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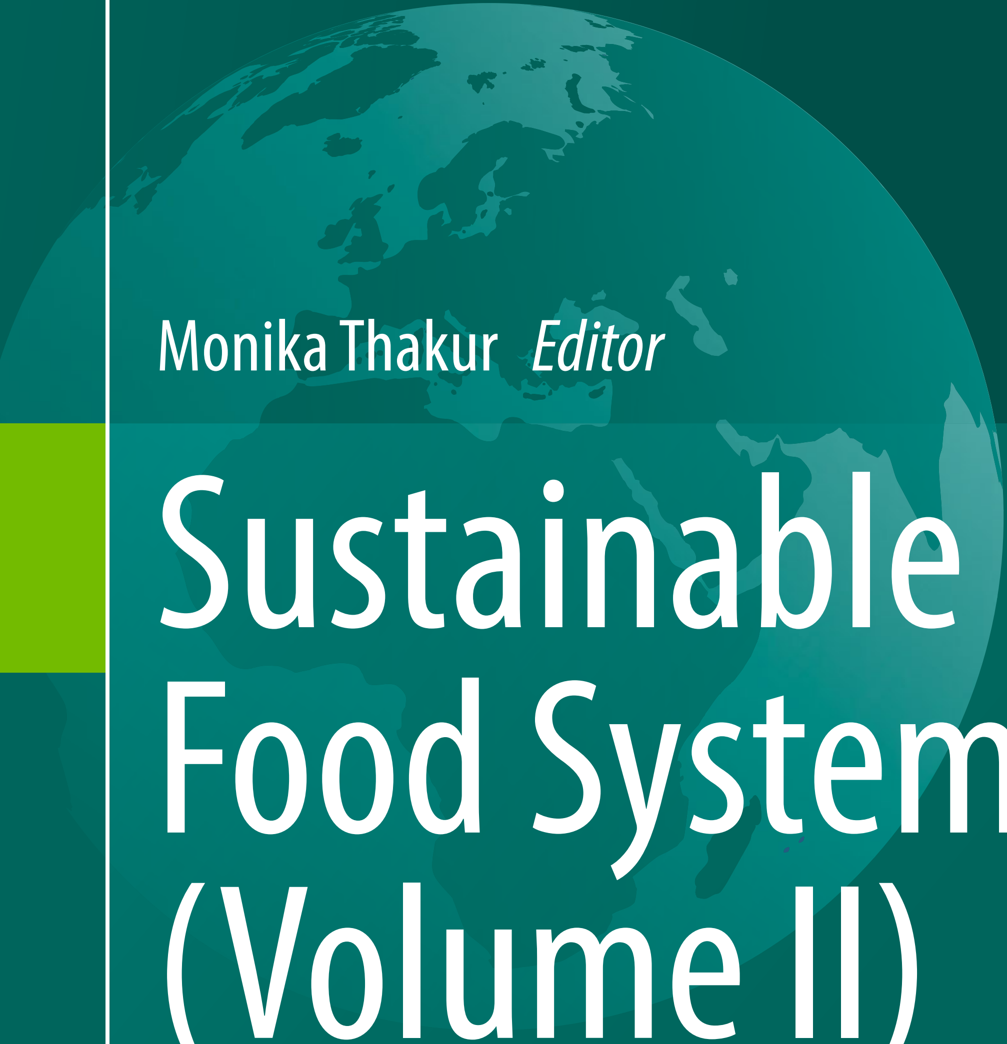

Monika Thakur *Editor*

Sustainable Food Systems (Volume II)

SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity

Springer

World Sustainability Series

Series Editor

Walter Leal Filho, European School of Sustainability Science and Research, Research and Transfer Centre “Sustainable Development and Climate Change Management”, Hamburg University of Applied Sciences, Hamburg, Germany

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

Sustainable Food Systems (Volume II)

SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity

Springer

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Sustainable Food Systems (Volume II)

SFS: Novel sustainable green technologies, circular strategies, food safety & diversity

part 5: Novel Sustainable Green Food Processing Technologies

part 6: Circular Strategies for Recovery and Valorization

part 7: Sustainable Techniques for Food Safety and Food Diversity

Preface

Food Systems (FS) refers to the sequence of actions and how they are linked together and involved in producing, preparing, distributing, consuming, disposing of, and valuing food products that come from plants, animals, and microorganisms. The farming system, waste management system, input supply system, and other subsystems of the food system interact with other elements like energy, trade, and the health system, among others. A **Sustainable Food System (SFS)** is one that provides nutrition for the masses while affecting their social, economic, and environmental foundations in order to provide nutritional food security for future generations, which shall not be compromised. SFS creates a solid system with significant social and economic benefits by focussing on the sustainability of the economy, society, and environment. The **Sustainable Development Goals (SDGs)** of the United Nations are built on an SF framework. 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 systematic problems that need different coordinated solutions at the local, national, regional, and international levels.

Innovative frameworks, sustainable diets, green & circular technologies and strategies, food safety, and diversity initiatives are part of the Sustainable Food System (SFS), which attempts to deliver high-quality, safe meals in a sustainable manner. Because the Sustainable Food System is such a vast subject, it has been impossible to highlight every facet of it in a single book. In order to achieve balance and organized structure, the Editor has separated this vast, detailed, and compendious approach into two series, **Sustainable Food Systems I and II**.

The **Sustainable Food Systems (Volume II): SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity** has a very comprehensive outline, divided into **3 major parts** and further **20 different chapters**. Sustainable Food System has cutting-edge strategies for Framework, Sustainable diets, Green & Circular Technologies and strategies, Food Safety & Diversity that aims to provide quality and safe foods in an environmentally conscious and sustainable way.

The Fifth Part: Novel Sustainable Green Food Processing Technologies consists of four different chapters primarily focussing on the novel green different food processing technologies in different food categories. **The Sixth Part: Circular Strategies for Recovery and Valorization**, elaborated in five different chapters. This section deals with different circular strategies for valorization of the food products. **The Seventh Part: Sustainable Techniques for Food Safety and Food Diversity**, compiled in 11 chapters will cover the food safety trends and food diversities nationally and internationally.

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, nutrition, 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.

