

2 Biofortification Approaches

There are three major approaches to biofortification (Garg et al. 2018; Fig. 1).

- Conventional/traditional plant breeding
- Genetic engineering or genetically modified (GM) food
- Agronomic biofortification.

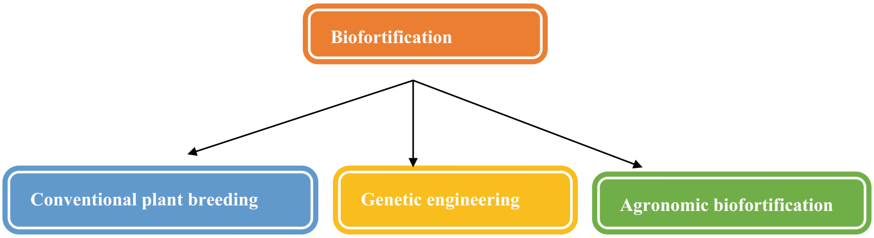

Fig. 1 Different biofortification approaches

2.1 Conventional Plant Breeding

Conventional plant breeding resulted in production of crop cultivars that are rich in target micronutrients viz., iron, selenium, zinc, iodine, etc. that otherwise are deficit in majority of staple crops. In this method, plants with desired traits e.g., higher nutrient content are selected and crossed with other parent, that have some other agronomical advantages, to develop cultivars possessing desired nutrient levels and agronomical parameters as a result of particular combination of genes inherited from the parental lines. Here, breeding is focused on enhancing the bio-availability of target nutrients viz., iron, selenium, zinc, iodine and vitamin A in staple crops to improve their concentration in edible grains or plant parts with the objective to meet the dietary needs of targeted low-income groups. In plant breeding approaches, the first and foremost step is to identify and characterize genetic diversity for up-taking capacity of essential nutrients, their transportation in plant system, and accumulation in the edible portion i.e. bioavailability of nutrients (White and Broadley 2009).

During the last few decades, this method has been widely adopted and has gained importance. The sufficient genetic variation present in the targeted trait is a pre-requisite for any conventional plant breeding and genetic enhancement program. It is a promising and long-term strategy to conquer human malnutrition by releasing new genotypes with high nutrient levels for the target populations (Bouis et al. 2011; Welch and Graham 2004; White and Broadley 2005). Large genotypic variation among modern wheat cultivars and their wild relatives were observed for grain Zn concentration (Cakmak et al. 2010; Gomez-Becerra et al. 2010), that can efficiently be utilized to inbred Zn enriched cultivars.

The Consortium of International Agricultural Research Centres (CGIAR) in collaboration with International Center for Tropical Agriculture (CIAT) and the International Food Policy Research Institute (IFPRI) initiated a project Harvest Plus for breeding biofortified crops to enhance the nutritional quality of staple food crops by exploiting the genetic variation present against a particular nutrient. The principal objective of this programme was to develop and promote vitamin-A, zinc, and iron-rich staple food crops viz., rice, wheat, maize, pearl millet, cassava, sweet potato, beans and so on (Bouis and Welch 2010). Its ultimate goal is to improve the nutritional status of targeted undernourished population, mainly resource poor individuals of developing countries, by considerably improving the concentration or availability

Table 1 Biofortified crops released by Indian Council of Agricultural Research (ICAR), New Delhi

Crop	Variety/ hybrids	Year of release	Nutritional characteristics	Developed by
Rice	CR Dhan 310	2016	Protein rich variety (10.3% protein in polished grains)	ICAR-National Rice Research Institute, Cuttack, Odisha
	DRR Dhan 45	2016	High in zinc content (22.6 ppm in polished grains)	ICAR-Indian Institute of Rice Research, Hyderabad
Wheat	WB 02	2017	Zinc and iron rich variety (42.0 ppm zinc and 40.0 ppm iron)	ICAR-Indian Institute of Wheat and Barley Research, Karnal
	PBW 01	2017	High iron (40.0 ppm) and zinc (40.6 ppm)	Punjab Agricultural University, Ludhiana under ICAR-All India Coordinated Research Project on Wheat and Barley
Maize	Pusa Vivek QPM9 Improved	2017	India's first provitamin A rich maize (8.15 ppm provitamin-A, 2.67% lysine and 0.74% tryptophan)	ICAR-Indian Agricultural Research Institute, New Delhi
Pearl millet	HHB 299	2017	Iron and zinc rich hybrid (73.0 ppm iron and 41.0 ppm zinc)	CCS-Haryana Agricultural University, Hisar in collaboration with ICRISAT, Patancheru under ICAR-All India Coordinated Research Project on Pearl millet
Lentil	Pusa Ageti Masoor	2017	Iron rich variety (65.0 ppm)	ICAR-Indian Agricultural Research Institute, New Delhi

Source Yadava et al. (2017)

of nutritionally important mineral elements and vitamins in the deficit food, that too in a sustainable manner. Indian Council of Agricultural Research (ICAR), New Delhi (India) has also initiated biofortification in crops as a cost-effective and sustainable way out to alleviate micronutrient malnutrition from target under-nourished low income groups. Several biofortified varieties of crops were developed by ICAR that could enable better health of our target population (Table 1).

2.2 *Plant Breeding Using Genetic Engineering*

When desired genetic variation is absent, plant breeding using genetic engineering can be used as another important option for the development of transgenic biofortified staple crops. This technology uses the modern molecular biology and its techniques to bring desirable traits in target crops. The pre-requisite for the development of transgenic or genetically modified crops is identification of target gene(s) and then their utilization to modify the metabolism of crop plants to bring desired change (Newell-McGloughlin 2008). Whenever the natural ability of any crop is insufficient to increase the availability of a particular crop nutrient or micro-nutrient, transgenic technique for stimulating the crop with that particular target nutrient seems to be the utmost viable alternative option (Perez-Massot et al. 2013). It not only improves the concentration but also enhances the bio-availability of deficit micronutrients in edible grains or plant parts of target crops (Agrawal et al. 2005; Yang et al. 2002). It also provides significant advantage over convention breeding as it permits inclusion of genes from other species that otherwise is not possible with conventional breeding. Although, lot of money, time and energy is required for the development of transgenic crops, but once it developed, can be sustainable in the long run. One such example of genetically modified staple crop is golden rice. Golden rice is genetically modified version of rice crop with higher concentration of beta-carotene, which is a pre-cursor of vitamin A in the rice grain with the objective to improve dietary intake of masses who suffer from deficiency of vitamin A.

2.3 Agronomic Biofortification

Agronomic biofortification is the process of application of mineral fertilizers containing micronutrients to soil or plant foliage with the objective to increase the bio-availability of deficit nutrients in edible parts of the staple food crops consumed by majority of human population. It is also considered as one of the cheapest and quickest means to ameliorate mineral elemental deficiencies such as iron, zinc, selenium, iodine, etc. in soil along with improving the nutritional status of food crops, with the ultimate aim to enhance the dietary intake of undernourished target masses (Cakmak and Kutman 2017). Biofortification through agronomical interventions usually relies on mineral fertilizers, their application methods and translocation of mineral elements from source (leaves) to sink (fruiting bodies) of plants.

During 1965–66, with the introduction of high yielding semi dwarf wheat and rice varieties, which are more responsive to chemical fertilization and irrigation, increased the production of these staple crops leading to green revolution, which saved the burgeoning populations from starvation, particularly in developing countries like India. But its concern was only to increase the food production and lacked the nutritional and quality aspects that ultimately created a new problem of deficit nutrition. But at present, when we have sufficient foodgrains to feed the population (Graham et al. 2007), more attention and focus should be given to improve their nutritional value and quality by enriching the plants with micronutrients which the plant is otherwise deficit in it.

Besides this, biofortification also had a significant effect on the productivity of staple crops by improving the status of target (deficit) nutrient in the soil as well as by correcting its deficiency in plant system. The main benefit of agronomic biofortification over other techniques is that mineral fertilizers and their application methods are not crop-specific, whereas breeding, genetic improvement and genetic engineering transformation techniques are highly crop-specific and requires much more time, energy and resources. In agronomic biofortification, if time and method of fertilizer application along with fertilizer forms (e.g. solid/liquid or water soluble/insoluble) are rightly managed, it evolved as a simple, inexpensive and effective method in a long run.

Zinc application through soil, spray or seed treatment is intended to augment the zinc uptake by the plant system (Rehman and Farooq 2016; Rehman et al. 2018). The agronomic biofortification strategies have been efficacious to improve the zinc concentration and bioavailability in the grains, crop productivity and net economic return with higher grain yield (Rehman et al. 2018; Ullah et al. 2019). Similar results were reported by various scientists as reported in Table 2.

3 Methods of Agronomic Biofortification

Globally, following agronomic biofortification techniques have been practices.

3.1 Soil Application

Soil application of micronutrients containing mineral fertilizers aids in improving the nutrient status of the soil, but has little effect on increasing the nutrient bioavailability in the edible portions of the plants viz., grains or fruiting bodies. Sometimes, the application of micronutrients to the soil through mineral fertilizers also gets immediately fixed and become unavailable to crop plants, due to poor soil conditions viz., high/low soil pH, poor soil organic matter content, etc. Alloway (2009) also reported that availability of Zn decreases in alkaline soil which covers the 30% of total arable land in the world. In addition, calcareous, waterlogged, sandy, saline and heavy cracking clay soils are also found deficit in Zn worldwide (Alloway 2008). Among various soil application methods, placement method of application has an advantage over broadcasting as placement method requires fewer amounts of fertilizers (Sarwar et al. 2017) with increased fertilizer use efficiency that also reduces the cost of production. Soil Zn fertilizer application may upsurge the crop yield, however, comparatively this is less effective in cumulative Zn concentration in grains (Pal et al. 2021). Whereas, Haider et al. (2018a) observed that soil application of Zn at 10 mg kg^{-1} was significantly better for improving the grain yield and grain biofortification of mung-bean. Further, it is observed that soil application along with foliar application is much more effective in increasing the productivity and nutrient accumulation of mungbean grains as compared to soil or foliar application alone (Kaur 2022). Nonetheless soil application is commonly used method for micronutrient application to the field crops, which is generally used to enhance the productivity of crops rather than biofortification of nutrients. This method exhibits

Table 2 Effect of agronomic bio-fortification of micronutrients on grain nutrient contents in field crops

Crop	Nutrient applied	Application method	Application rate	Grain nutrient concentration in control	Grain nutrient concentration in treatment	References
Rice	Zinc Iodine	Foliar	0.5% $ZnSO_4.7H_2O$, 0.05% KIO3	21.4 mg kg^{-1} Zn 11 μg kg^{-1} I	28.3 mg kg^{-1} Zn 204 μg kg^{-1} I	Prom-U-Thai et al. (2020)
	Micronutrient cocktail (i.e., Zinc, Iodine, Iron, Selenium)	Foliar	Cocktail solution (0.5% $ZnSO_4.7H_2O$, 0.05% KIO_3, 0.02% Fe-EDTA, 0.001% Na_2SeO_4)	21.4 mg kg^{-1} Zn 11 μg kg^{-1} I 12.7 mg kg^{-1} Fe 95 μg kg^{-1} Se	26.8 mg kg^{-1} Zn 181 μg kg^{-1} I 12.8 mg kg^{-1} Fe 380 μg kg^{-1} Se	
Bread Wheat Triticale Durum wheat	Zinc	Foliar	0.5% at maximum tillering, flower initiation, milk, and dough stages	31.8 mg kg^{-1} Zn 29.3 mg kg^{-1} Zn 30.2 mg kg^{-1} Zn	63.0 mg kg^{-1} Zn 61.8 mg kg^{-1} Zn 62.4 mg kg^{-1} Zn	Dhaliwal et al. (2019)
Chickpea	Iron	Foliar	0.5% at flowering 0.5% at flowering and pod formation	55.16 mg kg^{-1} Fe	69.12 mg kg^{-1} Fe 74.42 mg kg^{-1} Fe	Pal et al. (2019)
Mungbean	Zinc	Soil	10 mg Zn kg^{-1} of soil	25.56 mg kg^{-1} Zn	42.03 mg kg^{-1} Zn	Haider et al. (2018a)
Mungbean	Zinc	Foliar	0.5% at 35 and 50 DAS	29.9 mg kg^{-1} Zn	72.1 mg kg^{-1} Zn	Haider et al. (2018b)
Common bean	Zinc	Foliar	0.5% $ZnSO_4.7H_2O$ after flowering	68 mg kg^{-1} Zn	78 mg kg^{-1} Zn	Ram et al. (2016)
Wheat	Zinc	Foliar	0.5% $ZnSO_4.7H_2O$ at boot and milk stages	28 mg kg^{-1} Zn	41.2 mg kg^{-1} Zn	
Brown rice	Zinc	Foliar	0.5% $ZnSO_4.7H_2O$ at boot and milk stages	19.1 mg kg^{-1} Zn	24.1 mg kg^{-1} Zn	

lesser nutrient use efficiency (NUE) and cost-effectiveness, and creates soil pollution with time because of undue build-up of unutilized micronutrients. But can be used in combination with foliar application to harvest better grain yield and Zn-enriched grains of mungbean to overcome Zn malnutrition (Kaur 2022).

3.2 Foliar Application

Instead of soil application, foliar sprays of fertilizers in soluble form are also recommended for enhancing mineral bioavailability of crop plants. This application of micronutrients is much better than soil application of nutrients as the losses due to soil fixation is lower in this method and the mineral nutrients are directly adsorbed by the plant system and its tissues (Johnson et al. 2005; Garcia-Banuelos et al. 2014). Recently, Pal et al. (2021) also documented that foliar application of zinc and iron significantly increased grain nutrient contents in chickpea. In addition, foliar application at flower initiation and pod formation stages are much more effective for bioaccumulation of nutrient in edible portion of the plants rather than its foliar application at early vegetative stage (Kaur 2022; Yilmaz et al. 1997). Significant increase in cowpea growth, yield and productivity was also observed with application of molybdenum to the soil along with foliar application of 0.5% Fe and Zn sulphate (Dhaliwal et al. 2022).

Foliar application of micronutrients is an easy, cost effective method with higher nutrient use efficiency (NUE). It significantly improves the accumulation of target nutrient in the grains (sink). Poor physic-chemical properties of soil like poor water holding capacity, low organic matter content, high/low soil pH have no adverse affect on availability and uptake of nutrients by the crop plants. But it has certain limitations like crop's nutritional requirements during early vegetative growth stage is difficult to met simply by foliar application and secondly large amount of fertilizers cannot be applied by this method as high concentration may become phyto-toxic to crop plants.

3.3 Seed Priming

Priming of seed is the soaking of seed before sowing in a nutrient enriched solution (Raj and Raj 2019; Farooq et al. 2019). It has been principally utilized to improve seed germination, seedling establishment, development of vigorous root system, and yield enhancement. However, some researchers observed improvement in grain nutrient concentration using seed priming. Seed priming with $ZnSO_4$ upgraded zinc content in grains by about 29% in chickpea crop plants (Harris et al. 2008) and in wheat 12–15% (Praharaj et al. 2019; Harris et al. 2008). Furthermore, farmers can adopt this efficient approach without any additional cost of fertilizers (Harris et al. 2008). Seed priming with micronutrients is cost-effective, sustainable approach, which resulted in improved micronutrient content and crop yield. In addition, the efficiency of seed priming method depends primarily upon various critical factors such as genotype or cultivar, crop type, duration and osmotic potential of priming and prevailing environment conditions (Raj and Raj 2019; Farooq et al. 2019; Waqas et al. 2019). Large amount of fertilizers cannot be applied by this method as high concentration of priming fluid may harm the germination process. Furthermore, farmers are not much familiar with such type of techniques as it involves technical known how of priming methodology. Seed priming might also decline the shelf life of seed and accordingly, need either immediate sowing or ideal storage conditions otherwise germination of seeds greatly affected.

4 Biofortification Benefits

During Post COVID-19 pandemic, the awareness about the health and nutritional value of food items has increased tremendously. Now the demand of nutritionally enriched phytonutrient-based food is gaining popularity among common people. Biofortified food could bridge this gap. As per the definition of biofortification, it is the enrichment of the staple food crops with nutritionally important nutrients through biological approaches such plant breeding, agronomic management, and genetic transformation (Bouis 2002). The biological process could be the effectual in declining the malnutrition and hidden hunger as part of a policy that comprises diversified diet intake, supplementation, fortification of food items commercially and so on.

The biofortified food is the cheapest and best option for the consumers since it is obtained from the biological system which has no side effects as compare to synthetic supplements and secondly nutrient concentration is increased in edible portions of staple crops that are already consumed by majority of populations. Therefore, augmenting the nutritional and functional properties of staple food items offer the several advantages to all the communities, region, age groups irrespective of their economic status particularly for the women and children (Stein et al. 2006). Biofortified food could play a significant role to ameliorate the hidden hunger which is a great challenge for the food and nutrition researchers and policy makers. With such food, there is no change in the food pattern of the people and sustainable food system. A considerable quantity of the recommended dietary allowances (RDA) from dietary intake for various micronutrients could be achieved concurrently in a regular manner (Yadav et al. 2020).

5 Future Prospective

Across the globe, hidden hunger is the greatest challenge that is categorized by inadequate intake of various nutritionally important micronutrients, which are essential for normal functioning of human body. Biological fortification of staple crops is an efficient and effective approach to mitigate specific nutrient deficiency in humans. In coming years, biofortification will face new emerging challenges in order to correct malnutrition or hidden hunger of undernourished low-income populations of the world that has limited access to healthy, nutritious diet, that too under rapidly changing climatic scenario. Continued work in this area aims to achieve goals of sustainable development to achieve food security with improved nutrition on a sustainable basis and ensures healthy lives and promotes well-being of human populations globally. The need for diverse diets on sustainable basis is urgent and biofortification will expected to play a significant role in achieving this target.

References

Agrawal PK, Kohli A, Twyman RM, Christou P (2005) Transformation of plants with multiple cassettes generates simple transgene integration patterns and high expression levels. Mol Breed 16(3):247–260. https://doi.org/10.1007/s11032-005-0239-5

Alloway BJ (2008) Zinc in soils and crop nutrition. IZA Publications, International Zinc Association, Brussels, pp 23–26

Alloway BJ (2009) Soil factors associated with zinc deficiency in crops and humans. Environ Geochem Health 31:537–548

Bouis HE (2002) Plant breeding: a new tool for fighting micronutrient malnutrition. J Nutr 132:491–494

Bouis HE, Welch RM (2010) Biofortification-a sustainable agricultural strategy for reducing micronutrient malnutrition in the global south. Crop Sci 50:S20–S32

Bouis HE, Hotz C, McClafferty B, Meenakshi JV, Pfeiffer WH (2011) Biofortification: a new tool to reduce micronutrient malnutrition. Food Nutr Bull 32(1_suppl1): S31–S40

Cakmak I, Kutman UB (2017) Agronomic biofortification of cereals with zinc: a review. European J Soil Sci 69(1):172–180

Cakmak I, Pfeiffer WH, McClafferty B (2010) Biofortification of durum wheat with zinc and iron. Cereal Chem 87(1):10–20

Dhaliwal SS, Ram H, Shukla AK, Mavi GS (2019) Zinc bio-fortification of bread wheat, triticale, and durum wheat cultivars by foliar zinc fertilization. J Plant Nutr 42:813–822

Dhaliwal SS, Sharma V, Shukla AK, Verma V, Kaur M, Shivay YS, Nisar S, Gaber A, Brestic M, Barek V, Skalicky M, Ondrisik P, Hossain A (2022) Biofortification-A frontier novel approach to enrich micronutrients in field crops to encounter the nutritional security. Mol 27(4):1340. https://doi.org/10.3390/molecules27041340

Farooq M, Usman M, Nadeem F, Rehman HU, Wahid A, Basra SMA (2019) Seed priming in field crops: potential benefits, adoption and challenges. Crop Pasture Sci 70(9):731–771

Garcia-Banuelos ML, Sida-Arreola JP, Sanches E (2014) Biofortification–promising approach to increasing the content of iron and zinc in staple food crops. J Elem 19:865–888

Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V (2018) Biofortified crops generated by breeding, agronomy, and transgenic approaches are improving lives of millions of people around the world. Front Nutr 5:12

GHI Report (2020) https://www.globalhungerindex.org/pdf/en/2020.pdf

Gomez-Becerra HF, Erdem HAMİDE, Yazici A, Tutus Y, Torun B, Ozturk L, Cakmak I (2010) Grain concentrations of protein and mineral nutrients in a large collection of spelt wheat grown under different environments. J Cereal Sci 52(3):342–349

Graham RD, Welch RM, Saunders DA, Ortiz-Monasterio I, Bouis HE, Bonierbale M (2007) Nutritious subsistence food systems. Advan Agro 92:1–74. https://doi.org/10.2134/agronj2005.0222

Haider MU, Hussain M, Farooq M, Nawaz A (2018a) Soil application of zinc improves the growth, yield and grain zinc biofortification of mungbean. Soil Environ 37(2):123–128

Haider MU, Farooq M, Nawaz A, Hussain M (2018b) Foliage applied zinc ensures better growth, yield and grain biofortification of mungbean. International J Agri Biol 20:2817–2822

Harris D, Rashid A, Miraj G, Arif M, Yunas M (2008) "On-farm" seed priming with zinc in chickpea and wheat in Pakistan. Plant Soil 306:3–10

Huang S, Wang P, Yamaji N, Ma JF (2020) Plant nutrition for human nutrition: hints from rice research and future perspectives. Mol Plant 13:825–835

Johnson S, Lauren J, Welch R, Duxbury J (2005) A comparison of the effects of micronutrient seed priming and soil fertilization on the mineral nutrition of chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) in Nepal. Exper Agri 41(4):427–448. https://doi.org/10.1017/S0014479705002851