The readers are invited to learn more about the difficulties and cutting-edge solutions developed to address them as we travel through the Sustainable Food Systems (Volume II): SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity. 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, Food Science and Technology and help in building a strengthened Sustainable Food System globally.

Noida, Uttar Pradesh, India Dr. Monika Thakur

Acknowledgements

Sustainable Food Systems (Volume II): SFS: Novel Sustainable Green Technologies, Circular Strategies, Food Safety & Diversity is a comprehensive overview of *Sustainable Food System* with novel sustainable Green & Circular strategies, Food Safety & Diversity that aims to provide quality and safe foods in an environmentally conscious and sustainable way. I am extremely indebted to Respected Founder President, **Dr. Ashok K. Chauhan**, for his blessings and constant encouragement. It has been great pleasure to acknowledge the whole-hearted 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 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
µg	Microgram
µl	Microlitre
µm	Micrometre
AC	Alternating Current
AI	Artificial Intelligence
BOD	Biological Oxygen Demand
CFU/ml	Colony Forming Unit per ml
cm	Centimetre
CNCD	Chronic Non-communicable Diseases
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
conc.	Concentrated
COSE	Conventional Organic Solvent Extraction
CVD	Cardiovascular Diseases
DAGs	Diacylglycerols
DC	Direct Current
DFF	Deep Fat Frying
DH	Degree of Hydrolysis
dil.	Dilute
DIP	Digital Image Processing
DL	Deep Learning
DNA	Deoxyribonucleic Acid
e.g.	For example
EAE	Enzyme-Assisted Extraction
Ed.	Edition
ed.	Editor
eds.	Editors
eHFs	Extensively Hydrolysed Formulas

EN	Enteral Nutrition
et al.	et. alia; and others
etc.	et. cetera
FAO	Food & Agricultural Organization
FL	Fluorescence
FSMS	Food Safety Management System
FSSAI	Food Safety Standards Authority of India
FTIR	Fourier-Transform Infrared Spectroscopy
g	Gram
GAE	Gallic Acid Equivalent
GPS	Global Positioning System
GRAS	Generally Recognized as Safe
GC	Gas Chromatography
Gy	Grays
HACCP	Critical Control Points Hazard Analysis
HDC	Histidine decarboxylase
HPAE	High-Pressure-Assisted Extraction
HPP	High-Pressure Processing
hrs.	Hours
i.e.	That is
in vitro	With in glass
in vivo	With in living
IoT	Internet of Things
Kg	Kilogram
l	Litre
LAB	Lactic Acid Bacteria
LCS	Liquid Chromatographic Separation
m	Metre
MAE	Microwave-Assisted Extraction
MAGs	Monoacyl Glycerols
mg	Milligram
MH	Million Hectares
min	Minutes
ml	Millilitre
ML	Machine Learning
mln tons	Million tonnes
mm	Millimetre
MoFPI	Ministry of Food Processing Industry
MS	Mass Spectrometry
MT	Metric Ton
Ml	Microlitre
Nm	Nanometre
NN	Neural Networks
NTP	Non-thermal Processing
^{o}C	Degree Celsius

OMF	Oscillating Magnetic Field
OTA	Ochratoxin A
PFE	Pulsed Electric Field
pHFs	Partially Hydrolysed Formulas
RO	Reverse Osmosis
ROS	Reactive Oxygen Species
RTS	Ready to Serve
RUCO	REPLACE action package
SDG	Sustainable Development Goals
sp.	Species (Singular)
spp.	Species (Plural)
sq Km	Square Kilometre
TLC	Thin-Layer Chromatography
UAVs	Unmanned Aerial Vehicles
UCO	Used cooking oil
UV	Ultraviolet
var.	Variety
viz.	Videlicet; namely
vol.(s)	Volume(s)
VRT	Variable Rate Technology
w.r.t.	With respect to
WHO	World Health Organization

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Novel Sustainable Green Food Processing Technologies

Smart and Sustainable Food Production Technologies

Manisha Singh, Twinkle Kumar Sachchan, Prabhjot Kaur Sabharwal, and Ranjana Singh

Abstract This chapter explores the intersection of smart technologies and sustainability in the context of food production. It highlights the urgent need for innovative approaches to address the challenges of feeding a growing global population while minimizing environmental impact. The chapter provides an overview of various smart and sustainable food production technologies, including precision agriculture, vertical farming, aquaponics, and blockchain-based traceability systems. It also discusses their potential benefits, challenges, and implications for achieving a more sustainable and resilient food system. Overall, this book chapter provides insights into the transformative potential of smart and sustainable food production technologies, offering a roadmap for building resilient and efficient food systems that can meet the growing global demand while preserving our natural resources and ensuring food security for future generations.

Keywords Smart technologies · Precision agriculture · Vertical farming · Aquaponics · Block chain · Sustainable food system

1 Introduction

The global population is rapidly increasing, and it is projected to reach 9.7 billion by 2050. This population growth, coupled with urbanization and changing dietary patterns, poses significant challenges to the agricultural industry (Parfitt et al. 2010). Traditional farming practices often result in inefficient resource utilization, increased environmental degradation, and limited food production capacity. There is a critical need for innovative solutions that can optimize food production while minimizing environmental impact (Godfray et al. 2010). The conventional farming practices contribute to deforestation, soil erosion, water pollution, and greenhouse gas emissions (Sheoran et al. 2019). Smart and sustainable food production technologies aim

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to minimize these environmental impacts by optimizing resource usage, reducing chemical inputs, and promoting ecosystem health. The limited availability of arable land, freshwater resources, and fossil fuels necessitates the development of technologies that can produce more food using fewer resources. Smart technologies enable efficient resource allocation, precision application of inputs, and closed-loop systems that recycle and reuse resources (Kumar et al. 2022).

Smart technologies play a crucial role in revolutionizing food production practices, improving efficiency, and optimizing resource usage. These technologies leverage data, connectivity and automation to enable real-time monitoring, decision-making and control. There are so many smart technologies used in food production. Some of them are the Internet of Things (IoT), sensors and actuators, data analytics and artificial intelligence, robotics and automation, remote sensing and imaging and blockchain technology. By integrating these smart technologies into food production processes, farmers and food producers can optimize resource usage, improve productivity, reduce waste, and enhance sustainability. The combination of data-driven insights, automation, and connectivity enables more efficient and responsive food production systems, contributing to a more sustainable and secure food supply chain (Goel et al. 2021).

The global food system needs to produce enough nutritious food to feed the growing population. Smart and sustainable food production technologies increase productivity, enhance crop yields, and improve resilience to climate change and other challenges, thereby contributing to food security. These practices can lead to improved profitability for farmers, reduced input costs, and increased market opportunities. By adopting these smart technologies, farmers can optimize their operations, increase yields, and reduce waste, ultimately enhancing their economic viability and competitiveness. Consumers are increasingly conscious of the environmental and social impacts of the food they consume. There is a growing demand for sustainably produced food that is free from harmful chemicals and supports local communities (Kumar et al. 2022). Smart and sustainable food production technologies can meet these consumer demands and foster trust in the food supply chain. The advancement of digital technologies, such as IoT, AI, and big data analytics, has opened up new possibilities for optimizing agricultural practices. These technologies enable real-time monitoring, precise decision-making and automation, revolutionizing the way food is produced (Akella et al. 2023).

The smart and sustainable food production technologies offer a promising path towards a more efficient, environmentally friendly and resilient agricultural system. They provide opportunities to address the challenges faced by the industry and pave the way for a sustainable and secure food future.

2 Smart Technologies in Food Production

Smart technologies play a crucial role in revolutionizing food production practices, improving efficiency, and optimizing resource usage. These technologies leverage data, connectivity, and automation to enable real-time monitoring, decision-making, and control. Here are some key smart technologies used in food production:

- ***Internet of Things (IoT)***: IoT refers to a network of interconnected devices embedded with sensors, actuators, and software that enable them to collect and exchange data. In food production, IoT devices can monitor various parameters such as temperature, humidity, soil moisture and nutrient levels. These devices provide real-time data that can be analyzed to optimize resource allocation, detect anomalies, and enable timely interventions (Van et al. 2022).
- ***Sensors and Actuators***: Smart sensors and actuators are integral components of IoT systems in food production. They can be used to monitor environmental conditions, plant health and machinery performance. For example, soil moisture sensors can provide data on irrigation needs, helping farmers determine the optimal watering schedule. Actuators, such as automated irrigation systems, can be controlled based on sensor readings, ensuring precise and efficient water usage (El Bilali et al. 2020).
- ***Data Analytics and Artificial Intelligence (AI)***: Data analytics and AI technologies are used to process the vast amount of data collected from IoT devices and make informed decisions. Machine learning algorithms can analyze historical and real-time data to identify patterns, predict crop yields, detect diseases, and optimize resource allocation. AI-powered decision support systems can provide farmers with recommendations for planting, harvesting and pest management based on data-driven insights (El Bilali et al. 2020).
- ***Robotics and Automation***: Robotics and automation technologies are transforming various aspects of food production. Autonomous vehicles equipped with sensors can navigate fields and perform tasks like planting, spraying, and harvesting with precision. Robotic arms and grippers can handle delicate crops and perform repetitive tasks, reducing labor requirements and improving efficiency. Automated systems can also monitor and control environmental conditions in controlled environment agriculture, such as vertical farming (El Bilali et al. 2020).
- ***Remote Sensing and Imaging***: Remote sensing technologies, such as satellite imagery and aerial drones, provide valuable data for monitoring crop health, identifying disease outbreaks, and assessing vegetation growth. These technologies enable farmers to identify areas of concern, optimize fertilizer application and detect anomalies that may impact crop yields. High-resolution imaging techniques, such as hyperspectral imaging, can provide detailed information about crop health and nutrient deficiencies (El Bilali et al. 2020).
- ***Blockchain Technology***: Blockchain technology offers transparent and secure record-keeping capabilities in the food supply chain. It enables traceability and accountability by creating an immutable and decentralized ledger of transactions.

Blockchain can help track and authenticate food products, ensuring their origin, quality, and safety. This technology enhances food safety and allows consumers to make more informed choices about the food they consume (Akella et al. 2023).

By integrating these smart technologies into food production processes, farmers and food producers can optimize resource usage, improve productivity, reduce waste, and enhance sustainability. The combination of data-driven insights, automation, and connectivity enables more efficient and responsive food production systems, contributing to a more sustainable and secure food supply chain.

3 Sustainability in Food Production

Sustainability in food production is an essential aspect of ensuring the long-term availability of food while minimizing negative environmental impacts. It involves practices that promote efficient resource use, reduce greenhouse gas emissions, conserve biodiversity, and support social and economic well-being. Here are some key points and references on sustainability in food production:

- ***Sustainable Agriculture***: Sustainable agriculture integrates environmental stewardship, economic viability, and social responsibility. It includes practices such as organic farming, agroecology, and permaculture (Pretty 2008).
- ***Efficient Resource Use***: Sustainable food production aims to optimize the use of resources like water, energy, and land. This includes adopting precision agriculture techniques, drip irrigation systems, and efficient crop rotation methods (Garnett 2013).
- ***Reduced Food Waste***: Minimizing food waste throughout the production, distribution, and consumption phases is crucial for sustainability. It involves implementing efficient supply chains, improving storage facilities, and promoting consumer awareness (Parfitt et al. 2010).
- ***Biodiversity Conservation***: Sustainable food production supports the preservation of biodiversity by protecting natural habitats, promoting agroforestry systems, and encouraging the use of native plant species (Tscharntke et al. 2012).
- ***Climate Change Mitigation***: Sustainable food production aims to reduce greenhouse gas emissions through practices such as low-carbon farming techniques, renewable energy use, and carbon sequestration in agricultural soils (Vermeulen and BM 2012).
- ***Social Equity***: Sustainable food production should address social issues such as fair wages, safe working conditions, and access to nutritious food for all. It involves supporting small-scale farmers, promoting gender equality, and improving food security (De Schutter 2014).