Kaur L (2022) Agronomic biofortification of *kharif* mungbean (*Vigna radiata* L. Wilczek) with zinc. M.Sc. Thesis. Punjab Agricultural University, Ludhiana, India

Newell-McGloughlin M (2008) Nutritionally improved agricultural crops. Plant Physiol 147:939–953. https://doi.org/10.1104/pp.108.121947

Pal V, Singh G, Dhaliwal SS (2019) Yield enhancement and biofortification of chickpea (*Cicer arietinum* L.) grain with iron and zinc through foliar application of ferrous sulfate and urea. J Plant Nutr 42 (15):1789–1802

Pal V, Singh G, Dhaliwal SS (2021) New approach in agronomic biofortification for improving zinc and iron content in chickpea (*Cicer arietinum* L.) grain with simultaneous foliar application of zinc sulphate, ferrous sulphate and urea. J Soil Sci Plant Nutr 21(2):883–896. https://doi.org/10.1007/s42729-021-00408-0

Perez-Massot E, Banakar R, Gomez-Galera S, Zorrilla-Lopez U, Sanahuja G, Arjo G (2013) The contribution of transgenic plants to better health through improved nutrition: opportunities and constraints. Gen Nutr 8(1):29–41. https://doi.org/10.1007/s12263-012-0315-5

Praharaj S, Singh R, Singh VK, Chandra R (2019) Yield and grain zinc concentration of wheat as affected by nutripriming and foliar application of zinc. J Pharmacog Phytochem 8:503–505

Prom-U-Thai C, Rashid A, Ram H, Zou C, Guilherme LRG, Corguinha APB, Guo S, Kaur C, Naeem A, Yamuangmorn S, Ashraf MY, Sohu VS, Zhang Y, Martins FAD, Jumrus S, Tutus Y, Yazici MA, Cakmak I (2020) Simultaneous biofortification of rice with zinc, iodine, iron and selenium through foliar treatment of a micronutrient cocktail in five countries. Front Plant Sci 11:589835. https://doi.org/10.3389/fpls.2020.589835

Raj AB, Raj SK (2019) Seed priming: an approach towards agricultural sustainability. J Appl Nat Sci 11(1):227–234

Ram H, Rashid A, Zhang W, Duarte AP, Phattarakul N, Simunji S, Kalayci M, Freitas R, Rerkasem B, Bal RS, Mahmood K, Savasli E, Lungu O, Wang ZH, de Barros VLNP, Malik SS, Arisoy RZ, Guo JX, Sohu VS, Zou C Q, Cakmak I (2016) Biofortification of wheat, rice and common bean by applying foliar zinc fertilizer along with pesticides in seven countries. Plant Soil. https://doi.org/10.1007/s11104-016-2815-3

Rehman A, Farooq M (2016) Zinc seed coating improves the growth, grain yield and grain biofortification of bread wheat. Acta Physiol Plant 38(10). https://doi.org/10.1007/s11738-016-2250-3

Rehman A, Farooq M, Naveed M, Nawaz A, Shahzad B (2018) Seed priming of Zn with endophytic bacteria improves the productivity and grain biofortification of bread wheat. Euro J Agron 94:98–107

Sarwar N, Imran M, Shaheen MR, Ishaque W, Kamran MA, Matloob A (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosp 171:710–721

Stein AJ, Sachdev HPS, Qaim M (2006) Potential impact and cost-effectiveness of Golden Rice. Nat Biotechnol 24(10):1200–1201

Ullah A, Farooq M, Hussain M (2019) Improving the productivity, profitability and grain quality of kabuli chickpea with co-application of zinc and endophyte bacteria Enterobacter sp. MN17. Arch Agron Soil Sci 25:1–6

Waqas M, Korres NE, Khan MD, Nizami A, Deeba F, Ali I (2019) Advances in the concept and methods of seed priming. In:' Hasanuzzaman M, Fotopoulos V (eds) Priming and pretreatment of seeds and seedlings: implication in plant stress tolerance and enhancing productivity in crop plants. Springer, Singapore, pp 11–41. ISBN 9789811386251

Welch RM, Graham RD (2004) Breeding for micronutrients in staple food crops from a human nutrition perspective. J Exp Bot 55(396):353–364

White PJ, Broadley MR (2005) Biofortifying crops with essential mineral elements. Trends Plant Sci 10(12):586–593

White PJ, Broadley MR (2009) Biofortification of crops with seven mineral elements often lacking in human diets–iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytol 182:49–84

Yadav DN, Bansal S, Tushir S, Kaur J, Sharma K (2020) Advantage of biofortification over fortification technologies. Wheat and barley grain biofortification. Woodhead Publishing, UK, pp 257–273

Yadava DK, Choudhury PR, Hossain F, Kumar D (2017) Biofortified varieties: sustainable way to alleviate malnutrition. Indian Council of Agricultural Research, New Delhi

Yang SH, Moran DL, Jia HW, Bicar EH, Lee M, Scott MP (2002) Expression of a synthetic porcine a-lactalbumin gene in the kernels of transgenic maize. Trans Res 11(1):11–20. https://doi.org/10.1023/A:1013996129125

Yilmaz A, Ekiz H, Gultekin I, Torun B, Karanlik S, Cakmak I (1997) Effect of seed zinc content on grain yield and zinc concentration of wheat grown in zinc-deficient calcareous soils. In: Ando T, Fujita K, Mae T, Matsumoto H, Mori S, Sekiya J (eds) Plant nutrition for sustainable food production and environment. Kluwer Academic Publishers, Dordrecht, pp 283–284

Zinc Bio-Fortification in Food Crops to Alleviate zinc Malnutrition

Rajni Sharma and Vajinder Pal

1 Role of Zinc in Human Body

Zinc is a vital micronutrient for the human population, and its insufficiency poses a significant challenge to public healthcare systems in developing nations, leading to major diseases and mortality. Research studies have estimated a substantial portion of the population to be affected by zinc deficiency, resulting in stunted growth, abnormal or reduced infant birth weight, decreased energy levels, compromised immune function, increased child mortality, and other detrimental effects (Gibson, 2012; Krebs et al. 2014). Zinc plays a crucial role in catalyzing various enzymes such as RNA polymerase and superoxide dismutase, thereby enhancing the efficiency of cellular proteins. It is a constituent of nearly 3000 proteins, accounting for 10% of total human body proteins, and actively participates in neurological and physiological functions (Andreini et al. 2006; Krężel and Maret 2016). According to the World Health Organization (WHO), over 800,000 people are affected by zinc deficiency annually, with half of the mortality occurring among children under the age of 5. Consequently, zinc deficiency has emerged as a leading cause of death and disease in developing nations. The response to zinc deficiency varies depending on factors such as the amount of zinc present in the body and age. However, several problems directly influenced by low zinc intake include diarrhoea, skin diseases, increased susceptibility to infectious diseases, growth impairment in children, adverse pregnancy outcomes, and ulceration (Prasad et al. 2014; Roohani et al. 2013; Hambidge 1997). Although the exact mechanisms of zinc's actions in diseases such as diarrhoea and pregnancy are not yet fully understood, zinc supplementation is highly recommended. Consequently, scientists worldwide have developed a keen interest in studying different aspects related to zinc intake. Numerous strategies are being devised to enhance zinc intake and bioavailability in the human body (Moretti et al.

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2013; Udechukwu et al. 2016; Saha et al. 2017). A significant correlation has also been observed between high zinc deficiency prevalence in populations consuming cereals in developing countries, as cereals are low in nutrient content and high in phytate, thereby reducing zinc availability to end-users (Sharma et al. 2013).

2 Zinc Status in Soils

Zinc deficiency in soil detrimentally affects crop yield and compromises the nutritional quality of agricultural produce. It is estimated that approximately half of the world's soil is afflicted by zinc deficiency. This deficiency is particularly prevalent in major cereal-producing countries, including India, where cereals are cultivated in zinc-depleted soils, exacerbating the deficiency in humans. Soil sample analyses conducted in the northern plains of India have revealed that over 45% of soils exhibit zinc deficiency, with nearly half of India's total soil area being affected (Singh and Yadav 2006; Narwal et al. 2010). Insufficient zinc content in soils has detrimental consequences, leading to decreased crop yields and, in severe cases, complete crop failure. Furthermore, crops grown in zinc-deficient soils exhibit diminished nutritional value (De Valença et al. 2017; Liu et al. 2017). While advancements in technologies such as mutation breeding and improved breeding approaches have introduced various varieties capable of enhanced nutrient uptake, they have not successfully addressed the issue of zinc fortification in soils with low zinc content (Ortiz-Monasterio et al. 2011). The concentration of micronutrients in soils is influenced by various physiochemical soil properties, and arid and problematic soils contribute to zinc deficiency in different regions worldwide. The high incidence of zinc deficiency in Indian soils can be attributed to factors such as intensive cropping intensity, limited availability of organic manure, excessive use of chemical fertilizers, and high phosphorus fertilizer application in agricultural fields, among others. Moreover, there is a looming possibility of increased zinc deficiency in the future. Reports suggest that zinc deficiency could escalate from the current 50% to nearly 60% within a span of 5–10 years, primarily due to the conversion of non-cropped areas into intensive cultivation zone.

3 Possible solutions

There exist several options for fortifying the food we consume, including industrial fortification, supplementation, and bio-fortification. Industrial fortification necessitates substantial infrastructure, high consumer purchasing power, and easy market access to fortified products. Supplementation requires initial high costs, better accessibility for urban populations compared to non-urban areas, and readily available forms of zinc for efficient bioavailability in the human body. Genetic and agronomic bio-fortification represent crucial forms of bio-fortification. Genetic bio-fortification involves developing new varieties with the genetic capacity to accumulate higher zinc levels than traditional varieties. However, this approach is costly and requires significant infrastructure, hindering its implementation on a large scale. In contrast, agronomic bio-fortification is a cost-effective and successful approach that enriches the nutritional status of crops with zinc. Various methods are employed to apply zinc fertilizers to crops, enhancing the plant's zinc content. Current cereal grain zinc availability ranges from 10–30 mg/kg, while the desired level should be around 40–60 mg/kg (Cakmak 2008). Among agronomic bio-fortification techniques, foliar application of fertilizers is considered the most cost-effective and convenient method to enhance nutrient levels in the reproductive parts of plants. Zinc concentration in plant cells is inhibited by the limited translocation from roots to shoots and diffusion, which are critical factors to address when aiming to increase zinc levels.

4 Agronomic bio-fortification methods

Zinc can be administered to crops through various methods, including soil application, foliar application, seed priming, or a combination of these approaches. Each method employs distinct mechanisms to increase the zinc content in the reproductive components of plants.

4.1 Soil Application

Soil application of fertilizer is the predominant and straightforward method to enhance the plant's nutritional content. However, the efficacy of applied fertilizer relies heavily on the diverse physical and chemical properties of the soil. Zinc availability is relatively higher in acidic soils compared to other soil types. The solubility of zinc decreases significantly with each unit increase in pH, with a 100-fold reduction observed (Lindsay and Mortvedt 2018). Liming acidic soils can further decrease zinc availability to crops (Prasad et al. 2014). Conversely, alkaline soils also exhibit low zinc availability to crops. Calcareous soils may experience zinc deficiency due to the formation of insoluble calcium-zinc compounds (Prasad, 2007). Soil properties such as low moisture content and organic matter also impede zinc diffusion in the rhizosphere, thereby reducing its availability to crops (Cakmak 2008; Cakmak and Kutman 2018; Rengel 2015; Cakmak et al. 1996). Consequently, soils with arid and semi-arid conditions are more susceptible to limited zinc availability compared to irrigated conditions. The availability of zinc is also influenced by the presence of other nutrients. It exhibits positive interactions with nitrogen (Erenoglu et al. 2011; Kutman et al. 2010) but negative interactions with phosphorus (Mousavi 2011; Prasad et al. 2016), iron, and copper (Prasad et al. 2014). These interactions can vary depending on the soil type and nutrient concentrations. Moreover, soil biological characteristics play a role in increasing or decreasing zinc content in plants. Plant growth-promoting rhizobacteria and arbuscular mycorrhiza have been found to enhance zinc availability in the soil (Vejan et al. 2016; Cakmakçi et al. 2006; Cavagnaro 2008). The optimal dosage of zinc fertilizer and the specific crop type determine the appropriate amount of zinc fertilizer to be applied.

4.2 Foliar Application

Foliar application of nutrients offers several advantages over other methods. It requires a lower quantity of fertilizer compared to soil application. Zinc applied through foliar tissues can readily penetrate the outer cell wall and enter the phloem tissue, allowing for efficient transfer to both vegetative and developing grain tissues (Cakmak and Kutman 2018). Foliar application has proven to be highly effective in enhancing nutrient content in various crops, such as wheat and chickpea. Additionally, it is the most cost-effective approach for boosting crop nutrient levels. Applying nutrients during the later stages of crop growth is more likely to increase grain nutrient content compared to early-stage foliar application (Malesh et al. 2016). This may be attributed to the presence of more active photosynthates during the reproductive stage and the increased mobilization of these photosynthates towards the reproductive organs, which serve as the final sink for nutrients. The reproductive stage also exhibits higher phloem tissue mobility (Haslett et al., 2001), facilitating the re-translocation of zinc from vegetative tissues to reproductive organs. For instance, in chickpea, foliar application of zinc at the pod formation stage resulted in the highest zinc accumulation in sink tissues (Pal et al. 2021). Multi-location experiments conducted in seven different countries have reported that applying zinc fertilizer during the heading and milking stages of wheat resulted in the highest zinc accumulation in the grain (Zou et al., 2012). The efficacy of applied fertilizer is also dependent on the timing of application (Cakmak, 2008). Foliar application during the evening hours of the day has been shown to exhibit the highest tissue permeability (Alshaal and El-Ramady 2017). Moreover, foliar application can trigger defense mechanisms against oxidative damage caused by stress, thereby increasing crop yield (Karim et al. 2012; Cakmak 2000). Importantly, foliar application of zinc does not interact with other nutrients, avoiding potential fixation issues. Therefore, the application of micronutrients through foliar sprays has been discovered to have a beneficial impact on promoting growth and enhancing seed yield. Zinc sulfate, a common source of zinc fertilization plays essential role for plant development and is commonly used as both basal and foliar application. Although plants require zinc in small quantities, it plays a crucial role in the formation of enzymes and proteins within plants. Zinc also plays a vital role in the production of auxins, which regulate growth and stem elongation. Regardless of the concentration and method of application, the introduction of zinc resulted in increased growth parameters. Additionally, the application of zinc, whether through soil or foliar methods, effectively increases the zinc content in the plant shoots. While foliar sprays provide a solution for the plant, they do not address soil-related issues. The choice of application method also depends on the specific zinc fertilizer used.

4.3 Seed Priming

Seed priming, unlike foliar application of fertilizer, has not been observed as the most effective method for increasing zinc content in grain (Zaman et al. 2018), unless applied under low-fertility and resource-limited conditions in the field. The transportation of zinc primarily occurs through the diffusion process from the soil, followed by its transfer through the phloem tissues to the upper parts of the plant. Consequently, seed priming may not yield equally favorable results under conditions of low soil moisture. In rainfed environments, seed priming is not considered the optimal approach for improving crop zinc content. Studies have shown that seed priming can increase zinc content in plants by approximately 12% in wheat, 29% in chickpea, and 19% in maize (Harris et al. 2008).

5 Significance of Bio-Fortification in Present day Scenario

The global agricultural sector is under immense pressure to increase food production per unit of land in order to meet the nutritional demands of a growing population. However, the widespread adoption of high-yielding cereal varieties and the application of high doses of micronutrients have resulted in the depletion of essential micronutrients such as zinc in agricultural soils (Imtiaz et al. 2010). Therefore, our crop production systems must focus on producing nutrient-rich crops (bio-fortified) alongside increased yield to meet the nutritional needs of the expanding population (Jha and Warkentin 2020). Staple foods in many regions are deficient in micronutrients, failing to meet the daily requirements of the human body (Prom-u-thai et al. 2020). Various scientific approaches have been employed to develop crop plants enriched with zinc, aiming for easy adoption by populations at higher risk of malnutrition (hidden hunger). The deficiencies addressed by the modern healthcare system in both developed and developing nations incur significant financial costs, leading to profound economic challenges (Darnton-Hill et al. 2005; Stein 2014). These deficiencies are primarily attributed to low intake rates of micronutrients, such as zinc, in diets that are heavily reliant on cereal-based foods with limited consumption of non-vegetarian products. The modern intensive crop production system is not designed to supply nutrient-rich crops alongside high yields, which contributes to the pervasive presence of hidden hunger worldwide (Welch et al. 2013). Embracing bio-fortification practices would benefit farmers, as nutrient-rich seeds would command higher prices in the market compared to conventional practices. Additionally, farmers would eventually reduce their expenditure on micronutrient fertilizers by sowing seeds with higher zinc content. This approach would help alleviate micronutrient deficiencies in the population that consumes these bio-fortified crops.

6 Limitations and Benefits of Agronomic Bio-Fortification

One of the main challenges in bio-fortification is the additional costs associated with zinc fertilization. The returns on investment may not be optimal unless premium prices can be obtained for the bio-fortified produce. However, studies have shown that soil application of zinc through foliar sprays can have a significant positive effect on crop yield and quality, with marginal increases in production costs compared to the yield benefits achieved (Shivay et al. 2008; Joy et al. 2016). In-depth analysis by Joy et al. (2016) has indicated that foliar application of zinc fertilizers is a cost-efficient strategy for increasing grain zinc in cereals, as the cost is comparable to that achieved through zinc fortification in flour. The primary cost associated with zinc fertilization is the application cost, but this can be mitigated by timing the application to coincide with pesticide treatments for the crops (Ram et al. 2016). There are no published reports suggesting compatibility issues between pesticides and zinc fertilization. Zinc not only increases yield but also activates stress tolerance mechanisms in plants, improves germination, vigor, and disease tolerance (Cakmak 2008). There are indirect benefits of zinc fertilization reported by scientists worldwide. These include better field performance of seeds with higher zinc content, resulting in improved germination and establishment rates, thereby reducing seed rates and providing better economic returns to farmers (Yilmaz et al. 1998; Braun 1999). Zinc has been found to have an impact on various fungal diseases in wheat caused by Fusarium and Rhizoctonia spp., reducing disease infestation by enhancing disease resistance mechanisms (Braun 1999). One significant health benefit of zinc fertilization is its competitive effect on cadmium, a highly toxic heavy metal that is not essential for human health. Staple crops like rice and wheat have been found to increase dietary cadmium intake (Cakmak 2009). Crops grown in cadmium-rich soils tend to have higher cadmium uptake and accumulation in grain (Harris and Taylor, 2013). Zinc and cadmium have similar chemical properties and follow the same transport mechanisms. Transporters involved in zinc and iron regulation, such as ZRT, IRT, and heavy metal transporters, also transport cadmium from roots to the upper parts of plants (Cun et al. 2014). Genetic modifications that affect the genes responsible for heavy metal transport, including cadmium uptake, also impact zinc accumulation in grain. Detterbeck et al. (2016) reported a correlation between high zinc accumulation and high cadmium content in barley grain. In this context, agronomic bio-fortification has shown significant potential in optimizing cadmium content in grain. Agronomic interventions with zinc can help reduce cadmium uptake, root-to-shoot translocation, re-translocation, and deposition in grain tissues (Cakmak et al. 2000; Jiao et al., 2004). However, it is important to note that excessive amounts of zinc can also pose health hazards in humans, although zinc toxicity is rare and typically limited to areas affected by mining and smelting activities or contaminated water, industrial waste, and sewage sludge accumulation. Plant tissues show signs of toxicity at levels above 300 μg per gram of dry weight (Marschner 2012). Nevertheless, zinc toxicity in plant tissues is generally less severe compared to copper or cadmium toxicity (Alloway 2008).

7 Optimization of Zinc Doses Under Field Conditions

Zinc fertilization is highly dependent on crop, soil, and climate conditions, as well as the age and type of crop. Higher application rates are typically required in problematic soils, such as alkaline and calcareous soils (Alloway 2008). In the Indian context, a recommended practice for addressing zinc deficiency in soils is the blanket application of 5 to 25 kg of $ZnSO_4.7H_2O$ per hectare, regardless of soil type. If zinc sulphate heptahydrate ($ZnSO_4.H_2O$) is unavailable, an alternative recommendation is to apply approximately 5 kg of zinc per hectare annually or every other year as a soil application. For foliar application, a 0.5% spray solution of $ZnSO_4$ is generally recommended for all soil types. The residual effect of zinc in certain soil types can last up to 10 years, depending on the specific crop type and cultivation intensity (Singh 2008a, b). Foliar application of zinc sulphate typically contains 2–5 g of $ZnSO_4.7H_2O$ per liter, which supplies zinc at a rate of one kg per hectare or even less. As a result, foliar application is considered to be safer for the soil–plant ecosystem compared to soil application of zinc fertilization.

8 Limitations of Genetic Bio-Fortification

Another significant approach to bio-fortification involves utilizing genetic engineering techniques to develop crop varieties with larger sink sizes for zinc accumulation or enhanced zinc uptake from the soil. These genetically engineered varieties hold promise as a long-term strategy to address malnutrition in humans.

9 Processes Involved in Genetic Engineering

The genetic approach offers a long-term strategy to address micronutrient deficiencies by developing new crop varieties that are enriched with higher levels of zinc in their reproductive or edible parts (White and Broadley 2005; Zou et al. 2012). Although the initial investment and development process can be costly and time-consuming, once a new variety is created, farmers do not have to bear any additional costs. The primary expenses are incurred by breeding agencies and scientists involved in identifying suitable germplasm and conducting plant selection. This strategy involves several steps, including crossing, backcrossing, trait stabilization in different environments, and testing improved agronomic practices in diverse conditions (Cakmak 2008). The concept of enriching food through breeding strategies was introduced by Welch and Graham (2004). They emphasized the importance of maintaining nutrient content and yield stability across different environments while developing new genotypes for enhanced nutritional value. It is crucial that the end consumers can incorporate these new varieties into their traditional diets.