4 Environmental Challenges in Agriculture

Agriculture faces various environmental challenges that can have detrimental impacts on ecosystems, biodiversity and natural resources. Here are some key environmental challenges in agriculture:

- ***Soil Degradation***: Unsustainable agricultural practices, such as intensive monoculture, overuse of chemical fertilizers and pesticides, and improper irrigation techniques, can lead to soil degradation. This includes soil erosion, nutrient depletion, salinization, and loss of soil organic matter, affecting soil fertility and productivity (Lal 2015).
- ***Water Scarcity and Pollution***: Agriculture is a major consumer of freshwater resources. Irrigation practices, inefficient water management, and excessive water withdrawals can contribute to water scarcity in regions. Additionally, agricultural runoff containing fertilizers, pesticides, and animal waste can lead to water pollution, eutrophication of water bodies, and contamination of groundwater (Molden 2013).
- ***Greenhouse Gas Emissions***: Agricultural activities contribute to greenhouse gas emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Livestock production, rice cultivation, use of synthetic fertilizers, and on-farm energy use are major sources of emissions in agriculture, contributing to climate change (Golasa et al. 2021).
- ***Biodiversity Loss***: Intensive agricultural practices, such as large-scale monoculture, use of agrochemicals, and habitat destruction, can lead to the loss of biodiversity. Conversion of natural habitats for agriculture, fragmentation of landscapes, and the decline of pollinators and beneficial insects pose significant threats to biodiversity and ecosystem stability (Tscharntke et al. 2012).
- ***Deforestation***: Expanding agriculture, particularly for large-scale commercial production, often leads to deforestation, especially in tropical regions, which contributes to habitat loss, carbon emissions, and disruption of local ecosystems (Gibbs et al. 2015).
- ***Pesticide Use***: Excessive use of pesticides and herbicides in agriculture can have adverse effects on the environment. Pesticides may contaminate soil, water bodies, and non-target organisms, causing harm to beneficial insects, birds, and aquatic life. There are also concerns about the long-term effects of pesticide residues on human health (Pimental 2005).

Addressing these environmental challenges requires sustainable and regenerative agricultural practices that promote soil health, conserve water resources, reduce greenhouse gas emissions, protect biodiversity, and minimize chemical inputs. It involves adopting practices such as agroecology, organic farming, precision agriculture, conservation agriculture, and sustainable water management techniques.

These challenges highlight the need for a holistic approach to agriculture that balances production goals with environmental stewardship and the long-term sustainability of our natural resources.

5 Importance of Sustainable Food Production

Sustainable food production is of paramount importance for various reasons, including environmental, social, and economic aspects. Here are some key reasons highlighting the importance of sustainable food production:

- ***Environmental Preservation***: Sustainable food production practices minimize negative impacts on the environment, such as soil erosion, water pollution, deforestation, and greenhouse gas emissions (Garnett 2013).
- ***Conservation of Natural Resources***: Sustainable food production focuses on efficient resource use, including water, energy, and land, to reduce waste and ensure their availability for future generations.
- ***Climate Change Mitigation***: Sustainable food production contributes to mitigating climate change by reducing greenhouse gas emissions from agriculture, adopting agroecological practices, and promoting carbon sequestration in soils (Smith et al. 2014).
- ***Food Security and Nutrition***: Sustainable food production systems ensure long-term food security by promoting diverse and resilient agricultural practices, reducing food waste, and improving access to nutritious food for all (Godfray et al. 2010).
- ***Preservation of Biodiversity***: Sustainable food production practices help protect biodiversity by conserving natural habitats, promoting agroecological systems, and supporting the preservation of traditional crop varieties and livestock breeds (Tscharntke et al. 2012).
- ***Socioeconomic Benefits***: Sustainable food production fosters resilient and equitable food systems, supports rural livelihoods, promotes fair trade, enhances social well-being, and ensures the economic viability of farming communities (Hobbs 2007).

6 Key Principles of Sustainable Food Production

The key principles of sustainable food production encompass a range of practices and approaches that prioritize environmental stewardship, social equity, and economic viability. Here are some key principles of sustainable food production:

- ***Conservation of Natural Resources***: Sustainable food production emphasizes the responsible and efficient use of natural resources such as water, soil, and energy to minimize waste and preserve ecosystem integrity (Goel et al. 2021).
- ***Biodiversity Preservation***: Sustainable food production promotes practices that protect and enhance biodiversity, including preserving natural habitats, promoting crop and livestock diversity, and supporting ecological balance (Swift et al. 2004).

- ***Soil Health and Conservation***: Sustainable food production focuses on building and maintaining healthy soils through practices such as conservation tillage, cover cropping, organic matter management, and the reduction of soil erosion and nutrient runoff (Lal 2015).
- ***Integrated Pest Management (IPM):*** Sustainable food production promotes the use of Integrated Pest Management, which involves the judicious and minimal use of pesticides, prioritizing prevention, biological control, crop rotation, and other ecologically friendly pest management strategies (Ehler 2006).
- ***Water Management***: Sustainable food production emphasizes efficient water management, including practices such as water conservation, drip irrigation, precision agriculture, and the protection of water quality through minimizing nutrient runoff and pollution (Molden 2013).
- ***Social Equity and Fair Trade***: Sustainable food production ensures social equity by supporting fair wages and safe working conditions for farmers and workers, promoting gender equality, respecting land rights, and fostering community development (Schutter 2014).

These principles provide a foundation for sustainable food production systems, acknowledging the interconnectedness of environmental, social, and economic factors in ensuring long-term food security and well-being.

7 Precision Agriculture

Precision agriculture, also known as precision farming or site-specific crop management, is an approach that leverages technology and data to optimize agricultural practices and resource management. It involves the use of various tools, such as GPS, sensors, remote sensing, and data analytics, to gather real-time information about crops, soils, and environmental conditions. This information is then utilized to make precise and targeted decisions regarding planting, irrigation, fertilization, pest control, and harvesting (Gerbers and Adamchuk 2010).

The key components and techniques employed in precision agriculture include:

- ***Remote Sensing***: Remote sensing technologies, such as satellites, drones, and aerial imagery, are used to collect data on crop health, nutrient status, water stress, and weed infestations. This data helps farmers monitor field conditions and make informed management decisions.
- ***Global Positioning System (GPS)***: GPS technology is used to precisely locate field positions, enabling farmers to map and record data related to soil variability, crop growth, and yield. GPS also facilitates the use of auto-steer systems, guiding machinery along pre-defined paths with high accuracy.
- ***Variable Rate Technology (VRT)***: VRT enables farmers to apply inputs, such as fertilizers, pesticides, and irrigation water, at variable rates across a field based on the specific needs of different areas. This optimizes resource use, minimizes waste, and reduces environmental impacts.

- ***Yield Monitoring:*** Yield monitors installed on harvesters allow farmers to collect accurate data on crop yields across different areas of a field. This information helps in identifying spatial variability, understanding yield limiting factors, and evaluating the effectiveness of management practices.
- ***Decision Support Systems***: Decision support software and models are used to analyze data and provide recommendations for optimal management practices. These systems consider factors such as soil conditions, weather patterns, crop growth stages, and economic considerations to guide decision-making (Bongiovanni and Lowenberg 2004).

The benefits of precision agriculture include:

- ***Enhanced Productivity***: Precision agriculture enables farmers to optimize input use, improve crop health, and maximize yields by tailoring management practices to specific field conditions.
- ***Resource Efficiency***: By precisely applying inputs based on the needs of different areas, precision agriculture reduces resource waste, including water, fertilizers, pesticides, and fuel.
- ***Environmental Sustainability***: Precision agriculture practices promote sustainable farming by minimizing the environmental impacts associated with excessive fertilizer and pesticide use, reducing soil erosion, and conserving water resources.
- ***Cost Savings***: Improved resource efficiency and targeted management practices result in cost savings for farmers, including reduced input costs and improved machinery and labor utilization.
- ***Data-Driven Decision Making***: The use of data and technology in precision agriculture allows farmers to make more informed and evidence-based decisions, leading to better outcomes and increased profitability.

Overall, precision agriculture offers a promising approach to address the challenges of modern agriculture, optimize production, and promote sustainable farming practices. By leveraging technology and data, farmers can improve efficiency, productivity, and environmental stewardship in their operations (Bongiovanni and Lowenberg 2004).

7.1 Application of Smart Technologies in Precision Agriculture

Smart technologies play a crucial role in the implementation of precision agriculture practices. These technologies enable farmers to collect and analyze real-time data, make informed decisions, and automate various tasks. Here are some key applications of smart technologies in precision agriculture:

- ***Sensor Technology***: Sensors are used to monitor and collect data on various parameters such as soil moisture, temperature, nutrient levels, and crop health.

These sensors can be deployed in fields or integrated into irrigation systems, allowing farmers to gather precise information about the conditions in different areas of their fields.

- ***Internet of Things (IoT)***: IoT devices, such as weather stations, drones, and soil moisture sensors, can be interconnected to gather data from multiple sources. This data is then transmitted to a central system for analysis and decision-making. IoT devices enable real-time monitoring and provide farmers with up-to-date information about their crops and fields.
- ***Unmanned Aerial Vehicles (UAVs) and Drones***: UAVs equipped with high-resolution cameras or multispectral sensors can capture aerial imagery of fields. This imagery provides valuable insights into crop health, nutrient deficiencies, and pest infestations. Drones can cover large areas quickly and efficiently, allowing farmers to identify and address issues promptly.
- ***Data Analytics and Machine Learning***: The vast amount of data collected from sensors, drones, and other sources requires advanced analytics techniques. Machine learning algorithms can process this data to identify patterns, predict crop yields, optimize input applications, and make recommendations for improved management practices.
- ***Automated Machinery and Robotics***: Smart technologies enable the automation of various agricultural tasks. Autonomous machinery, such as self-driving tractors and robotic harvesters, can perform precise operations based on predefined maps and data. This automation reduces human labor, increases efficiency, and enables consistent and accurate operations.
- ***Farm Management Software***: Farm management software platforms provide a centralized system to collect, analyze, and visualize data from different sources. These platforms offer features such as field mapping, yield monitoring, inventory management, and decision support tools. Farmers can access this information on mobile devices, allowing them to make data-driven decisions in real-time.
- ***Precision Irrigation Systems***: Smart irrigation systems use data from sensors and weather forecasts to determine precise water requirements for different areas of a field. This helps optimize water use, prevent over- or under-irrigation, and conserve water resources.

The integration of smart technologies in precision agriculture enables farmers to improve productivity, reduce resource waste, and make informed decisions for sustainable farming practices. By leveraging real-time data and automation, farmers can enhance their operational efficiency, optimize input use, and mitigate environmental impacts (Liaghat and Balasundram 2010).

8 Vertical Farming

Vertical farming is a method of growing plants in vertically stacked layers or vertically inclined surfaces, using indoor environments such as buildings or shipping containers. It involves the use of controlled environments, artificial lighting, and soilless growing techniques to optimize plant growth and maximize production in a smaller footprint (Nichols 2014; Fig. 1). These are some key aspects and benefits of vertical farming:

- ***Vertical Structure***: Vertical farming utilizes vertical space to grow crops, allowing for multiple layers of plants. This vertical arrangement increases the growing area per unit of land, enabling higher crop yields and productivity.
- ***Controlled Environment***: Vertical farms create controlled environments where temperature, humidity, light, and nutrient levels can be precisely regulated. This control eliminates the dependence on external weather conditions and enables year-round production, independent of seasonal variations.
- ***Artificial Lighting***: Since natural sunlight may be limited or insufficient in indoor environments, vertical farms use artificial lighting, such as LED lights, to provide the specific light spectrum and intensity required for optimal plant growth. This ensures consistent and efficient photosynthesis.
- ***Soilless Growing***: Vertical farming often employs soilless growing techniques such as hydroponics, aeroponics, or aquaponics. These methods involve growing plants without soil, using nutrient-rich water solutions or misting systems. Soilless growing allows for precise control over nutrient levels, water usage, and eliminates the risk of soil-borne diseases.