In the context of staple food systems, particularly rice and wheat, genetic and agronomic bio-fortification approaches have been commonly employed (Cakmak and Kutman 2018). During the Green Revolution era, the focus was primarily on developing high-yielding varieties, with little attention given to enriching the nutritional content of the new genotypes (i.e., bio-fortification) alongside increased production. As a result, there are currently very few, if any, globally released varieties that have been bio-fortified with iron and zinc for general cultivation. The nutritional quality of new varieties was found to decrease due to the dilution effect while increasing yield (Davis 2009; Garvin et al. 2006).

References

Alloway BJ (2008) Zinc in soils and crop nutrition, 2nd edn. International Zinc Association and International Fertilizer Industry Association, Brussels

Alshaal T, El-Ramady H (2017) Foliar application: from plant nutrition to biofortification. Environ Biodiver Soil Sec 1:71–83

Andreini C, Banci L, Rosato A (2006) Zinc through the three domains of life. J Proteo Res 5:3173–3178

Braun HJ (1999) Prospects of Turkey's wheat industry, breeding and biotechnology. In: Ekiz H (ed) Hububat sempozyum. Intern Winter Cereal Res Center, Kenya, pp 1–74

Cakmak I (2000) Tansley review no. 111: possible roles of zinc in protecting plant cells from damage by reactive oxygen species. New Phytol 146:185–205

Cakmak I (2008) Enrichment of cereal grains with zinc: agronomic or genetic biofortification? Plant Soil 302:1–7

Cakmak I (2009) Enrichment of fertilizers with zinc: an excellent investment for humanity and crop production in India. J Trace Element Med Bio 23:281–289

Cakmak I, Kutman UB (2018) Agronomic biofortification of cereals with zinc: a review. European J Soil Sci 69:172–180

Cakmak I, Yilmaz A, Ekiz H, Torun B, Erenoglu B, Braun HJ (1996) Zinc deficiency as a critical nutritional problem in wheat production in Central Anatolia. Plant Soil 180:165–172

Cakmak I, Ozkan H, Braun HJ, Welch RM, Romheld V (2000) Zinc and iron concentrations in seeds of wild, primitive and modern wheats. Food Nut Bull 21:401–403

Cakmakçi R, Dönmez F, Aydın A, Sahin F (2006) Growth promotion of plants by plant growth-promoting rhizobacteria under greenhouse and two different field soil conditions. Soil Bio Biochem 38:1482–1487

Cavagnaro TR (2008) The role of arbuscular mycorrhizas in improving plant zinc nutrition under low soil zinc concentrations: a review. Plant Soil 304:315–325

Cun P, Sarrobert C, Richaud P, Chevalier A, Soreau P, Auroy P (2014) Modulation of Zn/Cd P(1B2)–ATPase activities in Arabidopsis impacts differently on Zn and Cd contents in shoots and seeds. Metall 6:2109–2116

Darton-Hill I, Webb P, Hunt JM, Dalmiya N, Chopra M, Ball MJ (2005) Micronutrient deficiencies and gender: social and economic costs. Am J Clin Nut 71:1198S-1205S

Davis DR (2009) Declining fruit and vegetable nutrient composition: what is the evidence? Hort Sci 44:15–19
De Valença A, Bake A, Brouwer I, Giller K (2017) Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa. Global Food Sec 12:8–14
Detterbeck A, Pongrac P, Rensch S, Reuscher S, Pecovnik M, Vavpetic P (2016) Spatially resolved analysis of variation in barley (*Hordeum vulgare*) grain micronutrient accumulation. New Phytol 211:1244–1251
Erenoglu EB, Kutman UB, Ceylan Y, Yildiz B, Cakmak I (2011) Improved nitrogen nutrition enhances root uptake, root-to-shoot translocation and remobilization of zinc (65 Zn) in wheat. New Phytol 189:438–448
Garvin DF, Welch RM, Finley JW (2006) Historical shifts in the seed mineral micronutrient concentration of US hard red winter wheat germplasm. J Food Sci Agri 86:2213–2220
Gibson RS (2012) Zinc deficiency and human health: etiology, health consequences, and future solutions. Plant Soil 36:291–299
Hambidge KM (1997) Zinc deficiency in young children. Am J Clin Nut 65:160–161
Harris NS, Taylor GJ (2013) Cadmium uptake and partitioning in durum wheat during grain filling. BMC Plant Bio 13:103–119
Harris D, Rashid A, Miraj G, Arif M, Yunas M (2008) 'On-farm' seed priming with zinc in chickpea and wheat in Pakistan. Plant Soil 306:3–10
Haslett BS, Reid RJ, Rengel Z (2001) Zinc mobility in wheat: uptake and distribution of zinc applied to leaves or roots. Ann Bot 87:379–386
Imtiaz M, Rashid A, Khan P, Memon MY, Aslam M (2010) The role of micronutrients in crop production and human health. Pakistan J Bot 42:2565–2578
Jha AB, Warkentin TD (2020) Biofortification of pulse crops: status and future perspectives. Plant 9:1–29
Jiao Y, Grant CA, Bailey LD (2004) Effects of phosphorus and zinc fertilizer on cadmium uptake and distribution in flax and durum wheat. J Sci Food Agri 84:777–785
Joy EJM, Ahmad W, Zia MH, Kumssa DB, Young SD, Ander EL (2016) Valuing increased zinc (Zn) fertilizer-use in Pakistan. Plant Soil 411:139–150
Karim R, Zhang YQ, Zhao RR, Chen XP, Zhang FS, Zou CQ (2012) Alleviation of drought stress in winter wheat by late foliar application of zinc, boron, and manganese. J Plant Nut Soil Sci 175:142–151
Krebs NF, Miller LV, Hambridge KM (2014) Zinc deficiency in infants and children: A review of its complex and synergistic interactions. Paed Int Child Health 34:279–288
Krezel A, Maret W (2016) The biological inorganic chemistry of zinc ions. Arch Biochem Biophy 611:3–19
Kutman UB, Yildiz B, Ozturk L, Cakmak I (2010) Biofortification of durum wheat with zinc through soil and foliar applications of nitrogen. Cereal Chem 87:1–9
Lindsay WL, Mortvedt JJ (2018) Inorganic equilibria affecting micronutrients in soils. Micronutr Agri Nut 4:89–112
Liu J, Yang M, Li H, Li D, Shi X, Zhang Y (2017) Genetic processes of iron and zinc accumulation in edible portion of crops and their agro-biofortification: a review. Am J Agri Forestry 5:65–72
Malesh AA, Mengistu DK, Aberra DA (2016) Linking agriculture with health through genetic and agronomic biofortification. Agri Sci 7:295–307
Marschner P (2012) Marschner's mineral nutrition of higher plants, 3rd edn. Academic Press, Elsevier, San Diego, CA
Moretti D, Biebinger R, Bruins MJ, Hoeft B, Kraemer K (2013) Bioavailability of iron, zinc, folic acid, and vitamin A from fortified maize. Ann New York Acad Sci 1312:54–65
Mousavi SR (2011) Zinc in crop production and interaction with phosphorus. Australian J Basic App Sci 5:1503–1509
Narwal RP, Malik RS, Dahiya RR (2010) Addressing variations in a few nutritionally important micro-nutrients in wheat crop. In: Proceedings of 19th world congress of soil science. Published on DVD.1–6 A Brisbane, Australia

Ortiz-Monasterio I, Trethowan R, Holm PB, Cakmak I, Borg S, Tauris BEB, Brinch-Pedersen H (2011) Breeding, transformation, and physiological strategies for the development of wheat with high zinc and iron grain concentration. In: Bonjean AP, Angus WJ, Van Ginkel M. (eds) The world wheat book, a history of wheat breeding, pp 951–977

Pal V, Singh G, Dhaliwal SS (2021) A new approach in agronomic biofortification for improving zinc and iron content in chickpea (*Cicer arietinum* L.) grain with simultaneous foliar application of zinc sulphate, ferrous sulphate and urea. J Soil Science Plant Nut 21:883–896

Prasad R (2007) Crop nutrition-principles and practices. New Vishal Publications, Delhi, India, p 272

Prasad R, Shivay YS, Kumar D (2014) Agronomic biofortification of cereal grains with iron and zinc. Advan Agron 125:55–91

Prasad R, Shivay YS, Kumar D (2016) Interactions of zinc with other nutrients in soils and plants-a review. Indian J Fert 12:16–26

Prom-u-thai C, Rashid A, Ram H, Zou C, Guilherme LRG, Corguinha APB, Guo S, Kaur C, Naeem A, Yamuangmorn S, Ashraf MY, Sohu VS, Zhang Y, Martins FAD, Jumrus S, Tutus Y, Yazici MA, Cakmak I (2020) Simultaneous biofortification of rice with zinc, iodine, iron and selenium through foliar treatment of a micronutrient cocktail in five countries. Front Plant Sci 11:1–12

Ram H, Rashid A, Zhang W, Duarte AP, Phattarakul N, Simunji S (2016) Biofortification of wheat, rice and common bean by applying foliar zinc fertilizer along with pesticides in seven countries. Plant Soil 403:389–401

Rengel Z (2015) Availability of Mn, Zn and Fe in the rhizosphere. J Soil Sci Plant Nutr 15:397–409

Roohani N, Hurrell R, Kelishadi R, Schulin R (2013) Zinc and its importance for human health: an integrative review. J Res Med Sci 18:144–157

Saha S, Chakraborty M, Padhan D, Saha B, Murmu S, Batabyal K, Seth A, Hazra GC, Mandal B, Bell RW (2017) Agro-nomic biofortification of zinc in rice: Influence of cultivars and zinc application methods on grain yield and zinc bioavailability. Field Crops Res 210:52–60

Sharma A, Patni B, Shankhdhar D, Shankhdhar SC (2013) Zinc-An indispensable micronutrient. Physiol Mol Biol Plants 19:11–20

Shivay YS, Kumar D, Prasad R (2008) Effect of zinc-enriched urea on productivity, zinc uptake and efficiency of an aromatic rice–wheat cropping system. Nutrient Cycl Agroecosys 81:229–243

Singh MV (2008a) Micronutrient deficiencies in soils and crops of India. In: Alloway BJ (ed) Micronutrient deficiencies in global crop production. Springer Sciences Business Media, Dordrecht, pp 93–125

Singh MV (2008b) Micronutrient deficiencies in crops and soils in India. In: Brown A (ed) Micronutrient deficiencies in global crop production. Springer, New York, pp 93–125

Singh R, Yadav DS (2006) Effect of rice (*Oryza sativa*) residue and nitrogen on performance of wheat (*Triticum aestivum* L.) under rice-wheat cropping system. Indian J Agro 51:247–250

Stein AJ (2014) Rethinking the measurement of under nutrition in a broader health context: Should we look at possible causes or actual effects? Glob Food Sec 3:193–199

Udechukwu MC, Collins SA, Udenigwe CC (2016) Prospects of enhancing dietary zinc bioavailability with food-derived zinc chelating peptides. Food Funct 7:4137–4144

Vejan P, Abdullah R, Khadiran T, Ismail S, Nasrulhaq Boyce A (2016) Role of plant growth promoting rhizobacteria in agricultural sustainability-a review. Mol 21:573

Welch RM, Graham RD, Cakmak I (2013) Linking agricultural production practices to improving human nutrition and health, expert paper written for ICN2. In: Second international conference on nutrition preparatory technical meeting, 13–15 November, Rome.

Welch RM, Graham RD (2004) Breeding for micronutrients in staple food crops from a human nutrition perspective. J Exper Botany 55:353–364

White PJ, Broadley M (2005) Biofortifying crops with essential mineral elements. Trends Plant Sci 10:586–593

Yilmaz A, Ekiz H, Gultekin I, Torun B, Barut H, Karanlik S (1998) Effect of seed zinc content on grain yield and zinc concentrations of wheat grown in zinc–deficient calcareous soils. J Plant Nut 21:2257–2264

Zaman QU, Aslam Z, Yaseen M, Ihsan MZ, Khaliq A, Fahad S, Bashir S, Amzani PMA, Naeem M (2018) Zinc biofortification in rice: Leveraging agriculture to moderate hidden hunger in developing countries. Achieves Agron Soil Sci 64:147–161

Zou CQ, Zhang YQ, Rashid A, Ram H, Savasli E, Arisoy RZ, Ortiz-Monasterio I, Simunji S, Wang ZH, Sohu VS (2012) Biofortification of wheat with zinc through zinc fertilization in seven countries. Plant Soil 361:119–130

Impact of Climate Change in Sustainable Food Production

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1 Introduction

1.1 Sustainable Food Production

One of the topmost challenges of the twenty-first century is feeding 9–10 billion people sustainably by 2050 while reducing environmental impacts {greenhouse gas (GHG) discharges, loss of biodiversity}, change in land use, loss of services by ecosystem, etc. For the same reason, food security must be achieved (Smith and Gregory 2013). According to the 1996 World Food Summit, "food security is defined when all people, at all times, have physical and profitable access to sufficient safe and nutritional food that meets their salutary requirements and food preferences for an active and healthy life."

This adverse effect on the earth has a knock-on effect on social and commercial concerns, such as human welfare, food security, social development, and commercial

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opulence, showing that agriculture and food production are crucial links connecting people and the environment.

As a result, achieving multiple Sustainable Development Goals (SDGs):

- ***SDG 2***—'End hunger, achieve food security and better nutrition and promote sustainable husbandry';
- ***SDG 12***—'insure sustainable consumption and product patterns';
- ***SDG 13—***'Take critical action to combat climate change and its impacts' &
- ***SDG 15***—" Sustainably manage timbers, combat desertification, help and rear land declination, halt biodiversity loss"

As food products increase, we must significantly reduce the climate impact of food products, as well as increase the adaptability of food products to unborn environmental changes. Fresh climate- related requirements include guarding our brackish coffers, guarding biodiversity, promoting healthy diets, and reducing the negative impacts of food product on all ecosystem services.

2 Inter Relationship Between Food Utilization, Food Access and Food Availability

The issue of global food security remains a critical concern, with millions of people worldwide facing challenges in penetrating sufficient, nutritional food. Food security is a multi-dimensional conception that encompasses three crucial factors: food application, food access, and food vacuity. These factors are interrelated and must be anatomized together to address the complex nature of food security challenges. This write up examines the non-intercourses between food application, food access, and food vacuity, drawing upon applicable exploration and data to give a comprehensive understanding of this pivotal issue.

2.1 Food Application

Food application refers to the capability of individualities to duly use the food they consume for optimal nutrition and health issues. This element of food security is told by colorful factors similar as salutary practices, nutritive knowledge, cooking styles, and artistic preferences. shy food application can lead to malnutrition, rotundity, and colorful diet- related health issues.

2.2 Food Access

Food access refers to the physical and profitable vacuity of food for individualities and homes. It's told by factors similar to income situations, food prices, transportation structure, and request availability. Limited food access can affect food comeuppance, where communities have confined access to fresh and nutritional food, aggravating food instability.

2.3 Food Vacuity

Food vacuity pertains to the overall food force and product at public and global situations. It's told by agrarian practices, food product systems, climate change, trade programs, and food distribution networks. inadequate food vacuity can lead to food heads and price oscillations, impacting food security for vulnerable populations.

There have been Interactions between Food Application, Food Access, and Food Vacuity. The interconnections between these three factors are complex and dynamic. For example:

- ***Food Access and Food Application***
  - Limited food access can lead to shy salutary choices and reliance on low- cost, energy- thick, but nutrient-poor foods. This, in turn, negatively affects food application and can contribute to malnutrition and affiliated health issues.
- ***Food Vacuity and Food Access***
  - Insufficient food vacuity, either due to product faults or distribution inefficiencies, can circumscribe food access in certain regions or communities. This frequently leads to increased food prices, making nutritional food unaffordable for numerous individualities.
- ***Food Application and Food Vacuity***
  - When food vacuity is limited, individualities may resort to lower nutritional, less different diets, leading to compromised food application and nutrition. This can have long- term consequences for public health and well- being.
- ***Policy Counter Accusations***
  - To effectively address food security challenges, policymakers must borrow a holistic approach that considers the non-intercourses between food application, food access, and food vacuity. Some implicit strategies include

- ***Enhancing Agricultural Productivity***
  - perfecting agrarian practices and investing in sustainable husbandry ways can boost food product and vacuity, appreciatively impacting food access and application.
- ***Strengthening Food Distribution Networks***
  - Developing effective food distribution systems can help ensure food reaches those in need, perfecting food access and application within vulnerable populations.
- ***Promoting Nutritional Education***
  - Educating communities about proper nutrition and healthy salutary practices can enhance food application, leading to better overall health issues.

Food is produced, processed, distributed, prepared, and consumed as a result of the dynamic interaction between and within the bio-geophysical environment and humans. This interaction creates a food system that assures food security. Food security declines when the food system is under stress because it affects food availability (production, distribution, and exchange), access to food (availability, distribution, and preferences), and food utilization (nutrition and value, as well as community security). These pressures may result from causes other than climate change and/or other environmental change (such conflict or HIV/AIDS), and they may be made worse when these causes interact. Additionally, urbanization and globalization are hastening changes in the food system.

The impact of climate change on the food system can range from direct effects on crop production (such as variations in rainfall leading to droughts or floods, or variations in the length of the growing season due to warmer or colder temperatures), to variations in the market and food prices, as well as having an impact on the infrastructure of the supply chain. For instance, because it is a significant, continuous issue with immediate effects, the climate is one of the most commonly mentioned drivers of food security in southern Africa. The inability to handle shocks and effectively deal with long-term stress means that any viable methods in other areas are either unavailable or ineffective. Drivers in other areas, including the Indo-Gangetic Plain in India, include labor concerns, the availability and quality of of groundwater for irrigation outweigh the direct effects of climate change as a factor affecting food security (Gregory et al. 2005).

Food systems and, by extension, food security are influenced by a variety of socioeconomic and biophysical factors, therefore there is variation in how well they can adapt to lessen vulnerability to climate change. It is crucial to support resilience in the face of such changes, but improving food production, distribution, and economic access can all help create an adaptive food system to fight climate change. Agricultural practices contribute significantly to the greenhouse gases nitrous oxide (N_2O) and methane (CH4), which must be reduced through regional policies that support resilient food systems (Gregory et al. 2005).

The distribution of money, rather than a scarcity of food, is the fundamental cause of the hunger problem. The wealthy overeat, which leads to obesity and chronic ailments, while the hungry purchase manufactured food, and the destitute become malnourished. Increasing the world's food output won't make this issue go away. Although the needs of the urban poor are now receiving more attention, the majority of poor people still reside in rural areas where they mostly rely on agricultural and subsistence activities for food and recreation. These regions are frequently characterized by naturally weak and fragile soil, soil, and water resources, which leaves little to no funding available for enhancing livestock and crops (Smith and Gregory 2013).

3 Interrelation of Climate Change and Food System

Climate change is experienced by temporal and spatial variations in temperature, precipitation, and wind, especially by increasing the frequency and magnitude of extreme events. Various extreme events that are likely to increase include the frequency and intensity of heat waves, the frequency of heavy rainfall events and floods, the intensity of tropical cyclone events, and extreme sea level rise due to typhoons. Some areas will experience longer dry spells and more areas are affected by drought each year. Extreme weather events such as cold spells and frosts will reduce the frequency and intensity. Therefore, short-term increases in climate change have a greater impact than long-term changes in average values, and a suitable area of adaptation is climate risk management.

Food production from agriculture is highly dependent on temperature and rainfall and is therefore vulnerable to climate change. The overall impact of climate change on agriculture is expected to be negative and threaten global food security. Despite gains in some crops in some areas, rising temperatures with future climate change will reduce crop yields, but also encourage the growth of weeds and pests, and changes in rainfall patterns will increase the likelihood of short-term crop failure and reduce production. in the long run. The analysis shows that populations in developing countries, which are already vulnerable to food insecurity and climate change, could be the worst affected (Smith and Gregory 2013).

The effect of weather changes in agriculture and human welfare are complex and include:

- biological effects on crop yields
- effect on results such as prices, production and consumption
- impact on per capita energy consumption and child malnutrition.

Climate change will lead to reduced yields for the most important crops in developing countries, and South Asia is particularly badly affected. Climate change will affect irrigated crops differently, but yields of all irrigated crops in South Asia will be greatly reduced. The availability of food energy in developing countries will decrease in 2050 compared to the level of 2000, which will increase child malnutrition by 20%

compared to the world without climate change; climate change will undo many of the improvements in child nutrition that would have occurred without climate change (Smith and Gregory 2013).

Weather events related to climate change (e.g., droughts, heat waves, and hurricanes) are expected to negatively affect food production, but their effects are still unknown. Because climate change is expected to adversely affect global food production, sustainable food production will be more difficult to achieve in the future, making climate mitigation even more important.

4 Changes in Climate and it's Impact on Food Security

The alteration in climate is a matter of concern in today's world and has greatly altered the processes of earth's ecosystems. The pace at which it is changing has increased manifolds.mThe major factors responsible for climate changes are:

- Natural factors
- Human activities like greenhouse gasses and methane emission
- Land-use

The agriculture and food sectors are clearly suffering from the consequences of climate change. Husbandry and climate change are inextricably linked, and the rapid changes in climatic conditions have threatened world food security. If this keeps happening, crop losses will soar, production will be drastically reduced, food costs will soar, and it would be challenging to fulfill the demands of the expanding population. Global population growth and rising food demand have led to increased usage of agrochemicals, animal production, water resource exploitation, etc., which has worsened greenhouse gas emissions.