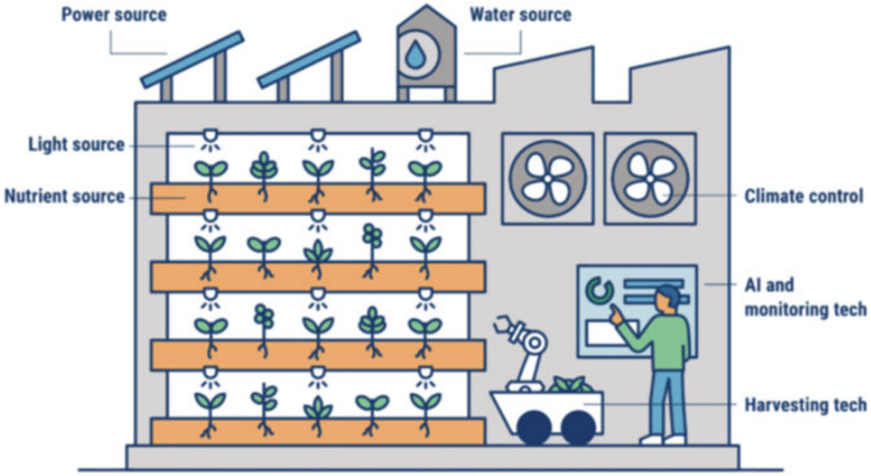

Fig. 1 Components of vertical farming (*Image* CB Insights)

- ***Water Efficiency***: Vertical farming systems are designed to be highly water-efficient. Techniques like recirculating water systems and precise irrigation methods minimize water waste compared to traditional field agriculture. Water can be reused and recycled, reducing overall water consumption.
- ***Reduced Land Requirement***: Vertical farming can be implemented in urban areas or locations with limited land availability. By utilizing vertical space, it reduces the need for large expanses of land, making it a viable option in densely populated areas.
- ***Reduced Environmental Impact***: Vertical farming systems can minimize environmental impacts associated with conventional agriculture. They require less land, reduce water usage, and minimize the need for pesticides and herbicides. Additionally, vertical farming can decrease transportation distances, reducing carbon emissions.
- ***Local and Fresh Produce***: Vertical farms can be located close to urban centers, allowing for the production of fresh, locally grown produce. This reduces the time and distance between harvest and consumption, ensuring high-quality, nutritious crops.
- ***Crop Diversity***: Vertical farming supports the cultivation of a wide range of crops, including leafy greens, herbs, fruits, and vegetables. The controlled environment facilitates the growth of various plant species, enabling diversification of crop production.
- ***Innovation and Technology***: Vertical farming often incorporates innovative technologies such as automated systems, robotics, and data analytics. These technologies help monitor and optimize plant growth conditions, automate tasks, and improve overall efficiency.

Vertical farming offers opportunities to address challenges in food production, including urbanization, land scarcity, and climate change. By utilizing controlled environments and advanced technologies, it presents a sustainable and efficient approach to growing crops in urban settings, providing fresh produce year-round while minimizing environmental impacts (Kalantari et al. 2018).

8.1 Integration of Smart Technologies in Vertical Farming

The integration of smart technologies plays a significant role in enhancing the efficiency and productivity of vertical farming systems. Here are some key smart technologies commonly used in vertical farming:

- ***Environmental Sensors***: Sensors are employed to monitor and collect data on various environmental factors such as temperature, humidity, CO_2 levels, and nutrient concentrations. This data helps optimize growing conditions and maintain an optimal environment for plant growth.

- ***Automated Irrigation Systems***: Smart irrigation systems utilize sensors and data analysis to provide precise and automated water delivery to plants. They optimize water usage, prevent over- or under-irrigation, and ensure plants receive the right amount of moisture.
- ***Artificial Intelligence (AI) and Machine Learning***: AI and machine learning algorithms are used to analyze data collected from sensors and environmental monitoring systems. They provide insights into plant health, growth patterns, and crop predictions. This information helps optimize cultivation strategies, predict yield, and detect early signs of plant stress or disease.
- ***LED Lighting Systems***: Vertical farms rely on artificial lighting, usually LED lights, to provide the necessary light spectrum and intensity for plant growth. Smart lighting systems can be programmed to adjust light levels based on plant growth stage and optimize energy consumption.
- ***Robotics and Automation***: Automated systems and robotics are used in vertical farming to perform tasks such as seeding, transplanting, harvesting, and maintenance. These technologies streamline operations, reduce labor costs, and ensure consistent and precise execution of tasks.
- ***Data Management and Analytics***: Integrated data management platforms collect and analyze data from various sources, including sensors, environmental monitors, and crop monitoring systems. This data helps farmers make informed decisions, optimize resource allocation, and monitor crop health and growth trends.
- ***Remote Monitoring and Control***: Remote monitoring and control systems allow farmers to access and manage their vertical farms from anywhere. They can monitor environmental conditions, adjust settings, and receive real-time alerts and notifications about potential issues or deviations from optimal conditions.
- ***Internet of Things (IoT)***: IoT technologies enable the interconnection of various devices and systems within a vertical farm. This integration facilitates data exchange, automation, and remote control, improving operational efficiency and enabling real-time decision-making.
- ***Vertical Farming Management Software***: Specialized software platforms provide comprehensive management tools for vertical farming operations. These platforms assist in crop planning, inventory management, scheduling tasks, data visualization, and analysis, helping optimize production and resource utilization.

The integration of smart technologies in vertical farming enables precise monitoring, automation, and optimization of various parameters critical for plant growth. These technologies enhance productivity, resource efficiency, and crop quality while reducing labor requirements and environmental impacts. By leveraging real-time data and intelligent systems, vertical farmers can make data-driven decisions and achieve optimal yields in their controlled environment (Srinivasan and Yadav 2023).

8.2 Advantages and Challenges of Vertical Farming

Advantages of Vertical Farming:

- ***Increased Crop Yield***: Vertical farming allows for multiple layers of crops, maximizing the use of vertical space and significantly increasing the overall crop yield compared to traditional farming methods.
- ***Year-Round Production***: Vertical farms create controlled environments that are not dependent on external weather conditions. This enables year-round crop production, providing a consistent and reliable supply of fresh produce regardless of the season.
- ***Efficient Land Use***: Vertical farming requires less land compared to conventional agriculture. It is particularly advantageous in urban areas where land is limited, making it possible to grow crops in locations where traditional farming is not feasible.
- ***Water Conservation***: Vertical farming systems are designed to be highly water-efficient. Techniques such as recirculating water systems and precise irrigation methods minimize water waste, reducing overall water consumption compared to conventional farming practices.
- ***Reduced Environmental Impact***: Vertical farming can significantly reduce the environmental impact associated with traditional agriculture. It minimizes the use of pesticides and herbicides, reduces soil erosion, and conserves water resources. Additionally, the proximity of vertical farms to urban centers reduces the need for long transportation routes, reducing carbon emissions.
- ***Fresh, Local Produce***: Vertical farms can be located close to urban areas, allowing for the production of fresh, locally grown produce. This reduces the time and distance between harvest and consumption, ensuring high-quality, nutritious crops (Benke and Tomkins 2017).