Deforestation has led to an imbalance of the carbon cycle, increasing carbon footprints and uneven climate patterns which all in turn has hampered agriculture production. Land degradation due to climate change has enhanced desertification and nutrient deficiencies in soil. Extreme drought conditions exacerbate productivity of crops resulting in accumulation of salt and immobilization of nutrients making it infertile for food production. Heavy floods cause soil erosion resulting in low productivity and rise in the sea levels increases the salinity of soil leading to crop stresses jeopardizing availability of food. Global warming leads to extreme warm events like low temperature stress events, reduced yield in huge amounts and fruitlessness. Low temperature stresses during critical growth rates reduces photosynthesis rate of plants and other non-biological stress like catalyzation of oxidation by metals like lead and aluminium which affects the morphological and physiological processes. Thereby, reducing production of crops, its quality and ultimately leading to food security. Warming and changes in precipitation have increased tree death and loss of various species of trees will lead to decline in the potential in terms of services by the ecosystem like prevention of landslides, land degradation, delivery of clean water supply etc.

Typhoons and wind storms reduce the farm productivity, cause trouble to farm resources, and vandalize the farm infrastructure. They also hinder the farm movement, trader routes, trader infrastructure and may also result in injuries to farmers. Due to recurring typhoons and wind storms the agricultural cost rises, and the production declines. Thus, food prices hike whereas there is decrease in supply. These disasters cause the accumulation of waste, water pollution, soil erosion, low soil fertility and enhancement of salt water ingress.

The other major effects are the increased risk of proliferation of food borne pathogens such as salmonella and campylobacter causing food borne illness due to average increase in the temperature of Earth. This could lengthen the duration of summer in which there are greater numbers of these diseases in humans. The alteration in climate may favor the growth of pests that affects the production of crops and also allow them to emerge earlier. They may also spread to new areas where conditions were not favorable to them. The dramatic effects have affected animal health, yield, productivity and bio variability. According to recent studies, dairy cows under the stress of heat are associated with reduced milk yield. Likewise, warming of fisheries reduces long chain polyunsaturated fatty acids and iron content. Thereby, reducing the overall nutritional value. It also decreases the highest body mass of fish and results in decreased catch potential. Therefore, all these disasters have a direct or indirect effect on agriculture and thus hamper food security, food distribution patterns and food quality.

4.1 Intertwined Relationship Between Climate Change, Agriculture Farming and Food Security

The main factors responsible for enhancing poor diet and affecting food security are alteration in climate and the extreme events occurring due to climate changes (Fig. 1). This in turn affects the livestock and crops, and will hamper the food production at global and regional levels.

Majority of the crops experience damage due to rise in temperature, change in pattern of rain, stresses as a result of accumulation of heavy metals, release of large amounts of greenhouse gasses disturbing the crop cycle and pathogen cycle enhancing the chances of pests and diseases invasion.

A 70 percent rise in food production is expected by 2050 because of the average rise in the Earth's temperature which will help to meet the demand of the growing population. Due to irresistible variation in the climate changes it will be a challenge to meet this food requirement. The changes in the climate are prevailing in Asian countries which will affect food security. Moreover, emission of greenhouse gasses is responsible for unsustainable agricultural practices. The variation in climate rises threatens the crop production system, and the rising temperature will lead to decline in the production of staple crops like wheat and rice. Thus, leading to restrictions to address food security challenges.

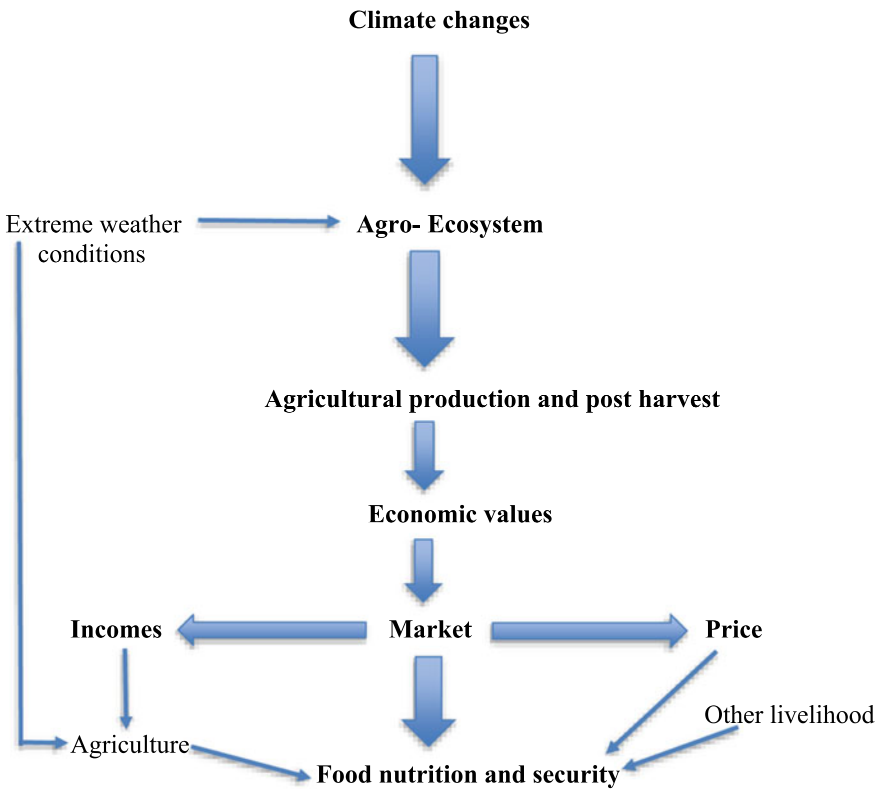

Fig. 1 Intertwined relationship between climate change, agriculture farming and food security

Climate change affects forest productivity in a similar manner as it affects the crop plants. It has an impact on resources management, economic approaches towards adaptation and forest produce. But it doesn't have a similar effect on forest farming as the agriculture sector. This could change the land use pattern and become an approach to improve livelihood. The integrated knowledge from agriculture, food security, climate change and forestry will aid in overcoming future challenges, facilitate making policies on sustainable food production and help overcoming the climatic changes. Malnutrition and hunger are two other major concerns related to food security. Hunger relates to scarcity of food causing nutrient deficiencies. Poverty and poor nutrition are directly linked to each other which results in hunger due to poor accessibility of food with respect to its quality and quantity. Thus, increasing susceptibility to infectious diseases resulting in bad health.

A very large number of people suffer from micronutrient deficiencies and inadequate dietary intake. These issues of hunger, poor nutrition and nutrient deficiency are important to combat food security goals globally. This could be achieved only by looking at the relationship between variation in climate, production of food. malnutrition and all the food security elements.

5 Climate Change Effect on Crop Production in India

The variation in the topography is responsible for varying climatic conditions over the subcontinent. The increasing temperature is a major factor responsible for global warming. According to the research, for every one fahrenheit rise in the temperature crop production decreases to about 3% to 5%. The rural population of India largely rely on climate dependent sectors like agriculture, fisheries and forest. The constantly changing climate has undesirable effects.

In order to cope up with these, careful supervision is required for soil, biodiversity and water. The adoption of sustainable food production systems, soil management and water management would help farmers to adopt climate resilient technologies.

Climate change has damaged the present crop profile and will have deleterious effects in the future. The production of crops is highly sensitive to climate change. Major factors responsible for damage are:

- long-term trends in average rainfall and temperature
- Variation of climate during the year
- shocks during specific phenological stages
- extreme weather events

The tolerance of crops towards stresses varies, and the impact of stress during different development stages also varies among species. The carbon dioxide levels alter the nutritional level of leaves, stem, tuber and fruits of C_3 plants. Future projection reveals a decline in agricultural productivity to 80% by 2080s. The temperature rise will impact the wheat growing regions, placing a huge number of people at the verge of chronic hunger.

The effect on the phenology of annual crop due to climate change hampering the production are as follows:

- The rise in the temperature during their growth forces plants to utilize more energy for respiration and maintenance. Thus, hindering their growth. According to research, major food and cash crops experience 5% to 10% lowering of yield for every one degree Celsius rise in the temperature.
- Plants often complete their phenological cycles more rapidly as a result of which they have less time to reproduce. Thus, increasing chances of reproductive failure eventually lowering productivity.
- C3 plants are more severely affected by C4 plants due to climatic changes.
- The market value of fruits and vegetables is affected by high temperatures as during transit large quantities of sugar are utilized during respiration resulting in less sugar in food products. Thereby, reducing its market value.
- The yield of crops declines during the reproductive stage when the daytime temperature exceeds 30 to 34 degree Celsius.
- Higher temperature during night may increase respiration rate reducing the yield in flowering and reproduction for rice and beans respectively.

Future projections indicate an increased occurrence of extreme and intense weather conditions during the twenty-first century and the effects due to variable frequencies and intensities of extreme weather, climate and sea level events are very likely to change. These could affect the availability and quality of food, accessibility to food, water availability and decline agricultural productivity. This will cause a spike in prices of staple crops like wheat, rice, maize etc.

6 Variation in Climate and it's Consequences on Various Elements of Food Security

6.1 Impact on Availability of Food

Food availability is determined by the production of food, accessible technologies, the catalog, supply chain productivity, and shifting legal frameworks on a national and international level. Diverse studies looked at how future weather predictions would affect different CO2 concentration tiers. They found that higher CO2 levels were likely to improve crop productivity because of advances in photosynthesis techniques and higher water use efficiency (WUE) as a result of high carbon fertilization.

Because of opportunity and complementary crop model estimates, the value of commerce in crop production will span the globe and the local and national economies of the United States. Because the influences are more severe across equitorial zones than at superior latitudes, the impact of climate exchange on food production is variable and inconsistent. Furthermore, it has been noted that the effects of climate change on grain productivity and cattle population will be particularly severe in the nations with higher hunger indices. Agriculture and agroforestry contribute in many different ways to household meals and nutritional safety in the forested environment. It's crucial to have a thorough understanding of how to systematically represent the consequences of weather change on forests in order to increase awareness of the issue in forest agriculture and in the long run meals provision throughout special landscapes and on most important signs like nutritional range methods.

Although the evaluation grew ambiguous and showed conflicting results for other major vegetation, such as rice and sugarcane, the drop in crop yield for staple crops like *Triticum, Zea mays*, and *Sorghum* may be full of life. Despite reasonable evidence for weather interchange influences on agricultural yield, there are still some drawbacks with regard to the widespread impacts of weather change on meal accessibility.

The first and most crucial point is that the most significant cereal plants, few rhizomes, and tubers are the best to be used as prototypes to explore and test the effects of weather trade. The effects of weather fluctuations on some plants, such as legumes and vegetables, which are considered to be the most important regionally (but worldwide minor) profit drivers of food crops, are deduced based on these same plant characteristics rather than fully understanding them. Second, there are few studies on the productivity of grasslands and superior farm animals that produce vegetation, which restrains knowledge about the relationship between climate change and livestock. Thirdly, the majority of agricultural studies concentrate on the effects of climate change rather than also detecting climate extremes, which occasionally may have more negative consequences on yield, cattle, and the productivity of forested areas. In addition, the income from agriculture in wooded areas is limited, which makes it more difficult to ensure food security. Finally, weather exchange expertise affects estimates of food provision.

6.2 Impact on Usage of Food

The utilization of food to conform to the nutritional and dietary necessities is strongly affected by any moderate trade in weather alongside various elements like availability of water and hygiene centres. There's an apparent hyperlink among meals usage and weather trade due to the fact climate variability limits the supply of meals gadgets together with water consumption. Developing areas are often without sound hygiene systems and result in hygiene problems specially during extreme cliamtic events like floods or droughts. Consequently, the inadequate exact sanitation systems cause special belly sicknesses, which lower the consumption of vital nutrients, which is directly linked to changes in temperature. Better expenses for foods usually occur under weather exchange-triggered events because weather trade interferes with food plan quality; consequently, the call for appropriate sterilized food improved, which requires appropriate strategies to prevent the contamination of food from any destructive elements of the environment.

The problems of food safety had been constantly increasing for decades. Stepped forward adaptive capacities like stepped forward profits structures to make the revenue from wealthy to bad, straightening occupation applications for the negative, movements that will fulfill childhood essential nutritional necessities, and so on, want growth to respond in opposition to climate exchange. A nutritional variation will proliferate within the coming a long time because of climate variability, which calls for the wider, ability and secured concerns of these phenomena. The usage of food mainly depends on: food safety elements via the supply chain of food, and indirect or direct health influences because of weather trade and intermediate dietary outcomes. Normally, elevated and declined temperature stresses are in all likely to lessen the safety of food of vital gadgets especially fishing banks, end result and harvest because of increased charges of microbial sports under modified environmental conditions.

Human and cattle fitness is threatened and compromise on food safety is observed because of water-associated impacts due to weather exchange which include reduced hygiene water availability or multiplied infected water provision because of rising frequency and severity of drought and floods. Climate change not directly impacts human fitness through jobs loss and important livelihoods, or resettlement and interposed community health offerings, which unreasonably have an impact on domestic communities and those who already suffer with fatalistic consequences for food safety.

6.3 Impact on Stability of Food

Stability of food has a direct relationship with changes in climate because the weather influences long term stability or short term variation in costs (Myers et al. 2017).Climate trade makes the inventory and need sides of the food more uncertain by using growing food variability. In general, it happens when governmental agendas and guidelines intrude, such as different types of allowances either in produce and farm animals or forest farming venture. The weather trade swings the requirements as a result, endangering the stability of food. A recent case of food instability demonstrated that lack of sound advice, reduced crop, livestock, fisheries, and agroforestry productivity, and loss of short- and long-term adaptation and mitigation strategies toward weather change and extreme events were the main causes of recent food crises. The condition of heads of reflections was troubled by the resource of content theft, considerably lower comprehension due to programs from established international locations, and limited access to clear. Consequently, troubles regarding meals destabilization are continuously growing because of variations in climate that is making extra uncertainty of the poor populations' food intake via volatile meals charges.

Due to climate change, a few secondary risks associated with food instability have increased somewhat, including those that affect indigenous people's loss of self-confidence and the economic and political risks that drive food consumption. Food safety and the environment are linked both directly and indirectly; it depends entirely on the supply (food, water), regulation (weather, extreme occurrences, pests, illnesses), and assistance (water and nutrient recycling) options. Climate change and other extreme activities are increasing the load on the atmosphere. A rise or fall in temperature, along with the regular occurrence of excessive activity due to weather changes, results in a reduction in biodiversity and further alters the dynamics of business connections and internal community dynamic.

This ultimately put food safety and agricultural and forestry productivity in jeopardy. Climate change has an impact on a variety of soil, water, cattle, and crop-related problems that lead to soil erosion, shifts in soil properties, low ground and surface water levels, problems with water availability, deteriorated food quality and quantity, harm to human health, and ultimately environmental damage. Therefore, the social and economic links in the food chain are also in danger due to climate trade.

6.4 Impact on Food Productivity

Notwithstanding intrinsic shortcomings in weather-crop prototype, climate projections have indicated with some actuality that international food manufacturing will decline due to uneven and uncertain conditions.

The variation in climate that has an influence on cattle production is reconciled by decreasing the quantity and quality of feed. In the interim, climate trade will influence cattle and fish manufacturing through competition for natural sources, exquisite and amount of feeds, farm animal's illnesses, heat and cold stresses, and loss of biodiversity. Some wooded place breeds are expected to end up confined because of direct impacts of climate change which in the long run will ward off the monetary increase and food safety of populations whose profits are worried with woodland farming. Wooded area productivity can be essentially moved around if mainly susceptible, yet the ecologically physiological impact of climate variations causes loss of critical species.

Direct consequences result whilst climatic variables technique, physiological restrictions of wooded areas and have an effect on tree functioning. Identity of physiological limits of various woodland species related with sustenance of various groups will assist researchers in describing their ability to live on in face of weather trade. The variation in weather also can immediately afflict the cattle meal manufacturing through way of stressing the physiological strategies. Agriculture is the dominant supply for the nutritional desires, but seafood additionally has the importance within the meals chain to meet the protein, vitamins, minerals, and fatty acids. There are numerous projections about the expected shifts in fish distribution due to advanced warming, fluctuations in vitamins availability, and modifications in pH. Bugs, pests, and weeds are major sources for decline in the fertility of harvest, around 25–40%, in line with various estimations, regardless of the reality of confined international data. Fungal assault absolutely reduces the hygienic meals availability by using 85% at some stage in the globe. Weather change, particularly international warming, will increase the survival chances of insects, pests, and weeds. Elevated CO2 concentrations reduce the effectiveness of herbicides and pesticides controlling weeds and pests.

6.5 Impact on Nutritional Components of Food

Political and economic factors determine how easily meals with essential nutritional supplements can be obtained. Due to the limited success of dietary requirements, it has been demonstrated by the interpretation of ancient records that temperature change and inter- and intra-institutional socio-economic disputes may also arise in the coming years and will occasionally hit the areas that are already struggling with malnutrition and undernourishment. Therefore, these social disputes between and within institutions have the potential to worsen the situation with regard to undernutrition, malnutrition, and ultimately food safety.

Climate change and extreme weather have an impact on the nutritional capacity of all types of societies because they exacerbate social and economic pressures that limit access to high-quality food. Profits and earnings profits may also outweigh the costs of expensive diets, which results in people receiving longer pay checks. The majority of analyses showed that higher food prices will typically lead to an increase in food insecurity issues. This is not only bad for city dwellers, for whom the impact is clear-cut, but also for the poor people of rural areas, where the majority of people are net consumers. Recent studies on the relationship between food price flexibility and dietary demand in less developed nations showed that higher food prices were associated with a higher cut rate in dietary consumption across all demographic categories. Loss of hygiene, subpar production, storage, and sanitation facilities, as well as an increase in the frequency and intensity of excessive events usually lead to a greater exposure of pathogens, bugs, and diseases, which restricts the consumption of essential nutrients, upsets dietary patterns, and impedes normal growth and development.

Due to variations in suggested alternative traits of crop, livestock, fisheries, and agroforestry productivities, price fluctuations, earnings variability, pests, illnesses, and other socio-economic constraints, future projected evaluation for all components of food security (availability, access, usage, and stability) is disturbed. In the meantime, estimates for the climate trade must also take into account a lack of volatility, often known as balance. Food costs could also increase significantly, limiting access to food to only those groups who can afford it. However, there are more significant uncertainties regarding weather change estimates, effects on food equipment, and factors that determine food safety. Therefore, despite the fact that most of the monetary, physical, and biophysical research is focused on the monetary, physical, and biophysical aspects of food access and utilization, a significant amount of targeted work fashions concluded that destiny worldwide might revel in greater problems regarding meals and loss of self-belief.

6.6 Impact on Diversity and Quality of Food

In the long term, climate change affects food consumption, food availability by affecting risk mediation through the food chain, and nutrient availability through the subtle and diverse fitness effects of climate change. Ensuring widespread and diverse sanitation use may be more difficult because climate change may lead to frequent extreme events, including drought, floods, drought stress, and heat stress. Meanwhile, with climate change and busy schedules, it may be difficult to eat good, clean, and varied foods. In addition, climate change and extreme events limit the availability and consumption of clean foods, which pose many health risks.

Extreme events and outbreaks of natural disasters are expected to become more common and severe, posing greater threats to resource-limited communities with a diverse and clean diet, especially those with greater socioeconomic disparities. This in turn increases fitness and nutritional constraints, which affect overall food defence. Today, new pathogens and common invasions of plants, farm animals, and forestry structures have led to the spread of insecticides and pesticides that threaten human health.

Aiming towards getting better production of food, abnormal usage of various chemicals in farm animals and fisheries, and overuse of artificial fertilizers in cropping systems have put human fitness at threat. Hence, it's concluded that climate alternate and extreme occurrence of intense occasions is predicted to the livelihoods erratically in particular in growing and underdeveloped nations.

6.7 Impact on Nutritional Balance and Overall Health

The impact of climate change on the productivity of crops, fisheries, animal husbandry and forestry also affects the nutritional configuration of food. CO_2 levels are low in the climatic conditions for amino acid production so the protein content is suitable for edible plant parts. Comparative analysis between multigrain and legume crops has shown a decrease in protein content of the former due to better exposure to CO_2. If this change in the protein content of flowers continues, it is estimated that two hundred million people will suffer from protein deficiency, worse among the poor and causing high health risks. On the side of protein deficiency, increased CO_2 causes depletion of important minerals in staple food crops. According to previous findings, zinc (Zn) and iron (Fe) in cereal and leguminous plants are reduced by 3–11% at a CO_2 concentration of 550 ppm. More than 1 billion people worldwide suffer from Zn deficiency, and if atmospheric CO_2 enrichment continues, another 200 million people will suffer from this deficiency. Overall, tens of millions of people are expected to be deficient in protein, Fe, and Zn due to increased CO_2 levels, and the scenario will worsen among communities already in a state of demanding these deficiencies.

7 Climate Change and Related Risks

Climate change poses significant pitfalls to food security, and it's pivotal to understand these pitfalls and take preventative measures to alleviate their impact. There are some crucial points about the relationship between climate change and food security, along with forestalment strategies.

7.1 Impact of Climate Change on Agriculture

- ***Changing Weather Patterns***: Climate change leads to irregular and extreme rainfall events, similar as famines, cataracts, heatwaves, and storms. These events can damage crops, disrupt planting and harvesting schedules, and reduce overall agrarian productivity.
- ***Rising Temperatures***: Advanced temperatures can affect crop yields and alter the geographical distribution of agrarian regions, making some areas infelicitous for traditional crops.
- ***Changing downfall Patterns***: Altered rush patterns can lead to water failure, affecting irrigation and reducing water vacuity for husbandry.
- ***Increased Pests and conditions***: Warmer temperatures can favor the spread of pests and conditions, damaging crops and reducing yields.

7.2 Food Security Risks

- ***Reduced Crop Yields***: Climate- related impacts on husbandry can lead to reduced crop yields, potentially causing food deaths and price volatility.
- ***Dropped Nutritional Value***: Climate change can alter the nutrient content of crops, leading to reduced nutritive value in staple foods.
- ***Dislocation of Food Supply Chains***: Extreme rainfall events and changing agrarian patterns can disrupt transportation and distribution networks, affecting food access for vulnerable populations.
- ***Impact on Livestock and Fisheries***: Climate change can also affect beast and fishery sectors, leading to reduced product and food vacuity.

7.3 Prevention and Mitigation Strategies

- ***Sustainable husbandry***: Promote sustainable husbandry practices, similar to crop gyration, agroforestry, and conservation husbandry, which can ameliorate soil health, water operation, and biodiversity.
- ***Climate- Resistant Crops***: Invest in exploration and development of climate-resistant crop kinds that can repel extreme rainfall conditions and give better yields under changing climates.
- ***Water Management***: Ameliorate water resource operation through effective irrigation systems, rainwater harvesting, and water- use effectiveness measures to manage with changing downfall patterns and water failure.
- ***Disaster Preparedness***: Develop and apply early warning systems and disaster preparedness plans to minimize the impact of extreme rainfall events on husbandry and food force chains.

- ***Diversification of Food Sources***: Encourage diversification of food sources by promoting the consumption of underutilized crops and indispensable protein sources like insects or factory- grounded proteins.
- ***Reducing Food Loss and Waste***: Address food loss and waste throughout the force chain to insure that further food reaches consumers and vulnerable populations.
- ***International Cooperation***: Encourage transnational cooperation to address global food security challenges, support developing countries, and apply climate adaptation strategies.

8 Climate Change Impact on Household Food Security

Climate change can have a profound impact on household food security, particularly in vulnerable communities and regions that heavily rely on agriculture for sustenance. Here are some of the ways climate change affects household food security:

1. ***Crop Yield Reductions***: Changes in temperature and rainfall patterns can lead to decreased crop yields and agricultural productivity. Droughts, floods, and extreme weather events disrupt planting and harvesting schedules, affecting the availability of staple crops and reducing food production.

2. ***Food Price Volatility***: Climate-related disruptions in agricultural production can lead to fluctuations in food prices. When crop yields decline, the scarcity of food can result in higher prices, making it difficult for households with limited resources to afford adequate and nutritious food.

3. ***Loss of Livelihoods***: Small-scale farmers and rural communities are particularly vulnerable to the impacts of climate change. Decreased crop yields and agricultural losses can result in the loss of livelihoods, forcing households to seek alternative income sources, which may not be readily available.

4. ***Water Scarcity***: Changes in precipitation patterns can lead to water scarcity, affecting irrigation for crops and water availability for households. In regions heavily reliant on rainfed agriculture, reduced rainfall can lead to water stress and hinder agricultural activities.

5. ***Nutrition and Health Impacts***: Climate change can influence the nutritional value of crops. Rising temperatures and changes in soil conditions may lead to reduced nutrient content in staple foods, impacting the nutritional intake of households.

6. ***Increased Food Insecurity***: The combination of reduced crop yields, loss of livelihoods, and rising food prices can result in increased food insecurity. Households may struggle to access sufficient and nutritious food, leading to malnutrition and related health issues.

7. ***Displacement and Migration***: In some cases, the impacts of climate change on agriculture can force households to leave their homes and seek better opportunities elsewhere. Climate-induced displacement and migration can exacerbate food security challenges, especially in areas with limited resources and infrastructure to support incoming populations.

8. ***Social and Gender Implications***: Climate change can have differential impacts on men and women in households. In many cultures, women play a significant role in food production and preparation. As climate change affects agricultural practices, it can alter gender dynamics within households and communities.

8.1 Prevention and Mitigation:

To address climate change's impact on household food security, a combination of short-term and long-term strategies is needed:

- Implement climate-resilient agricultural practices to enhance crop yields and increase adaptability to changing climate conditions.
- Improve water management and irrigation systems to cope with water scarcity.
- Enhance early warning systems and disaster preparedness to mitigate the impact of extreme weather events.
- Invest in research and development to promote climate-resistant crop varieties.
- Support small-scale farmers and vulnerable communities with access to resources, credit, and agricultural training.
- Promote sustainable land-use practices to conserve natural resources and protect ecosystems.
- Strengthen social safety nets and food assistance programs to support households during times of food insecurity.
- Foster international cooperation and climate change mitigation efforts to reduce global greenhouse gas emissions and limit further climate change impacts.

Addressing climate change and its effects on household food security requires comprehensive, collaborative efforts from governments, organizations, communities, and individuals to build resilience and ensure sustainable food systems for the future.

9 Cutting-Edge global's Food Manufacturing Systems and Their Proportion in Climatic Variabilities

The world's population is expected to reach 9.8 billion and more than eleven billion by 2050, thanks to the arrival of the twenty-first century, and Africa is likely to make a significant contribution. Global food production must diversify to meet the nutritional needs of this growing population.

Modern agriculture uses artificial inputs like greater usage of fertilizers and pesticides for improved yields together with green techniques (fertilizers, precision farming, fallowing, crop rotation) due to competition and rising food demand. One of the most significant industries for greenhouse gas emissions is agriculture. Due to the combustion of fossil fuels during the mechanized production process of artificial N-dump, significant volumes of greenhouse gases (methane, N_2O, CO, and CO_2) are released into the atmosphere. Thus, the usage and manufacturing of synthetic N-dump increases N2O emissions, which increases the amount of heat being released into the atmosphere as a result. Last but not least, the widespread occurrence of extreme weather events is caused by global warming, which is brought on by the use of unconventional artificial inputs in agriculture. The finest part is that when artificial N-discharges are conveyed to lakes and rivers by different shifts, the water cycle alters the chemical equilibrium of water. As a result, pesticide use in agriculture and synthetic N-discharges are the two main causes of water contamination.

Accelerating demand for healthy and nutritious food has forced small and large landowners to tap additional land for non-agricultural prospects. Forests increase ventilation and the frequency of extreme activities, as crop agriculture and forests are considered natural scavengers due to their ability to absorb CO_2 and release oxygen (O_2). Deforestation thus contributes significantly to climate change and natural cycles through natural warming, salinization, soil erosion, and desertification. Primary food production contributes to climate change.

The luxurious lifestyle of the upper and middle class population and city life has drastically changed the eating patterns. The maximum amount of nutrients includes meat, which has increased by more than 350% in the last 50 years, and at the same time, farm animals represent the main percentage of greenhouse gas emissions. Introducing the meat weight reduction program has boosted livestock production, which requires 20% more energy in production and processing than vegetables and grains. First, based on the evidence, it is clear that food production, processing and consumption have direct and indirect impacts on climate change. Enhanced anthropogenic greenhouse gas emissions are accelerating a global warming system that is finally approaching natural disaster. Food production and processing affects food security, because the misuse of artificial agricultural inputs can damage the soil structure, thereby reducing the soil's ability to produce crops or livestock.

10 Achieving Food Security Through Sustainable Development Goals

Today, enough food is produced per area to feed the rapidly growing population, but some 811 million people suffer from undernourishment amid warnings that the momentum to reach starvation levels is slowing. At the same time, the shortage has a large share in some developing and developed countries. At the same time, the enlarged upper, lower and lower weight for age. Therefore, the consequences are more negative in areas other than public health, our country's financial system, tourism and wealth. These negative trends include the depletion of land resources, soil expansion and loss of biodiversity, and the impact of extreme events such as climate change on agriculture worsens the situation.

SGR 2030 provides a better vision of a non-violent global society where no one is left behind. The whole food system, including agriculture and agroforestry, is essential to achieve a set of SDGs that can be uniquely identified by improving agriculture and investing in one of the agricultural inputs (crops, livestock, forestry, fisheries). and water management. This will empower society and move towards more sustainable development with additional powerful tools to tackle poverty, malnutrition and hunger. The SDGs include the following 17 key factors defined through a systematic selection process by the United Nations (UN). However, the implementation of the SDGs creates additional scope for effective monitoring, evaluation and implementation as the basis of this new international framework for mutual accountability. In addition, good governance among organizations is required to obtain SGRs through critical methods that include participatory action, reflexivity, environmental coherence, mitigation, adaptation and, most importantly, democratic institutions.

Action-based research is needed to document the impact of climate change on food security and the global mission to reduce greenhouse gas emissions from agriculture. Past research findings have expressed the need for changes in the agricultural production system (such as the introduction of new crops and better control measures for crops, animal husbandry, fisheries, and agroforestry) and variables (such as crop rotation, dietary changes, and incentives). environmental services.

11 Challenges in Implementing Sustainable Development Goals

11.1 Development of Actions at Local, Regional and National Level

Uncertainties in alternative climate change research and the impacts of climate trade on food security make the research implementation system extremely difficult. The availability of natural resources becomes scarce, so studies should be more targeted with several potential boons. Documenting the effects of climate change on global food and food security requires contextually prioritizing research, sharing movements and studies, and implementing large-scale and multi-level narratives.

Region-based policy making and action plans streamline and optimize the process of collaboration and implementation. A powerful technique for policy making and implementation aims to integrate collaborative measures between unique sectors of food production, processing and garage that can be implemented from neighborhood to country.

In order to better implement the hypothetical technology, standards, equipment with expected results, and the related impact on the surrounding environment should be explored. Understand achievements and experience. Therefore, the use of available and affordable tools makes it difficult to confront the demands (socio-economic, financial, social and political) associated with current or near-future changes, threats and the impact of climate change on food security. This can be recognized through shared priorities.

Local organizations such as electoral support and broader climate modeling tools, local planning activities, and such processes can be organized at different stages and various positions. An integrated approach to targeted research and capacity building is essential to share and implement research experiences in the near future, beyond individual national governments.

Action-based public planning, learning on the job, and extended management after experiencing shared learning can also be effective, but are rarely reported. Institutional support for enjoying strong collaboration and sharing efforts and implementing shared performance can be powerful for adapting and improving change plans.

11.2 Incentives Studies

Studies of food security and climate variability are usually affected by uncertainties that require a focus on meeting the objectives of the studies. Carrying out incentive studies and increasing profits from breakthrough research are usually very challenging. As a result, there is a need to narrow the gap between research incentives regarding climate change impacts on food security and implementation.

The components of action based research are listed below (Fig. 2).

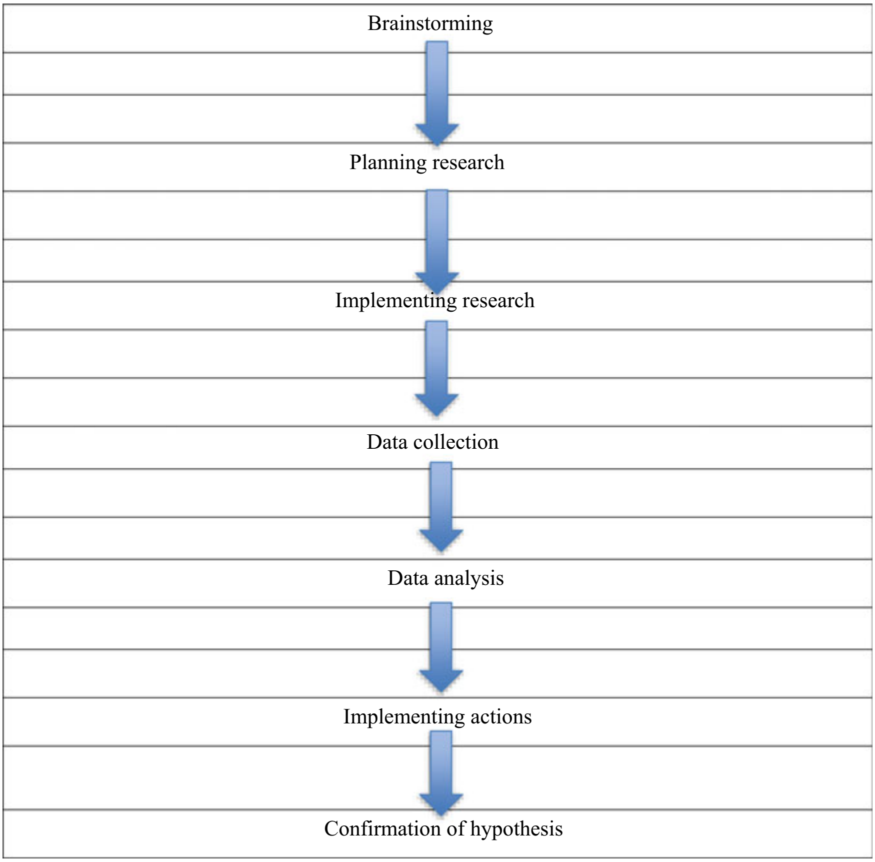

Fig. 2 Steps for studies of food security and climate variability

11.3 Implementing Appropriate Adaptation Measures Against Vulnerabilities and Risks of Climate Change

Finding measures to adapt to specific climatic vulnerabilities and hazards is more difficult than the above requires. Vulnerability to climate change consists of various geographical, social, economic and political factors, and in the geometry of climate change, men or women household resources for food security depend.

Human health security, especially women, is severely affected in situations where household resources are scarce due to ventilation and crop disasters. Like drought and flood. The size of the model is affected by the situation. Girls do not receive important information and do not participate widely in community organizations, especially in rural areas due to earthquakes. Therefore, to reduce inequality and improve the transition process, we must take measures that can be optimally implemented at every scale, from the country to the environment. Sustainable food structures through mitigation and adaptation measures are essential to reduce gender and other socio-economic constraints and increase the number of households that can increase food production to meet food requirements.

11.4 Role of Financial Institutes to Address the Issue of Food Security Globally

Agriculture is the main source of employment or income for most of the growing population in the developing world. It is estimated that among developing countries, about 80% of food is consumed by small farmers using one of these farming systems. But with food shortages and at the height of international attention, the farmers are often vulnerable. Many small farmers live in sparsely populated areas, so they cannot access the financial services they need, making them vulnerable to failure and low-return investments that reduce food production and net income. Access to a variety of financial services can enable farmers to make profitable investments that

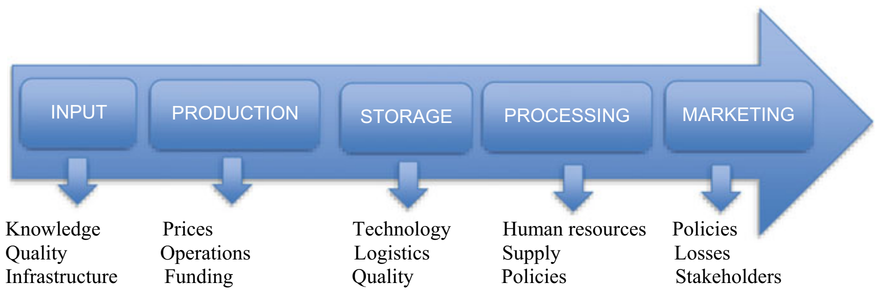

Fig. 3 Role of financial institutes to address the issue of food security globally

improve their crops. Formal and informal financial proposals significantly compare their positions to reduce threats and vulnerability to food structures due to ventilation (Fig. 3).

12 Conclusion

Climate change, food products and food security are all connected. Changes in one directly or indirectly have an adverse effect on others. For example, the rapidly growing population raises the issue of food security; Solving such problems is complemented by increased food production through agricultural management practices (deforestation, heavy use of fertilizers and insecticides), which in the long term worsen ventilation. In addition, the use of energy in the production of crops, fisheries, animal husbandry, forestry, and food production accelerates climate change. Frequent incidents of plant diseases and the fate of determinants of food security due to climate change and food security (farming, animal husbandry, fisheries, forestry) and determinants of food security must be evaluated based on interactive research in depth, because these changes are both destructive and invaluable. In the face of the determinants of food security and ventilation, there are many impacts of different sectors that affect food security, changes and ways to reduce the impact are important to improve and ensure food security. In addition, climate trade and extreme events together with several factors (political, economic and social) to address research gaps on climate trade and the impact of climate trade on food (livestock), vegetation, fisheries and forestry), access, access, use and sustainability.

References

Gregory PJ, Ingram JS, Brklacich M (2005) Climate change and food security. Philos Trans R Soc B: Biol Sci 360(1463):2139–2148

Myers SS, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ, Carlisle E, Dietterich LH, Fitzgerald G, Hasegawa T, Holbrook NM, Nelson RL, Ottman MJ, Raboy V, Sakai H, Sartor KA, Schwartz J, Seneweera S, Tausz M, Usui Y (2017) Increasing CO_2 threatens human nutrition. Nat 540(7632):212–219

Smith P, Gregory PJ (2013) Climate change and sustainable food production. Proceed Nutr Soc 72(1):21–28

Impact of Climate Change on Livestock and Poultry for Sustainable Food Production

Dhananjay Gaikwad, Jaydip Rokade, Mahesh Kadam, and Mahua Bhattacharjee

1 Introduction

Livestock production occupies the largest portion of the world's land use, covering approximately 45% of the Earth's land surface. A significant amount of this land is located in hostile and unpredictable environments that are unsuitable for other activities. The changing climate can influence the quantity and caliber of crops, the dependability of production, and the natural resources that support animal farming. Climate plays a crucial role in agricultural output, and the anticipated impact of climate change on livestock production systems is significant (Koirala and Bhandari 2019). Livestock production in the developing world is evolving quickly due to various environmental factors. The global population is projected to rise from 6.5 to 9.2 billion by 2050. Developing countries are also experiencing rapid urbanization, and there will be a significant increase in demand for livestock products worldwide in the coming decades, according to Delgado et al. (1999).

It is unclear how climate change will affect livestock production systems, particularly in developing nations. While there may be some advantages, the majority of livestock producers will likely encounter significant challenges. Climate changes can occur quickly within a couple of years or gradually over several decades, which can

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impact livestock's ability to adapt. Acute challenges are very different to chronic long-term challenges, and in addition, animal responses to acute or chronic stress are also very different. The ability of animals to adapt is primarily limited by their physiological and genetic constraints. Understanding animal responses becomes crucial when considering animal adaptation (Gaughan 2015). This chapter focuses on the impact of climate change on livestock and poultry for sustainable food production.

2 Global Climate Change and Livestock

Global carbon production, man-made activities and fossil fuel consumption are the highest in human history, disrupt the global carbon cycle and contribute to the main cause of global warming, in which air and sea temperatures are dangerously rising. In the last century. Climate change poses direct and indirect challenges to livestock production and health (Ali et al. 2020).

3 Climate Change Influences Livestock and Poultry Production

Through its potential effects on heat stress, food and water security, extreme weather events, susceptible shelter, and population migration, climate change poses a serious threat to animal production. Temperature and humidity are common environmental stressors that negatively affect oocyte growth, puberty, quality, and developmental competence as well as the production of milk among the climatic variables (Mondal and Reddy 2018; Fig. 1).

4 Milk Production

In temperate zones, the dairy business is already impacted by climatic changes. In the upcoming years, climatic changes are predicted to worsen and continue to influence the dairy business in temperate climates. Compared to cows, goats are far more adapted to heat stress. In the upcoming years, goats will become more crucial to the dairy business in direct proportion to how severe temperature fluctuations become (Silanikove and Koluman 2015). Heat stress reduces the composition and quality of milk. This may cause a 40% drop in milk production. Heat stress raises body temperature and alters components including fat (%), solid-non-fat, protein, casein, and lactose content. It also influences the synthesis of fat in the mammary gland. The somatic cell count is also raised, which lowers milk quality. A further effect of heat stress on the body is an imbalance in the amounts of prolactin, thyroid

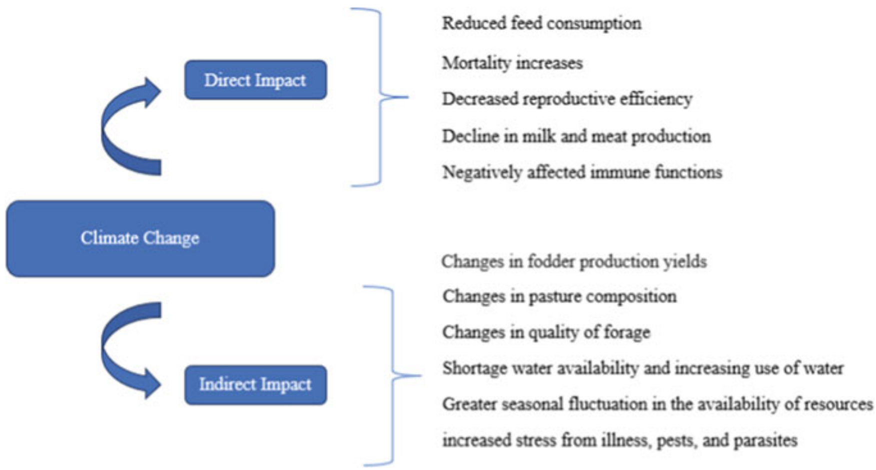

Fig. 1 Impact of climate change (*Sorce* Cheng et al. 2022)

hormones, glucocorticoids, growth hormone, estragon, progesterone, and oxytocin, which ultimately impacts milk production. (Prathap et al. 2017).

5 Climate Change on Livestock Diseases

Heat stress affects an animal's health in both direct and indirect ways, changing its physiology, metabolism, hormonal balance, and immune system. The voluntary intake of feed and the effectiveness of feed utilization are directly adversely affected by an increase in ambient temperature (Baile and Forbes 1974). The high rising temperatures and more frequent extreme weather events, livestock health is affected by follow-on immune suppression, metabolic disorders, oxidative stress, and heat stress resulting in increased disease incidence and mortality. Indirect health effects relate to the multiplication and distribution of parasites, reproduction, viruses, and infectious pathogens and/or their vectors (Ali et al. 2020). Mitigation and adaptation practices can be used in the livestock sector to reduce the effects of climate change on livestock (Bett et al. 2017).

6 Heat Stress Management in Poultry

In the poultry industry heat stress is the foremost environmental stressor causing significant economic loss. Heat stress causes weight, and physiological changes such as suppressed immunity, oxidative stress and acid imbalance, Heat stress increases mortality, feed consumption, feed efficiency, live weight and egg production and affects egg and meat quality (Wasti et al. 2020). Heat stress was found to negatively affect poultry production, particularly in tropical regions (Abu-Dieyeh 2006). High environmental temperature and restriction of feed for a long time substantially affect the performance of broilers. Furthermore, feed restriction for long time during the high environmental temperature raises heat resistance and develops heat resistance in growing broiler poultry birds, during summer seasons birds are exposed to heat waves (Abu-Dieyeh 2006).

7 Reproductive Performance

Livestock producers are facing the main issue arising from climate change. Rapid changes in climate in very short duration or more elusive changes over years. Several factors are responsible for adapting livestock to climate change. Production will most likely decline because of adaptation to ongoing pressures, and input costs could go up as well (Gaughan and Cawdell-Smith, 2015). Cattle and buffalo reproduction are significantly impacted by climate change. (Dash et al. 2015). Climate change impacts numerous factors associated with the reproduction, health, and adaptation of animals. The temperature humidity index negative impact on reproductive efficiency which results in significant economic losses (Sinha et al. 2017). The summertime reproduction of cattle is negatively impacted by high temperatures and high relative humidity levels. The temperature humidity index (THI), which measures the impact of heat stress on reproductive features in cattle and buffaloes, can be used to quantify these effects. Increased THI of more than 72–73 in cattle has resulted in a decrease in nursing dairy animals' conception rates. (Morton et al. 2007; Schuller et al. 2014).

8 Growth Performance

The primary response of animals to hot weather is an increase in respiration rate, heart rate and rectal temperature. The expected temperature increase carried on by climate change is likely to make livestock more susceptible to heat stress, which would negatively impact their ability to reproduce and production performance and in severe circumstances result in their death (Kebede 2016). A hot environment impairs production growth performance (Nardone et al. 2010). The Bos Indicus cattle responded to the changing environment by drinking more water, which increased from about 3 kg DM intake at 10 °C to 5 kg at 30 °C and to around 10 kg at 35 °C (Getu 2015).

9 Conclusion and Recommendations

This chapter provides a detailed description of climate change and its effects on livestock and poultry production for sustainable food production. The livestock sector is considered a major part of food security for India, alongside agriculture. An important step towards breeding superior dairy animals is understanding the biological mechanisms of climatic adaptations, recognizing, and analyzing selection signatures, and genomic diversity, and determining candidate genes for heat tolerance within Bos indicus and Bos taurus dairy cattle breeds. Cattle adapted to the tropical region's shifting climate. Therefore, crossbreeding is useful for the adaptation of animals in future days in tropical or high environmental temperature regions.

References

Abu-Dieyeh Z (2006) Effect of chronic heat stress and long-term feed restriction on broiler performance. Int J Poult Sci 5(2):185–190

Ali MZ, Carlile G, Giasuddin M (2020) Impact of global climate change on livestock health: Bangladesh perspective. Open Vet J 10(2):178–188

Baile CA, Forbes JM (1974) Control of feed intake and regulation of energy balance in ruminants. Physiol Rev 54(1):160

Bett B, Kiung P, Gachohi J, Sindato C, Mbotha D, Grace RT, D, (2017) Effects of climate change on the occurrence and distribution of livestock diseases. Prevnt Vet Medi 137:119–129

Cheng M, McCarl B, Fei C (2022) Climate change and livestock production: a literature review. Atmosphere 13(1):140

Dash S, Chakravarty AK, Sah V, Jamuna V, Behera R, Kashyap N, Deshmukh B (2015) Influence of temperature and humidity on pregnancy rate of Murrah buffa-loes. Asian-Aust. J Anim Sci 28(7):943–950

Delgado C, Rosegrant M, Steinfeld H, Ehui S, Courbois C (1999). Livestock to 2020: The next food revolution. Food, Agriculture, and the Environment Discussion Paper 28. IFPRI/FAO/ILRI, Washington, DC, USA

Gaughan J, Cawdell-Smith AJ (2015). Impact of climate change on livestock production and reproduction. Climate change Impact on livestock: adaptation and mitigation, 51–60

Getu A (2015) The effects of climate change on livestock production, current situation, and future consideration. Int J Agric Sci 5(3):494–499

Kebede D (2016) Impact of climate change on livestock productive and reproductive performance. Liv. Res. Rural Devolp 28(12):227

Koirala A, Bhandari P (2019) Impact of climate change on livestock production. Nepalese Vet. J. 36:178–183

Mondal S, Reddy IJ (2018). Impact of climate change on livestock production. In Biotechnology for sustainable agriculture (pp 235–256). Woodhead Publishing

Morton JM, Tranter WP, Mayer DG, Jonsson NN (2007) Effect of environmental heat on conception rates in lactating dairy cows: Critical periods of exposure. J Dairy Sci 90:2271–2278

Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U (2010) Effects of climate changes on animal production and sustainability of livestock systems. Liv Sci 130(1–3):57–69

Prathap P, Archana PR, Joy A, Veerasamy S, Krishnan G, Bagath M Manimaran V (2017) Heat stress and dairy cow: impact on both milk yield and composition. Int J Dairy Sci 12:1–11

Schuller LK, Burfeind O, Heuwieser W (2014) Impact of heat stress on conception rate of dairy cows in the moderate climate considering different temperature humidity index thresholds, periods relative to breeding, and heat load indices. Theriogenology 81:1050–1057

Silanikove N, Koluman N (2015) Impact of climate change on the dairy industry in temperate zones: predications on the overall negative impact and on the positive role of dairy goats in adaptation to earth warming. Small Ruminant Res 123(1):27–34

Sinha R, Ranjan A, Lone S, Rahim A, Devi I, Tiwari S (2017) The impact of climate change on livestock production and reproduction: ameliorative management. Int J Liv Res 7(6):1–8

Vandana GD, Sejian V, Lees AM, Pragna P, Silpa MV, Maloney SK (2021) Heat stress and poultry production: impact and amelioration. Intern J Biomet 65:163–179

Wasti S, Sah N, Mishra B (2020) Impact of heat stress on poultry health and performances, and potential mitigation strategies. Animal 10(8):1266

Novel Approach of Using LEDs to Grow Indoor Lettuce Hydroponically

Sheetal Deshmukh, N. Thejo Kalyani, and Shreya Raghorte

1 Introduction

In micro-scale indoor crop systems, sustainability is the most crucial factor in agricultural production. By raising the yield and lowering the cost of production, it can be made better. The optimization of all production elements, including water, nutrients, and energy in plant factories, can help achieve this objective. With a notable decrease in energy usage, light-emitting diodes (LED) can be used to provide precise modulation of light intensity and spectrum. LEDs had a variety of beneficial effects on lettuce plant growth, development, nutrition, beauty, and edible quality. By varying the light quality and intensity, lettuce productivity and quality can be improved (Loconsole et al. 2019). Chlorophylls a and b are effective in absorbing red and blue light. Previous and present studies have focused mostly on the impact of red and blue light on lettuce's development and nutritional qualities (Kaiser et al. 2019). A hydroponic plant grows more quickly and produces more of its crop than a comparable soil-grown plant. Additionally, the hydroponic system requires less water because the nutrient solution is continually recycled, and it also lowers the danger of soil-borne infections. In order to thrive, hydroponically grown lettuce requires a specified temperature range of 68 °F to 77 °F, a humidity level of 60%, 10 to 12 h per day of direct sunlight, and a pH level of 5.5 to 6.2. Hydroponic lettuce requires a nutrient solution that is well-balanced and contains all the necessary nutrients. In a nutritional solution, the N-P-K ratio should be high for nitrogen, moderate for phosphorus, and low for potassium. Additionally, calcium is crucial for lettuce. The development of cell walls, cell division, and membrane transport activities all depend on it (Pati 2015). When osmotic or salt stress is produced with a high nutrient solution electrical

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conductivity (EC) in the root zone of a hydroponic system, phytochemical contents in fresh produce can be improved (De Pascale et al. 2001).

2 Nutritional Value and Health Benefits of Lettuce

The perennial shrub lettuce is an Asteraceae (daisy) family member and a green leafy vegetable. Next to the tomato, and is a crucial salad vegetable in terms of cost (FAOSTAT 2012). Instead of India, it is primarily discovered and consumed in China and the United States of America. Western Asia is said to be the region of origin for garden lettuce (*Lactuca sativa*). Garden lettuce comes in three to four popular varieties: Various varieties include leaf lettuce, which has loosely curled, soft, and tender leaves, cos or romaine lettuce, which forms conical heads with narrow pointed leaves that are crisp and dark green, and cabbage or head lettuce, which has a cabbage-like spherical and compact head with green outer leaves and light green inner leaves. The nutritional values of lettuce are listed in Table 1. Darker lettuce varieties, such as romaine, green leaf, and red leaf, were said to provide richer sources of vitamin A, niacin, riboflavin, thiamine, Ca, Fe, K, Mn, Se, and beta-carotene (Bunning et al. 2010). Colourful lettuce varieties have grown in popularity in recent years. Different variations can have different phytochemical compositions, so it's important to choose specific types of kinds that are high in these compounds. Due to their increased total phenol and flavonoid content, red lettuce types have a high concentration of bioactive components and antioxidant properties (Kim et al. 2016). Acording to Niederwieser (2001), lettuce can help obese persons lose weight. Because lettuce contains a lot of lutein and B-carotene, the risk of developing cancer, cataracts, heart disease, and stroke is reduced. For optimal health, lettuce should be a part of our diets because it aids in digestion because to its high dietary fiber content (USDA 2004). The phenolic chemicals in lettuce proffer antioxidant capabilities, Vitamin C and carotenoids (Lopez et al. 2014).

3 Working of Light Emitting Diodes (LEDs)

A current is passed through an LED, a special kind of solid-state semiconductor diode, to cause it to emit light. In essence, it is a p–n junction constructed of p-type and n-type semiconductors, which are treated materials. At the P–N junction, which is created when a forward voltage is supplied across the LED with the positive terminal linked to the P-type region and the negative terminal attached to the N-type region, the electrons and holes start to travel in the direction of one another. A photon is produced when an electron collides with a hole because it enters a lower energy level as a result. The term "electroluminescence" refers to the light that results from a solid state operation. According to Patil (2014), the materials used in LEDs have energies that correspond to near-ultraviolet, visible, or near-infrared light (Table 2).

Table 1 Nutritional value of lettuce/100gm. *Source* http://ndb.nal.usda.gov/ndb/foods

Phytochemicals	Value / 100gm	Phytochemicals	Value / 100gm
Energy	55 kJ (13 kcal)	Vitamin E	0.18 mg
Carbohydrates	2.23 g	Vitamin K	102.3 μg
Sugars	0.94	Water	95.63 g
Dietary fiber	1.1 g	Fat	0.22 g
Vitamins		Protein	2 g
Vitamin A equiv	166 μg	Minerals	
β-Carotene	1987 μg	Calcium	35 mg
Lutein/zeaxanthin	1223 μg	Iron	1.24 mg
Thiamine	0.057 mg	Magnesium	13 mg
Riboflavin	0.062 mg	Manganese	0.179 mg
Pantothenic acid	0.15 mg	Phosphorus	33 mg
Vitamin B6	0.082 mg	Potassium	238 mg
Folate	73 μg	Sodium	5 mg
Vitamin C	3.7 mg	Zinc	mg

The energy gap of the semiconductor controls the color (wavelength) of the light. The architecture of the LED has been enhanced to allow for efficient light extraction. The material is frequently shaped as a small chip or housed in a plastic shell with a lens to control the direction of the emitted light.

4 Comparison Between LED and Conventional Lightning Systems

In comparison to conventional light sources, LEDs have a number of advantages, making them appropriate as electrical lighting for plant photobiology research. Figure 1 provides a comparison of LED and conventional lighting systems. The use of LEDs in research has significantly expanded due to their many benefits over traditional lighting systems (Bantis et al. 2018). Regarding maintenance of optical, mechanical, and spectral qualities, LED users need to be informed and vigilant. Numerous studies have examined how plants respond to abiotic stress, chlorophyll fluorescence, and photosynthetic activity using LEDs (Meng et al. 2019; Parrine et al. 2018). LED lights may be placed close to plants because of its compact size and minimal heat emission. Depending on the needs of plant growth, the spectrum of LEDs can be modified. High Pressure Sodium (HPS) and LED lightning systems with the highest efficiency are nearly equivalent, although the initial capital cost per photon delivered by LED systems is 5–10 times greater than HPS systems. Only 30% of the energy used by conventional HSP lamps is transformed into visible light; the remainder is transferred to heat. 70% of energy is converted into light by LEDs. Given

Table 2 Commercially available LEDs with colors and semiconductor material used. *Source* Gupta and Jatothu- 2013

Colour & Wavelength range (nm)	Semiconductor material
Ultraviolet (<400)	• Aluminium nitride (AlN) • Aluminium gallium nitride (AIGaN) • Aluminium gallium indium nitride (AlGaInN)
Violet (400–450)	• Indium gallium nitride (InGaN)
Blue (450–500)	• Indium gallium nitride (InGaN) • Silicon carbide (SiC)
Green (500–570)	• Gallium phosphide (GaP) • Aluminium gallium indium phosphide (AlGaInP) • Aluminium gallium phosphide (AlGaP)
Yellow (570–590)	• Gallium arsenide phosphide (GaAsP) • Aluminium gallium indium phosphide (AlGaInP) • Gallium phosphide (GaP)
Orange/amber (590–610)	• Gallium arsenide phosphide (GaAsP) • Aluminium gallium indium phosphide(AlGaInP) • Gallium phosphide (GaP)
Red (610–760)	• Aluminium gallium arsenide (AlGaAs) • Gallium arsenide phosphide (GaAsP) • Aluminium gallium indium phosphide (AlGaInP) • Gallium phosphide (GaP)
Infrared (>760)	• Gallium arsenide (GaAs) • Aluminium gallium arsenide (AlGaAs)

that 14W LED and 150W HSP lamp impacts on bedding plant flowering patterns are comparable, LED is more cost-effective for greenhouse producers (Meng and Runkle 2014). Conventional lighting systems' spectral characteristics change during warm-up, when they are dimmed, and over time (Bubenheim et al. 1995; Lister and Liu 2014).In contrast, the junction temperature of LEDs affects their spectral characteristics, and the amount of spectrum shifting varies with LED colour (Schanda et al. 2014). According to Li et al. (2014) and Schanda et al. (2014), high junction temperature might cause an intensity drop or potentially shorten the lifespan of an object. When wavelength/intensity and plant response are correlated with one another in plant photobiology experiments, such fluctuations in spectral characteristics could cause misunderstandings. When opposed to a completely contained indoor setting, environmental elements like ambient temperature and moisture are harsher and fluctuate more in a greenhouse. Depending on the plant species, greenhouse type, location, and time of day, different environmental conditions have different effects (McCartney and Lefsrud, 2018). When adopting electrical lighting technology, these variable conditions make it challenging for producers and users to maintain spectral performance. Data cannot be taken at face value if light characteristics are not consistently verified or trustworthy during plant growth phases (Wu et al. 2020).

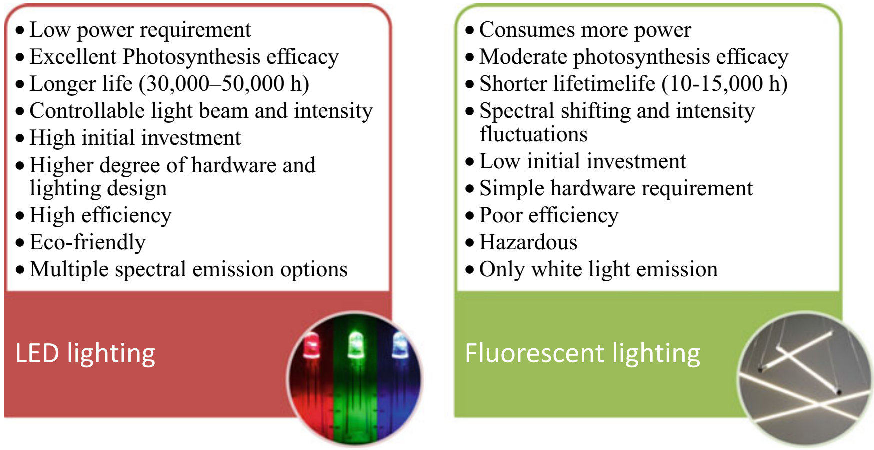

Fig. 1 Comparison between LED and Conventional Light System (Yeh and Chung 2009)

5 Effects of Various Lighting Spectral Conditions on Lettuce Plants' Quality and Production

Numerous experts have studied the effects of various LED light types with variable peak wavelengths and light intensities on the development and photosynthesis of lettuce. The two light spectrums generally recognized as being most important for plant growth and development are red and blue. Table 3 displays the effect of various LED light types on lettuce growth and morphology, as reported by earlier researchers. The lettuce plants grown under the RBW and FL treatments had significantly higher biomass in their leaves and roots than the plants grown under the RB treatment. Plant appearances under RBW light treatment were comparable to those of expensive greenhouse-grown plants. In addition to growth, morphology, and yield, sensory aspects including the shape, crispness, color, and sweetness of the lettuce also have a significant impact on consumers' judgments of vegetable quality and their purchasing decisions (Lin Kuan-Hung et al. 2013). A detailed sensory analysis revealed that plants produced under the RBW and FL treatments performed much better overall. Plant pigments' absorption spectra are specific wavelength absorption patterns. When it comes to light absorption, carotenoids and chlorophyll have similar high values between 400 and 500 nm and 630 to 680 nm, respectively, and low values between 530 and 610 nm. Plants displayed identical absorption spectra of photosynthetic pigments, Chlorophyll a, b, a + b, and carotenoids, even though different quality lights for each treatment were used at the same PFD level. The nutritious content of vegetables for human consumption will surely increase if the nitrate concentration is reduced. Broad spectrum energy (energy between 500 and 600 nm) boosted the accumulation of sugars and lowered the amount of nitrate in plants that had received RBW treatment. While the food may taste sweeter due to the enhanced sugar content, the decreased nitrate level may be beneficial to human health. Changes in lighting had an effect on sugars, a marker of nutritional quality. A high proportion of soluble sugar may be advantageous in terms of food quality. The highest concentration of soluble sugars was found in lettuce plants grown under RBW LEDs (Fig. 2), indicating that this light source may assist lettuce plants in storing soluble sugars. When assessing the nutritional value of lettuce plants, the soluble protein concentration and the light spectrum may not be ideal for protein synthesis.

Thus various wavelengths of light emitted from LEDs play a vital role in nurturing the lettuce in numerous aspects as listed in the Table 3.

6 Conclusion

The modification of light quality and intensity as well as other agronomical factors have a favorable impact on the quality of the lettuce grown in an indoor growing system. The ideal spectra and photosynthetic flux densities for different lettuce species and kinds at different ontogenetic phases. This means that the most productivity and finest nutritional quality lettuce will be produced by selecting the proper wavelength combination, species to use, specific spectra, and photosynthetic flux densities. LED lightning systems can deliver photons with more accuracy and at a cheaper cost for added greenhouse illumination. The high initial cost of LED technology is a major barrier to its usage in greenhouse and laboratory lighting. Economic research has conclusively shown that LEDs may reduce electricity prices and that the initial investment (high capital cost) will pay off in the long run. All sorts of lighting technologies are being developed by manufacturers, and it is anticipated that the cost per photon will continue to decrease as new developments, reduced costs, and more dependability become accessible. Despite technological breakthroughs opening up a vast range of potential and solutions for growing plants nearly anywhere, the energy need is still the biggest barrier to many growth methods. Economic and environmental studies will be necessary in order to accurately evaluate and take into account the viability of these options.

Table 3 Effect of different types of LED lights on growth and quality of lettuce

Type of LED light	Effect on growth and quality of lettuce	References
Red light	Encourages the production of biomass, growth, and photosynthesis in lettuce	Goins et al. (2001)
Green LED light	Regulates stomatal conductance, leaf expansion, and stem elongation. increased dry mass accumulation and stimulation of growth	Kim et. al. (2005)
Far-red light + red LED or with cool white fluorescent light	Effective in increasing leaf length and biomass accumulation	Li and Kubota (2009)
Blue LED light	Effective in increasing biomass accumulation, chlorophyll and anthocyanin biosynthesis, and adaptation processes including the stomata opening/closing regulatory mechanism	Chen et al. (2017), Li and Kubota (2009)
High intensity of green light	Boosted the phenyl-propanoid pathway in lettuce plants, drove the main metabolism, which included the green light receptor, and promoted the secondary metabolism, which included anthocyanin synthesis	Johkan et al. (2012)
Combined Red Blue White LED Light	Improves the lettuce plant's nutrient content, growth, development, beauty, and edible quality	Lin et al. (2013)
Red: Far-red (R:FR) ratio	Influences growth, plant structure, and root exudate's emission	Lee et al. (2016)
Different radiation modes of red and blue LED light	By using varying alternating red and blue light intervals, lettuce growth and quality may be purposefully altered without requiring additional energy	Chen et al. (2016)
100% Red, 90% Red & 10% Blue, 80% Red & 20% Blue, 70% Red & 30% Blue	The highest yield, but low levels of ascorbic acid, xantophylls, and phenolic compounds were produced with 100% Red LED light treatment. Good yields with the most satisfying composition of soluble sugars, ascorbic acid, carotenoids, and polyphenols, as well as good antioxidant qualities and decreased nitrate levels in leaves, were produced by supplemental lighting with 80% red and 20% blue light	Długosz-Grochowska et al. (2017)

(continued)

Table 3 (continued)

Type of LED light	Effect on growth and quality of lettuce	References
Red & Blue LED illumination	In addition to increasing plant biomass and nutritional value by raising photosynthetic activity, antioxidant qualities, phenolic and flavanoids levels, red and blue LED illumination is more dependable and effective than full spectrum illumination	Rahman et al. (2021)
Red/blue lights can be combined in three different ways: red 660 nm and blue 450 nm at a 1:1 ratio; red 660 nm and blue at a mix of 450 nm and 435 nm at a 1:1 ratio; and red/blue with green and far red (B/R/G/FR, ratio: 1:1:0.07:0.64)	The B/R/G/FR improved lettuce's growth and yield metrics, but it also caused more stem elongation (bolting), which had an adverse effect on the quality of the plants that were cultivated. Some physiological properties, such as the instantaneous photosynthetic rate, which speeds up growth but increases stem elongation and decreases marketability, could be improved by employing R/B or R/Bl/G spectra	Alrajhi et al. (2023)

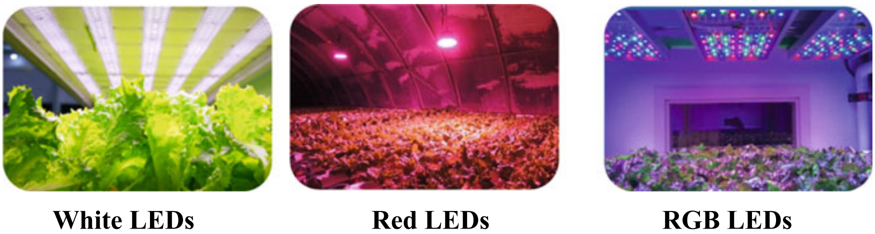

Fig. 2 Lettuce farming under different wavelengths of LED lighting

References

Alrajhi Abdullah A, Abdulaziz S, Alsahli Ibrahim M, Alhelal Hail Z, Rihan Michael P Fuller Abdullah A, Alsadon, Abdullah A Ibrahim (2023) The effect of LED light spectra on the growth, yield and nutritional value of red and green lettuce (*Lactuca sativa*). Plant 12(3):463

Bunning ML, Kendall PA, Stone MB, Stonaker FH, Stushnoff C (2010) Effects of seasonal variation on sensory properties and total phenolic content of 5 lettuce cultivars. J Food Sci 75:156–161

Bantis Filippos, Sonia Smirnakou, Theoharis Ouzounis, Athanasios Koukounaras, Nikolaos Ntagkas, Kalliopi Radoglou (2018) Current status and recent achievements in the field of horticulture with the use of light-emitting diodes (LEDs). Scientia Hort 235:437-451

Bubenheim David L, Raman Sargis, David Wilson (Spectral changes in metal halide and high-pressure sodium lamps equipped with electronic dimming. Hort Sci 30(5):1086–1089

Chen XL, Yang QC, Song WP, Wang LC, Guo WZ, Xue XZ (2017) Growth and nutritional properties of lettuce affected by different alternating intervals of red and blue LED irradiation. Sci Hortic 223:44–52

De Pascale S, Maggio A, Fogliano V, Ritieni AP, A, (2001) Irrigation with saline water improves carotenoids content and antioxidant activity of tomato. J Hort Sci Biotechnol 76:447–453

Olga D-G, Wojciechowska R, Kruczek M, Habela A (2017) Supplemental lighting with LEDs improves the biochemical composition of two *Valerianella locusta* (L.) cultivars. Horticul Environ Biotechnol 58:441–449

FAOSTAT (2012) *FAOSTAT Databasefor Crops [Online]*, Food and Agricultural Organization of the United Nations (FAO), Rome, Italy. http://faostat.fao.org/site/567/DesktopDefault (accessed August 30, 2022)

Goins GD, Ruffe LM, Cranston N A, Yorio NC, Wheeler RM, Sager JC (2001) Salad crop production under different wavelengths of red light-emitting diodes (LEDs). In Proceedings of the 31st International Conference on Environmental Systems, Orlando, FA, USA, 9–12 July 2001; pp 1–9

Gupta SD, Jatothu B (2013) Fundamentals and applications of light-emitting diodes (LEDs) in in vitro plant growth and morphogenesis. Plant Biotechnol Rep 7:211–220

Elias K, Ouzounis T, Giday H, Schipper R, Ep, Heuvelink, Marcelis LFM (2019) Adding blue to red supplemental light increases biomass and yield of greenhouse-grown tomatoes, but only to an optimum. Front Plant Sci 9:2002

Kim HH, Wheeler R, Sager J, Norikane J (2005) Photosynthesis of lettuce exposed to different short-term light qualities. Environ Control Biol 43:113–119

Lee MJ, Son KH, Oh MM (2016) Increase in biomass and bioactive compounds in lettuce under various ratios of red to far-red LED light supplemented with blue LED light. Hortic Environ Biotechnol 57:139–147

Li Q, Kubota C (2009) Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ Exp Bot 67:59–64

Lister G, Liu Y (2014) Low pressure gas discharge lamps. Handbook of Advanced Lighting Technology, pp 1–11

Lin Kuan-Hung, Meng-Yuan Huang, Wen-Dar Huang, Ming-Huang Hsu, Zhi-Wei Yang, Chi-Ming Yang (2013) The effects of red, blue, and white light-emitting diodes on the growth, development, and edible quality of hydroponically grown lettuce (*Lactuca sativa* L. var. capitata). Scientia Horticult 150:86–91

Danilo L, Cocetta G, Santoro P, Ferrante A (2019) Optimization of LED lighting and quality evaluation of romaine lettuce grown in an innovative indoor cultivation system. Sustain 11(3):841

LO´PEZ A, JAVIER G, FENOLL J, HELL´IN P, FLORES P (2014) Chemical composition and antioxidant capacity of lettuce: Comparative study of regular-sized (Romaine) and baby-sized (Little Gem and Mini Romaine) types. J Food Comp Anal 33:39–48.

Qingwu M, Runkle ES (2019) Regulation of flowering by green light depends on its photon flux density and involves cryptochromes. Physiol Plan 166(3):762–771

McCartney L, Lefsrud M (2018) Protected agriculture in extreme environments: a review of controlled environment agriculture in tropical, arid, polar, and urban locations. Appl Engg Agri 34(2):455–473

Niederwieser JG (2001) Guide to Hydroponic Vegetable Production, 2nd Ed., p. 140, Agricultural Research Council, Roodeplaat Vegetable and Ornamental Plant Institute, Pretoria, South Africa

Pati R (2014) Use of LED lights in plant tissue culture and greenhouse industry 10(2.1):2893–1842

Momtazur RM, Field DL, Ahmed SM, Hasan MT, Basher MK, Alameh K (2021) LED illumination for high-quality high-yield crop growth in protected cropping environments. Plants 10(11):2470

Stutte GW, Edney S, Skerritt T (2009) Photoregulation of bioprotectant content of red leaf lettuce with light-emitting diodes. Hort Sci 44:79–82

Schanda János, PéterCsuti, Ferenc Szabó (2013) Laboratory measurement of optical properties of LEDs. In: Thermal Management for LED Applications, pp 167–196. New York, NY: Springer New York

USDA (2004) U.S. Department of Agriculture, Agricultural Research Service, National nutrient data base for standard Reference, Release 17. http://www.nal.usda.gov/fnic/foodcomp/Data/SR17/sr17.html. Accessed March 27, 2005

Wu, Bo-Sen, Hitti Y, MacPherson S, Orsat V, Lefsrud MG (2020) Comparison and perspective of conventional and LED lighting for photobiology and industry applications. Environ Exper Bot 171:103953

Naichia Y, Chung J-P (2009) High-brightness LEDs—energy efficient lighting sources and their potential in indoor plant cultivation. Renew Sustain Energy Rev 13(8):2175–2180

Environmental Effects on Sustainable Food Production Affecting Food and Nutrition Security

Sunayan Sharma

1 Introduction

Food and Nutrition is the one the fundamental human need, which made this the reason that "the human's right to food has been recognised in many instruments under international law (UN 1999). Food and nutrition security is said to exist when everyone, always, attain physical, social, and economic reach to adequate, safe, and nutritious food items that meets their dietary needs and food preferences for an active and healthy lifestyle (FAO 2009b). The environmental change is severely impacting the conditions majorly within which agricultural activities are involved. This definition includes four key dimensions: availability, stability, access, and utilization. The dimensions *availability* is related to the availability of sufficient food, meaning the overall ability of the agricultural system to meet food demand including agro-climatic fundamentals of crop production (Tubiello and Howden 2007). The stability dimension is related to individuals at high risk of completely losing the access to the resources leading to consumption of adequate food, either because these individuals cannot confirm *ex ante* in contradiction of income shocks, or they absence enough "reserves" to smooth consumption *ex post* or both. Certain unstable access is climate variability, e.g., landless agricultural labourers who are dependent upon agricultural wages specifically in region with erratic rainfall and have huge risk of losing their access to food. The third dimension of *stability* involves adequate reach of human beings to resources to obtain suitable foods for healthy diet. Therefore, the main element is the purchasing power of consumers and the evolution of real income and food prices. The final dimension is utilization which encompasses all food safety and quality aspects of nutrition (Tubiello and Howden 2007). Figure 1 illustrated the schematic representation of cascading impact on environmental changes on food security and nutrition.

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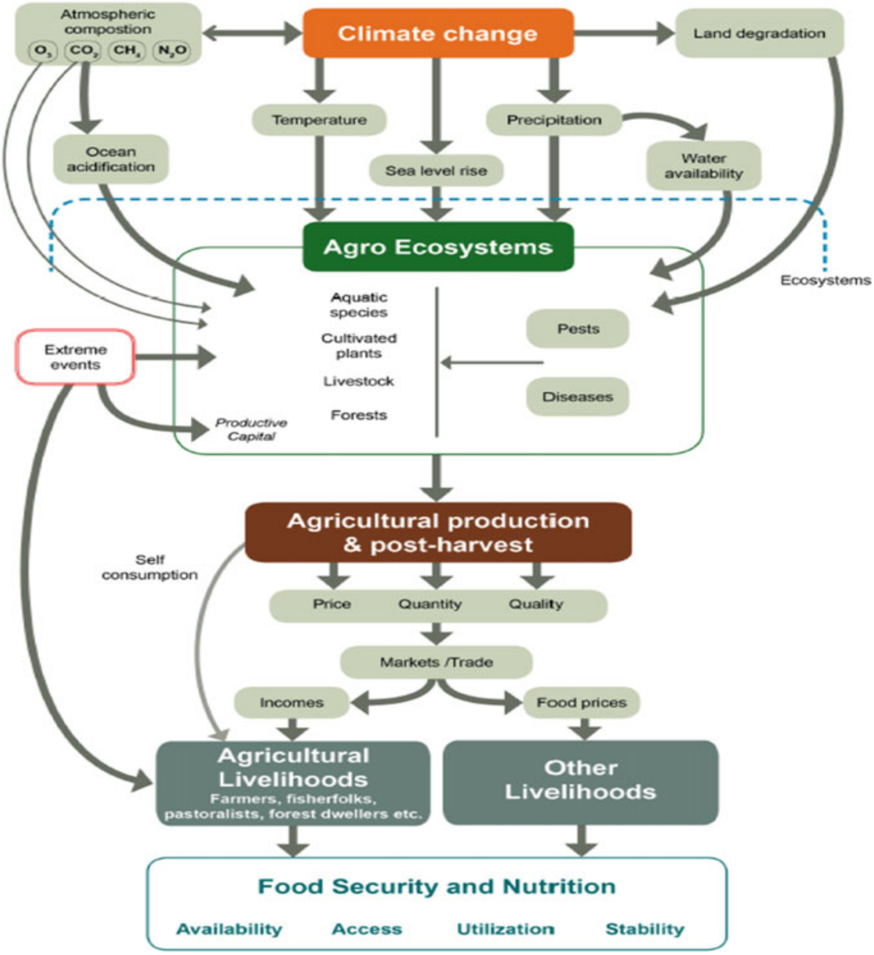

Fig. 1 The schematic representation of cascading impact on environmental changes on food security and nutrition (*Source* FAO 2015)

The most vulnerable people are those who depend on agriculture and natural resources for their livelihoods, especially the most vulnerable people who depend on the most affected systems, and the poor people (FAO 2015). According to the World Bank, 836 million people worldwide were still living in extreme poverty (less than $1.25/day) in 2015. And according to IFAD, at least 70% of the very poor live in rural areas, with most of them deriving part (or all) of their livelihood from agriculture. It is estimated that 500 million smallholder farms in the developing world feed nearly 2 billion people, and in Asia and sub-Saharan Africa, these small farms produce about 80% of the food consumed. The rural poor often rely in part on forests for their livelihoods (World Bank 2002). It is estimated that between 660 and 820 million people are (workers and their families) depend wholly or partly on fisheries, aquaculture, and related industries for income and livelihoods. WHO (2021) report stated that, 149.2 million children under the age of 5 years were stunted and 45.4 million were found to be wasted, partially due to poor diets. The change in the environmental condition worsens the unsustainable food systems by impacting the fertility of the soil, excessive rain, crop yields and food production, food-nutrient and anti-nutrient arrangement, and nutrition bioavailability. Such changes alter macro- and micronutrient available in the global food supply. Furthermore, the issue arises from indirect effects such as pests that trigger a reduction in damage and food safety hazards at several steps of the food chain from primary production to post-harvest security through to utilization. These factors may lead to deleterious impacts in human nutrition (Parfitt et al. 2010; Tirado et al. 2010; Hodges et al. 2011). The global climatic condition showed change on >0.5 °C in surface temperature will lead to devastating, irreparable effects on the planet's habitability for humans and many other species (Hoegh-Guldberg et al. 2018). With increase in temperature results in increased demand for water for evapotranspiration by crops and natural vegetation leading to depletion in soil moisture (Fig. 2).

The change in the environmental condition affect the food system in many ways from direct effects on crop production (e.g., changes in rainfall leading to drought or flooding, or hotter or colder temperature leading to changes in the length of growing season). For example, in Southern Africa, environment condition is one of the most cited elements of food insecurity because they act both as an underlying, ongoing issue and as a short-lived stock (Gregory 2005).

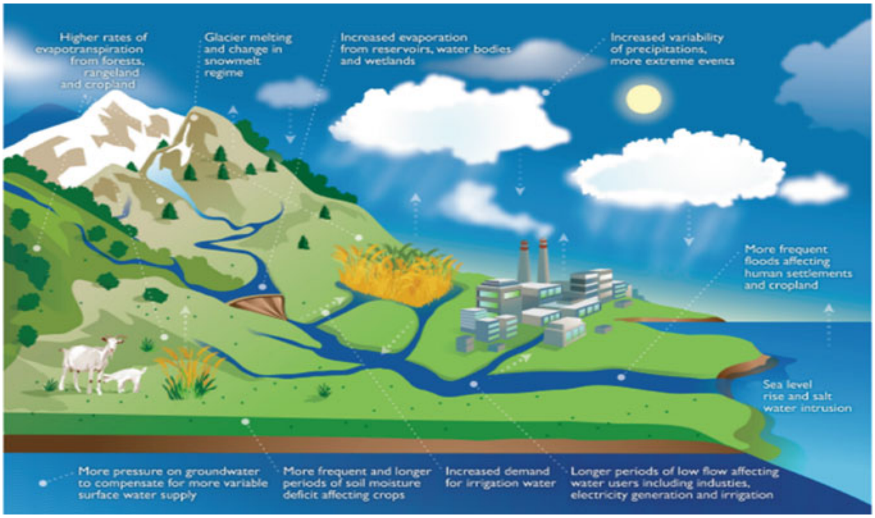

Fig. 2 Climate change affecting the water cycle and its impact on agriculture (*Source* FAO 2013)

2 Climate Change and Impact on Health and Nutrition Content

Environmental Change will continue to impact human health on wide scale. As climate change progresses, the environmental conditions require optimal human health that come under threat which includes clean air, drinkable water, low pathogen exposure, harvest crops, animal, seafood in appropriate and safe capacities. The change in climate advances variability into the food supply, rise in prices of food, and eventually decreases the access to nutrient-dense and healthy foods (Willett et al. 2019). For example, rise in sea temperatures affect the marine life effecting fish populations, a major source of protein, essential fatty acids. The impact of lost biomass from oceans affect disproportionally to numerous countries (Golden et al. 2016; Boyce 2020). Certain models implies that changes in food availability because of climate change, exclusively decreased accessibility of fruits and vegetables, are anticipated to result in an additional 529,000 deaths by 2050 (Springmann 2016). Changes in climatic conditions affect the nutritional status of populations, but it will continue impact the poor and marginalized populations. Change in the environmental conditions may alter human health by changing the nutrient content present in food through increasing the concentration of CO_2 in the atmosphere (Dietterich et al. 2015). The elevated level of CO_2 leads to rapid growth, but it also delimits the plant protein and micronutrients like calcium, iron, and zinc (Medek et al. 2017; Myers 2017; Smith et al. 2017; Uddling et al. 2018). Preeminent CO_2 concentrations of 550 ppm directs to 3–11% regression in zinc and iron absorption of cereal grains and legumes (Myers et al. 2014). Under more extreme circumstances, CO_2 concentrations of 690 ppm, lead to 5–10% reductions in the concentrations of phosphorus, potassium, calcium, sulphur, magnesium, iron, zinc, copper across a varied choice of crops (Loladze 2014).

3 Changes in Environmental Conditions and Impact on Crop Production and Availability

The environmental changes render additional stress on India's long-term food security encounters long-term food security argues as it affects food production in several ways. The influence of environmental change on the water availability severely impacts major parts of India due to water scarcity largely depending on groundwater for irrigation. The decline in precipitation and drought in India leads to drying up of wetlands and adversely affecting to degradation of ecosystems (Cruz et al. 2007). Its straight affect food production directly through transformation in agro-ecological settings and incidentally by altering growth and allocation of income and consequently demand for agricultural products (IPCC 2007). Higher temperatures are presumed to bring primarily advantages to agriculture: the areas potentially appropriate for cropping will increase, the length of the growing period will enhance production and reduce the need for housing and for multiple feed. These improvements must be set alongside an improved occurrence of extreme procedures, for instance, heat waves and droughts in the Mediterranean area or amplify substantial rainfall and submerging in temperate regions, including the option of increased coastal storms (Rosenzweig 2002). In Asia, environmental variability (temperature and rainfall) and climate-driven extremes (flood, drought, cold waves, and storms) have induced negative influences on the agriculture sector (FAO 2016), especially in the cropping system which has a major role in food and nutrition security, and thus created the food and nutritional security in Asia (Cai et al. 2016; Aryal et al. 2019). The adverse environmental condition has impacted the quality and quantity of wheat and rice crops (Din et al. 2022; Wasaya et al. 2022).

The variability of climatic conditions has marked several determining factors to rice production in Asia. Floods and drought have been induced due to climate variability have diminished the rice yield in South Asia and several other parts of Asia (Mottaleb et al. 2017). With high temperature for a sustained period as well as water shortages decreased the seed germination which restraint to poor stand establishment and seeding vigour resulting in reduction in grain weight of rice (Fahad et al. 2017; Liu et al. 2019). There has been great challenge to increase wheat production by 60% by 2050 to meet the food demands (Rezaei et al. 2018). With increase in temperature, water availability will decrease predominantly at the low latitudes countries and upsurge at the extreme latitude countries in areas like Southern part of Australia and Europe, New Zealand by 2030 due to drought and forest fire which will further result in increased market price of fruits and vegetables by 43% and 33% respectively (Quiggin 2010). The climate fluctuations develop more definite and more prevalent, droughts and floods, the central reasons of short-term instabilities in food production in semiarid and subhumid regions, will turn into more critical and more repeated. In semiarid regions, droughts can significantly decrease crop yields and livestock numbers and production (IPCC 2001).

4 Environmental Change on Variability on Livestock

Within arid to semi-arid areas, the stock of livestock has been highly liable to increased temperatures and decreased precipitation (Downing et al. 2017; Balamurugan et al. 2018). Temperature within the range of 10–30 °C has been comfortable for domestic livestock, but with the reduction of 3–5% in animal feed intake with each degree rise in temperature. Likewise, with lower temperature would strengthen the requirement of up to 59%. Although, the conditions like drought and heat waves have drastically influenced the production of livestock under such adverse climate change scenarios (Habeeb et al. 2018) Foe example. The Rift Valley Fever (RVF) due to surge in rainfall, and tick-borne diseases (TBDs) due to an elevation in temperature, have converted outbreaks for sheep, goats, cattle, buffalo, and camels (Bett et al. 2019). With different breeds of livestock exhibits different responses to higher temperature and scarcity of water. In India, the thermal emphasis has adverse influence on the

Animals	Forage and feed crops	Labour force and capital
• Water management (e.g. boreholes) • Breed on resistance to drought, heat and harsh environments • Shifts in species, breeds and/ or production system (e.g. small ruminants, poultry) • Disease control and animal health • Cooling (indoor systems) or provide shade (e.g. trees)	• Irrigation • Purchase feed, supplementation • Breed feed crops and forages for water use efficiency and for resistance to drought, salinity and waterlogging • Grazing management • Changes in cropping calendar • Agroforestry • Increase mobility for resources	• On- and off-farm diversification • Insurances • Reconversion (in the context of national/regional production zoning) • Institutional changes (e.g. trade, conflict resolution, income stabilization programmes

Fig. 3 Change in climatic conditions adaptation in the Livestock sector (*Source* Climate Change and Food Security: Risks and Responses)

breeding traits of animals and eventually it leads to poor growth and high mortality rates of poultry (Balamurugan et al. 2018). Within the dry regions of Asia, due to extreme irregularity in rainfall and drought would affect serious feed scarceness (Arunrat et al. 2018). This results in a high concentration of CO_2 reduces the quality of fodder like the reduction in protein, iron, zinc, and vitamins (Ebi and Lolade 2019). The scenarios in future exhibit that grasslands, pastures, feed quality and quantity as well as biodiversity would be highly affected. Livestock's susceptibility varies first on their revealing to climate shocks: duration, incidence and seriousness of shocks, situation of stock and of appropriate assets such as feedstock, housing, water points etc. It also be determined by on their understanding: type of breed, of housing or feeding system, status of animal health (e.g., vaccination rate) and the magnitude of livestock to the household in terms of food security and livelihoods (ICEM 2013). In addition, several factors increase livestock's vulnerability to climate change, especially in semi-arid and arid regions. They include rangeland deprivation, breakup of grazing area, changes in land tenure, conflicts and insecure access to land and finally markets (e.g., crop residues and by-products for feed, animal products). A range of adaptation options are available for livestock production, Fig. 3 exhibits the different scales like animals, feeding/housing system, system of production. These are differed between small-scale livestock production with low market integration and large-scale production with high market integration.

5 Impact of Climate Change in Fisheries and Aquaculture Systems

The environmental changeability and extreme weather circumstances had an intensifying hazard to the sustainability of seize fisheries and aquaculture systems in marine and to freshwater environments. Such an impact occurs due to the consequence of both continuing atmospheric warming and correlated with physical (sea surface temperature, ocean circulation, waves, and storm systems) and chemical changes of ocean water like salinity content, oxygen concentrations and acidification of the aquatic atmosphere (IPCC 2013). The extreme weather events like deep sea ocean swells, specifically high temperatures and cyclones, may impact the ability of ecosystems like coral reefs and mangroves to provide crucial services which are important for livelihoods and food and nutrition security. Changes in the environmental conditions and carbon absorption within the aquatic systems may continue the manifest changes through an increase in water temperature, increased thermal stratification, changes in salinity and freshwater content, changes in oxygen concentrations and ocean acidification. The coral reef systems will be at risk because of increased double pressure of rising temperatures and increasing acidification. Mass coral bleaching has been witnessed, for example, the Phoenix Islands, with 100 percent of coral mortalities in the lagoons and almost 62% of coral mortality on the outer slopes of leeward of the Kanton Atoll in 2002–2003 (Alling et al. 2007). The changes in temperature have significant influence on the reproductive cycle of fish, including the speed at which they grow, reach sexual maturity, and the timing of spawning (Parry et al. 2005). There has been reduction in available oxygen levels (related to the warming the surface water) that will lead to decrease in maximum body weight of fish across the globes leading to lowering down the catch potential soon. This has also been analysed that species of various fishes had migrated to poleward resulting in the rapid ‘tropicalization’ of mid- and high-latitude systems. The models based on such predicted changes on the environmental conditions, habitat types and phytoplankton primary production forecast a wide scale of redistribution of global marine fish catch, with an average of 30–70% in increase in high-latitude areas and decline in almost 40% in the tropics (Cheung et al. 2010). In the Mediterranean region, it has been observed that one invasive species has been introduced from lower latitudes every four weeks in recent years. Most non-native species have been observed to migrate an average of 300 km northward since the 1980s to follow their natural chemical and physical habitat. Increasing pressure on aquatic resources from climatic influences and human stressors such as pollution and overfishing could lead to serious shortages in capture fisheries production. In addition to the gradual evolution of climate change-related drivers, variability events (e.g., El Niño) and extreme events (e.g., floods, droughts, storms) are likely to affect the stability of marine and freshwater resources that are adapted to or affected by them. For example, rising sea levels and flooding displace brackish and freshwater in river deltas, thereby nullifying some aquaculture practices and destroying water resources (Streftaris et al. 2005). That inland fisheries production is in danger by modifications in rainfall and water administration, and by the occurrence and concentration of extreme climate events (Brander 2007), is obvious. The abundance and biodiversity of fish in rivers are mainly subtle to disturbance because lower water levels during the dry season diminish the quantity of individuals that can efficaciously spawn, and numerous fish species are adapted to spawn synchronously with the flood pulse so that their eggs and larvae can be transported to nursery grounds in floodplains. River ecosystems are particularly sensitive to changes in the amount and timing of water discharge, which are likely to change with climate change. Changes in river flows may be exacerbated by human efforts to retain water in reservoirs and irrigation canals (FAO 2009a). Initial assessments indicate that the impacts of climate change on fisheries and aquaculture will be felt most severely in Africa and South Asia (Allison et al. 2009). Ocean acidification and temperature increases have had an adverse effect on the natural habitats of many species in Asia, including Hilsa fish and numerous forms of algae (Jahan et al. 2017). Coral reefs are seriously threatened by high ocean temperatures and acidity from land-based agriculture. Coral bleaching episodes can occur in India and other parts of Asia with just a 1 °C increase in average temperature over four weeks (Hilmi et al. 2019; Lam et al. 2019). Due to elements like intense cyclonic activity, rising sea levels, temperature swings, and an increasing influx of saline water close to the Indus Delta, Pakistan's habitat quality for aquaculture and fisheries, especially fish breeding areas, has been compromised (Ali et al. 2019). The main threat to algae and fish is increasing levels of ocean acidity. Among various climate-driven extremes like drought, flood, and temperature rising, drought is more dangerous as there is not enough rainfall especially for aquaculture. Ocean acidification and warming of 1.5 °C was closely associated with anthropogenic absorption of CO_2 (Adhikari et al. 2018). The greatest threat to algae and fish is the increasing acidity of the oceans. Among the various climate-related extremes such as drought, flood, and temperature rise, drought is the most dangerous because there is not enough rainfall, especially for aquaculture. Ocean acidification and 1.5 °C warming is closely related to anthropogenic uptake of CO_2 (Islam and Haq 2018).

6 Net Impact of Climate Change on Food Security

Climate change directly affects agroecosystems, which in turn has potential impacts on agricultural production, which in turn has economic and social impacts that affect livelihoods and food security. In other words, impacts are transmitted from climate to environment, to production, and to economic and social dimensions. At each stage of this stress transmission chain, the impacts are determined by the shock itself and the vulnerability at the stage/level of the stressed system. The transmission of a stress can be increased or decreased depending on the vulnerability at each level of the system. Vulnerability may increase over time as systems/households are exposed to repeated shocks that continuously erode their base/assets. These transmission mechanisms and the role played by different vulnerabilities at each level are critical to the ultimate impact on food security and nutrition (FAO 2015). The IPCC's synthesis report (2014) highlights that a variety of social and economic elements that have not yet been fully considered influence exposure and susceptibility to climate-related impacts, complicating quantitative assessments. The research also emphasizes how climate-related hazards frequently magnify existing stressors, having detrimental effects on livelihoods, especially for people who are already poor. As a result, it is critical to include both the physical and social aspects of vulnerability when evaluating how climate change may affect food security. Examining a population's demographic, social, economic, and other traits that affect their susceptibility to hazards as well as their ability to recover from and handle negative shocks is known as social vulnerability. In Fig. 4, illustrates the food security vulnerability to different climatic hazards and their changes mentioned.

7 Conclusion

The security of food and nutritional supplies is already being impacted by climate change and will continue to do so. It significantly impacts agricultural output, the welfare of people and nations that depend on it, and ultimately consumers through increased price instability through affecting agro ecosystems. Both the direct effects of climatic changes and the preexisting vulnerabilities of agricultural systems contribute to the implications of climate change on food security and nutrition. The best way to understand these effects is as a series of consequences that start with climate change, move on to biophysical effects, then economic and social repercussions, and lastly affect households and food security. Vulnerabilities amplify the effects at each stage of this process. These observations lead to important discoveries:

- The most vulnerable populations (the poor), whose livelihoods depend on climate-sensitive industries like agriculture, located in areas susceptible to climate change, bear the early and most severe effects.
- To address long-term effects and mitigate eventual repercussions on food security and nutrition, vulnerabilities must be reduced.
- Reduced access to and stability of resources will be the main and most significant effects on food security and nutrition, mostly affecting the most disadvantaged groups in society.

From an agronomic perspective, favourable conditions for crops and other species will shift geographically due to climate change. Therefore, to optimize these conditions, it will be necessary to change the types of crops and cultivated species and move them to a different location. Even taking advantage of potential positive impacts, such as extended growing seasons in colder regions, would often require significant changes in farming practices and systems to effectively increase production. In addition, these shifts in climatic conditions will be accompanied by changes in other biotic factors, such as pests and diseases, that could potentially offset the benefits of climatic changes.

Globally, and particularly in the developing world, the effects of changing climatic patterns because of increased human activities have been keenly felt. The Asian continent is vulnerable to numerous challenges arising from climate change, with South Asian countries particularly at risk due to their higher population density, geographic location, and underdeveloped technologies. Increases in seasonal temperatures are

Environmental	Polar systems.
	High exposure to sea-level rise and coastal flooding including storm surge of people, economic activity and infrastructure in low-lying coastal zones, small island developing states (SIDS), and other small islands.
	Mountain areas (landslide, erosion, water cycle perturbation, shift of ecosystems).
	Coastal and SIDS fishing communities depending on ecosystem services.
	Warm water coral reefs and respective ecosystem services for coastal communities.
	Already degraded areas (land degradation, droughts, not having recovered from extreme events).
	Areas facing water scarcity and irregular supplies, or constraints on increasing supplies.
	Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water.
	Areas having suffered diminution of genetic pools.
	Populations and infrastructure exposed to novel hazards and lacking historical experience with these hazards.
	Monoculture-based systems (pests and diseases, drought).
Economic	Populations with limited ability to compensate for losses in rainfed systems and pastoral systems.
	Populations prone to conflict over natural resources.
	Societies susceptible to loss of provisioning, regulation and cultural services from terrestrial ecosystems.
	Undernourished and malnourished populations.
	Poorer populations in urban and rural settings; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers.
Social	Marginalized rural population with multidimensional poverty and limited alternative livelihoods.
	Limited ability to cope and adapt due to marginalization, high poverty and culturally imposed gender roles.
	Limited ability to cope among the elderly and female-headed households.
	Countries in protracted food security crisis.
Institutional	Areas with inadequate water services and infrastructures.
	Lack of capacity and resilience in water management regimes.
	Inappropriate land policy (including lack of tenure systems).
	Misperception and undermining of pastoral livelihoods. Insufficient local governmental attention to disaster risk reduction.
	Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability.

Fig. 4 IPCC's food security vulnerability to different climate hazards and changes (*Source* IPCC 2014)

expected to negatively impact agricultural production. Crop growth simulation models that account for these changing conditions are crucial.

References

Adhikari S, Keshav CA, Barlaya G, Rathod R, Mandal RN, Ikmail S (2018) Adaptation and mitigation strategies of climate change impact in freshwater aquaculture in some states of India. J Fish Sci 12:16–21. https://doi.org/10.21767/1307-234X.1000142

Ali S, Eum HI, Cho J, Dan L, Khan F, Dairaku K (2019) Assessment of climate extremes in future projections downscaled by multiple statistical downscaling methods over Pakistan. Atmos Res 222:114–133. https://doi.org/10.1016/j.atmosres.2019.02.009

Alling A, Doherty O, Logan H, Feldman L, Dustan P (2007) Catastrophic coral mortality in the remote Central Pacific Ocean: Kiribati, Phoenix Islands. Atoll Res Bull 551:1–19

Allison EH, Perry A, Badjeck MC, Adger WN (2009) Vulnerability of national economies to the impacts of climate change on fisheries. Fish Fish 10(2):173–196

Arunrat N, Pumijumnong N, Hatano R (2018) Predicting local-scale impact of climate change on rice yield and soil organic carbon sequestration: a case study in Roi Et Province, Northeast Thailand. Agric Sys 164:58–70. https://doi.org/10.1016/j.agsy.2018.04.001

Aryal JP, Sapkota TB, Khurana R, Khatri Chhetri A, Jat ML (2019) Climate change and agriculture in South Asia: adaptation options in smallholder production systems. Environ Develop Sustain 20:1–31. https://doi.org/10.1007/s10668-019-00414-4

Balamurugan B, Tejaswi V, Priya K, Sasikala R, Karuthadurai T, Ramamoorthy M (2018) Effect of global warming on livestock production and reproduction: an overview. Res Rev 6:12–18

Bett B, Lindahl J, Delia G (2019) Climate change and infectious livestock diseases: the case of rift valley fever and tick-borne diseases. Climate Smart Agri Pap 3:29–37. https://doi.org/10.1007/978-3-319-92798-5_3

Boyce DG, Lotze HK, Tittensor DP, Carozza DA, Worm B (2020) Future ocean biomass losses may widen socioeconomic equity gaps. Nat Commun 11:2235

Brander KM (2007) Global fish production and climate change. Biol Sci 104(50):19709–19714

Cai Y, Bandara JS, Newth DA (2016) Framework for integrated assessment of food production economics in South Asia under climate change. Environ Model Softw 75:459–497. https://doi.org/10.1016/j.envsoft.2015.10.024

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Zeller D, Pauly D (2010) Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. Glob Change Biol 16:24–35

Cruz RV (Ed) (2007) Climate change: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, UK, pp 469–506

Dietterich LH, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ (2015) Impacts of elevated atmospheric CO_2 on nutrient content of important food crops. Sci Data 2:1–8. https://doi.org/10.1038/sdata.2015.36

Din MSU, Mubeen, M, Hussain S, Ahmad A, Hussain N, Ali MA (2022) World Nations priorities on climate change and food security. Building climate resilience in agriculture. Springer, pp 365–384. https://doi.org/10.1007/978-3-030-79408-8_22

Downing MMR, Nejadhashemi AP, Harrigan T, Woznicki SA (2017) Climate change and livestock: impacts, adaptation, and mitigation. Climate Risk Manag 16:145–163. https://doi.org/10.1016/j.crm.2017.02.001

Ebi KL, Loladze I (2019) Elevated atmospheric CO_2 concentrations and climate change will affect our food's quality and quantity. Lancet Planet Health 3:283–284. https://doi.org/10.1016/S2542-5196(19)30108-1

Fahad S, Bajwa AA, Nazir U, Anjum SA, Farooq A, Zohaib A (2017) Crop production under drought and heat stress: plant responses and management options. Fron Plant Sci 9:1147. https://doi.org/10.3389/fpls.2017.01147

FAO (2009a) The state of food and agriculture: livestock in the balance, Rome. https://www.fao.org/3/i0680e/i0680e00.htm

FAO (2009b) The state of food insecurity in the world-economic crisis impacts and lessons learned, food and agriculture organization of the united nations. Rome

FAO (2013) The state of food and agriculture: Food system for better nutrition. https://www.fao.org/3/i3300e/i3300e.pdf

FAO (2015) Climate change and food security: risks and responses

FAO (2016) The impact of disasters on agriculture: addressing the information gap. Rome, p 19

Golden CD, Allison EH, Cheung W, Dey MM, Halpern BS, McCauley DJ, Smith M, Vaitla B, Zeller D, Myers SS (2016) Fall in fish catch threatens human health. Nature 534:317–320

Gregory PJ, Ingram JSI, Brklacich M (2005) Climate change and food security. Philos Trans R Soc B Biol Sci. https://doi.org/10.1098/rstb.2005.1745

Habeeb AA, Gad AE, Atta AM (2018) Temperature-humidity indices as indicators to heat stress of climatic conditions with relation to production and reproduction of farm animals. Int J Biotechnol Recent Adv 1:35–50. https://doi.org/10.18689/ijbr-1000107

Hilmi N, Osborn D, Acar S, Bambridge T, Chlous F, Cinar M (2019) Socio-economic tools to mitigate the impacts of ocean acidification on economies and communities reliant on coral reefs–a framework for prioritization. Reg Stud Mar Sci 100:559–566. https://doi.org/10.1016/j.rsma.2019.100559

Hodges RJ, Buzby JC, Bennett B (2011) Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. J Agric Sci 149:37. https://doi.org/10.1017/S0021859610000936

Hoegh-Guldberg O, Jacob D, Taylor M, Bindi M, Brown S, Camilloni I, Diedhiou A, Djalante R, Ebi KL, Engelbrecht F (2018) An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland, pp 175–311

Intergovernmental Panel on Climate Change (2007a) Climate change 2007: the physical science basis, contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, UK in press

Intergovernmental Panel on Climate Change (2007b) Climate change: synthesis report. https://www.ipcc.ch/report/ar4/syr/

International Centre for Environmental Management (ICEM) (2013) USAID Mekong ARCC climate change impact and adaptation on livestock. Prepared for the United States Agency for International Development by ICEM

IPCC (2001) TAR climate change: the scientific basis. https://www.ipcc.ch/report/ar3/wg1/

IPCC (2013) Climate change: the physical science basis. https://www.ipcc.ch/report/ar5/wg1/

IPCC (2014) Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. In: Pachauri RK, Meyer LA (eds) Core writing team. Geneva, Switzerland, p 151

Jahan I, Ahsan D, Farque MH (2017) Fishers' local knowledge on impact of climate change and anthropogenic interferences on Hilsa Fishery in South Asia: evidence from Bangladesh. Environ Develop Sustain 17:461–478. https://doi.org/10.1007/s10668-015-9740-0

Liu J, Hasanuzzaman M, Wen H, Zhang J, Peng T, Sun H (2019) High temperature and drought stress cause abscisic acid and reactive oxygen species accumulation and suppress seed germination growth in rice. Protoplasm 256:1217–1227. https://doi.org/10.1007/s00709-019-01354-6

Loladze I (2014) Hidden shift of the ionomers of plants exposed to elevated CO_2 depletes minerals at the base of human nutrition. Elife 3:02245. https://doi.org/10.7554/eLife.02245

Medek D, Schwartz J, Myers S (2017) Estimated effects of future atmospheric CO_2 concentrations on protein intake and the risk of protein deficiency by country and region. Environ Health Perspect 125:087002. https://doi.org/10.1289/EHP41

Mottaleb KA, Rejesus RM, Murty MVR, Mohanty S, Li T (2017) Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. Miti Adap Strat Global Change 22:879–901. https://doi.org/10.1007/s11027-016-9705-0

Myers SS, Zanobetti A, Kloog I, Huybers P, Leakey AD, Bloom AJ (2014) Increasing CO_2 threatens human nutrition. Nature 510:139–142. https://doi.org/10.1038/nature13179

Myers SS, Smith MR, Guth S, Golden CD, Vaitla B, Mueller ND (2017) Climate change and global food systems: potential impacts on food security and undernutrition. Annu Rev Public Health 38:259–277. https://doi.org/10.1146/annurev-publhealth-031816-044356

Parfitt J, Barthel M, Macnaughton S (2010) Food waste within food supply chains: quantification and potential for change to 2050. Philos Trans R Soc B Biol Sci 365:3065–3081. https://doi.org/10.1098/rstb.2010.0126

Parry M, Rosenzweig C, Livermore M (2005) Climate change, global food supply and risk of hunger. Phil Trans Roy Soc B 360:2125–2138. https://doi.org/10.1098/rstb.2005.1751

Quiggin J (2010) Drought, climate change and food prices in Australia. Melb Aust Conserv Found

Rezaei EE, Siebert S, Huging H, Ewert F (2018) Climate change effect on wheat phenology depends on cultivar change. Sci Rep 8:48–91. https://doi.org/10.1038/s41598-018-23101-2

Rosenzweig C, Tubiello FN, Goldberg RA, Mills E, Bloomfield J (2002) Global Environ Change 12:197–202

Smith M, Golden C, Myers S (2017) Potential rise in iron deficiency due to future anthropogenic carbon dioxide emissions. Geo Health 1:248–257. https://doi.org/10.1002/2016GH000018

Springmann M, Mason-D'Croz D, Robinson S, Garnett T, Godfray HCJ, Gollin D, Rayner M, Ballon P, Scarborough P (2016) Global and regional health effects of future food production under climate change: a modelling study. Lancet 387:1937–1946

Streftaris N, Zenetos A, Papathanassiou E (2005) Globalisation in marine ecosystems: the story of non-indigenous marine species across European seas. Ocean Mar Biology–An Annu Rev 43:419–453

Tirado MC, Clarke R, Jaykus L, Mcquatters-Gollop A, Frank J (2010) Climate change and food safety: a review. Food Res Int 43:1745–1765. https://doi.org/10.1016/j.foodres.2010.07.003

Tubiello FN, Soussana JF, Howden SM (2007) Proc Natl Acad Sci USA 104:19686–19690

Uddling J, Broberg MC, Feng Z, Pleijel H (2018) Crop quality under rising atmospheric CO_2. Curr Opin Plant Biol 45:262–267. https://doi.org/10.1016/j.pbi.2018.06.001

UN (1999) The right to adequate food (Art. 11): 12/05/1999.E/C/.12/1999/5, Committee on Economic, Social and Cultural Rights, Twentieth session, Geneva, Agenda item, vol 7. United Nations

Wasaya A, Yasir TA, Sarwar N, Mubeen K, Rajendran K, Hadifa A (2022) Climate change and global rice security in modern techniques of rice crop production. Springer, Singapore, pp 13–26. https://doi.org/10.1007/978-981-16-4955-4_2

WHO (2021) Levels and trends in child malnutrition: UNICEF/WHO/The World Bank group joint child malnutrition estimates: key findings of the 2021 edition. World Health Organization, Geneva

Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A (2019) Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393:447–492

World Bank (2002) World development report: building institution for markets. https://openknowledge.worldbank.org/entities/publication/cde48204-41c4-5370-958a-1c27c817f375