8.3 Challenges of Vertical Farming

High Initial Investment: The setup costs for vertical farming can be substantial. The required infrastructure, such as lighting systems, environmental controls, and automation technologies, can be expensive. It may take time for farmers to recoup their initial investment.

Energy Consumption: Vertical farms heavily rely on artificial lighting and controlled environments, which consume significant amounts of energy. Finding sustainable energy sources and optimizing energy efficiency are ongoing challenges.

Technical Expertise: Operating a vertical farm requires specialized knowledge and skills in areas such as plant biology, environmental control systems, and data analytics. Farmers need to continuously update their understanding of emerging technologies and best practices.

Plant Health Management: The dense and controlled environment of vertical farms can create favorable conditions for pests and diseases. Maintaining plant health and implementing effective pest and disease management strategies are essential to prevent crop losses.
Crop Selection and Diversity: While certain crops, such as leafy greens and herbs, are well-suited for vertical farming, the cultivation of some crops with extensive root systems or tall growth habits may be more challenging. Expanding the range of crops suitable for vertical farming is an ongoing area of research.
Scalability and Commercial Viability: Scaling up vertical farming operations to meet larger market demands can present logistical and economic challenges. The cost-effectiveness of vertical farming compared to traditional farming methods is a consideration for commercial viability.

Despite the challenges, vertical farming has the potential to revolutionize food production by providing a sustainable solution to feed growing populations, reduce food waste, and mitigate the environmental impact of agriculture. Continued advancements in technology, increased knowledge sharing, and ongoing research will contribute to addressing the challenges and improving the efficiency and scalability of vertical farming systems (Kalantari et al. 2018).

9 Aquaponics

Aquaponics is a sustainable food production system that combines aquaculture (fish farming) with hydroponics (soilless plant cultivation). It is a closed-loop system where fish waste provides nutrients for plants, and the plants filter and purify the water for the fish. Aquaponics offers several benefits as a sustainable food production system:

- ***Water Efficiency***: Aquaponics systems use a fraction of the water compared to traditional soil-based agriculture. The water is recirculated within the system, and any evaporative losses can be replenished. This conservation of water resources is especially important in areas facing water scarcity.
- ***Nutrient Recycling***: Fish waste, which is rich in nutrients, serves as a natural fertilizer for the plants in aquaponics. The waste is broken down by bacteria into forms that can be readily absorbed by plants, providing them with essential nutrients. This nutrient recycling reduces the need for additional fertilizers, minimizing nutrient runoff and environmental pollution.
- ***Organic and Chemical-Free***: Aquaponics systems can be managed organically, without the use of synthetic pesticides, herbicides, or fertilizers. This results in cleaner, chemical-free produce that is suitable for organic farming practices.

- ***Enhanced Crop Yield and Growth***: The nutrient-rich water in aquaponics systems provides plants with a consistent and balanced supply of nutrients, promoting healthy growth and high crop yields. Plants in aquaponics often grow faster and produce higher-quality produce compared to traditional soil-based methods.
- ***Efficient Space Utilization***: Aquaponics can be implemented in various settings, including urban environments, where land availability is limited. Vertical or stacked systems maximize the use of vertical space, allowing for higher crop density and increased productivity per unit area.
- ***Reduced Environmental Impact***: Aquaponics systems have a lower environmental impact compared to conventional agriculture. They eliminate the need for synthetic fertilizers and reduce the risk of nutrient runoff into water bodies. Additionally, they require less land and have minimal soil erosion, protecting natural habitats and preserving biodiversity.
- ***Climate Resilience***: Aquaponics can be practiced in controlled environments, such as greenhouses or indoor facilities, providing protection against extreme weather conditions, pests, and diseases. This climate resilience allows for year-round production and reduces crop losses due to unfavorable environmental factors.
- ***Educational and Community Benefits***: Aquaponics systems can be used as educational tools to teach about sustainable agriculture, biology, and ecological systems. They also offer opportunities for community engagement, local food production, and food security initiatives.

Aquaponics demonstrates the potential for sustainable food production by integrating fish farming and hydroponics in a symbiotic system. It offers efficient resource utilization, reduced environmental impacts, and year-round production, making it a promising approach for sustainable agriculture (Greenfeld et al. 2019; Fig. 2).

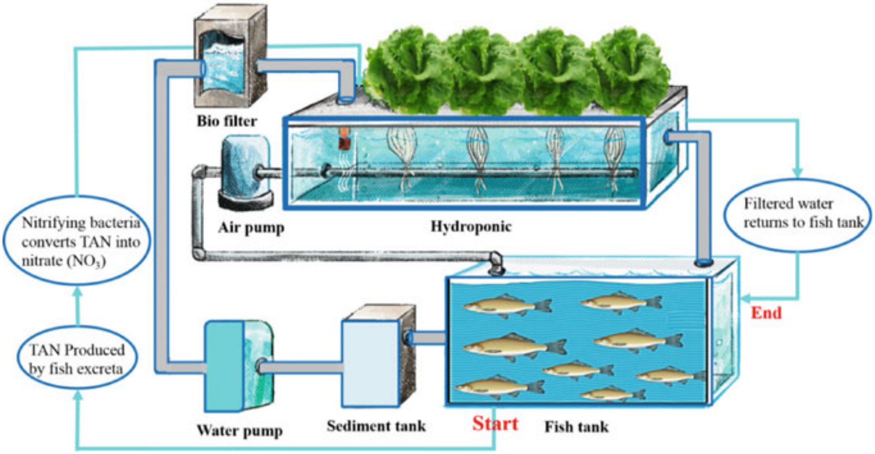

Fig. 2 Systematic diagram of aquaponics (*Source* Taha et al. 2022)

9.1 Smart Technologies in Aquaponics

Smart technologies play a crucial role in optimizing and improving the efficiency of aquaponics systems. Here are some examples of smart technologies used in aquaponics:

- ***Monitoring Sensors***: Various sensors are deployed to monitor key parameters such as water temperature, pH levels, dissolved oxygen, and nutrient concentrations. These sensors provide real-time data that helps ensure optimal conditions for both fish and plants.
- ***Automated Feeding Systems***: Smart feeding systems can be programmed to dispense precise amounts of feed to the fish based on their nutritional requirements. These systems help prevent overfeeding, maintain water quality, and optimize fish growth.
- ***Water Quality Management***: Smart technology can be used to continuously monitor water quality parameters and automatically adjust them as needed. For instance, pH controllers and dosing systems can maintain stable pH levels, and automated systems can regulate dissolved oxygen levels.
- ***Remote Monitoring and Control***: Aquaponics systems can be remotely monitored and controlled using smart devices and internet connectivity. This allows farmers to monitor system parameters, receive real-time alerts and notifications, and adjust settings from anywhere, improving efficiency and enabling timely interventions.
- ***Data Analytics and Decision Support***: Smart technologies enable the collection and analysis of data from various sensors and monitoring systems. Advanced analytics and algorithms can process this data to provide insights, trends, and predictions, aiding in decision-making for optimizing system performance.
- ***Environmental Control Systems***: Smart systems can control and automate environmental factors such as lighting, temperature, and humidity. LED lighting systems can be programmed to deliver specific light spectra optimized for plant growth, and climate control systems can maintain ideal temperature and humidity levels for both fish and plants.
- ***Integration with Aquaculture and Hydroponics***: Smart technologies can facilitate the integration of aquaculture and hydroponics components in the aquaponics system. Automation systems can regulate the flow of water, nutrient distribution, and timing of water cycling between the fish tank and plant beds.
- ***Integration with IoT and Cloud Platforms***: Aquaponics systems can be integrated with IoT (Internet of Things) platforms, enabling data exchange, remote monitoring, and centralized control. Cloud-based platforms can store and analyze data, provide historical trends, and facilitate collaboration and knowledge sharing among aquaponics practitioners.

By leveraging smart technologies, aquaponics systems can achieve optimal resource utilization, minimize risks, and enhance productivity. These technologies enable real-time monitoring, precise control, and data-driven decision-making, contributing to the sustainability and efficiency of aquaponics as a food production system (Taha et al. 2022).

9.2 Environmental and Economic Benefits of Aquaponics

Aquaponics offers a range of environmental and economic benefits, making it an attractive and sustainable method of food production. Here are some key benefits:

Environmental Benefits of Aquaponics:

- ***Water Conservation***: Aquaponics systems use significantly less water compared to traditional soil-based agriculture. The water is recirculated within the system, reducing overall water consumption. This conservation of water resources is particularly important in regions facing water scarcity or where water quality is a concern.
- ***Reduced Environmental Pollution***: Aquaponics minimizes the need for synthetic fertilizers and pesticides, which can contribute to water pollution and soil degradation in conventional farming. The natural nutrient cycling in aquaponics eliminates or significantly reduces nutrient runoff into water bodies, reducing the risk of eutrophication and maintaining water quality.
- ***Soil Preservation***: Aquaponics eliminates the need for soil-based cultivation, reducing soil erosion and degradation. This is particularly beneficial in areas with poor soil quality or limited arable land, as it preserves valuable land resources and protects natural habitats from the negative impacts of traditional agriculture.
- ***Conservation of Biodiversity***: Aquaponics minimizes the negative impact on biodiversity associated with traditional agriculture, such as habitat destruction, pesticide use, and soil degradation. By reducing these impacts, aquaponics contributes to the preservation of local ecosystems and biodiversity.
- ***Energy Efficiency***: Aquaponics systems can be designed to be energy-efficient, using technologies such as LED lighting and energy-efficient pumps. These systems can optimize energy use, reducing the carbon footprint associated with food production (Greenfeld et al. 2022).

9.3 Economic Benefits of Aquaponics

- ***Year-Round Production***: Aquaponics allows for year-round production of fish and crops, irrespective of weather conditions or seasonal variations. This continuous production can lead to a more reliable and consistent supply of fresh produce, which can be advantageous for commercial growers and market demand.
- ***Diversification and Productivity***: Aquaponics systems offer the potential to cultivate a variety of fish and crops simultaneously, providing opportunities for diversification and expanding product offerings. This diversification can enhance market competitiveness and profitability.

- ***Local and Urban Farming***: Aquaponics can be implemented in urban areas, including rooftops, vacant lots, or unused buildings. This proximity to urban markets reduces transportation costs, enables local food production, and fosters direct connections between farmers and consumers, supporting local economies.
- ***Reduced Input Costs***: Aquaponics systems can reduce the need for costly inputs such as synthetic fertilizers, pesticides, and herbicides. The recycling of nutrients and closed-loop system design minimizes the need for external inputs, resulting in cost savings for farmers.
- ***Scalability and Efficiency***: Aquaponics systems can be designed to maximize space utilization, particularly in vertical or stacked systems. This vertical integration and efficient use of space allow for increased productivity per unit area, enhancing profitability and scalability.

Aquaponics offers a sustainable and economically viable alternative to traditional farming methods. Its environmental benefits, including water conservation, reduced pollution, and soil preservation, contribute to long-term ecological sustainability. Simultaneously, the economic benefits of year-round production, diversification, and reduced input costs make aquaponics an appealing option for farmers and entrepreneurs seeking sustainable and profitable food production systems (Greenfeld et al. 2022).

10 Integration of Smart and Sustainable Technologies

The integration of smart and sustainable technologies is a powerful approach to address environmental challenges while optimizing resource efficiency and productivity in various sectors. Here are some examples of how smart and sustainable technologies can be integrated:

- ***Smart Grids***: Smart grids integrate renewable energy sources, energy storage systems, and advanced metering technologies to optimize energy distribution and consumption. These grids enable the efficient integration of renewable energy, load balancing, and demand response, reducing reliance on fossil fuels and minimizing greenhouse gas emissions (Chhaya et al. 2018).
- ***Internet of Things (IoT) in Energy Management***: IoT devices and sensors can be deployed to monitor energy usage, optimize energy efficiency, and automate energy management systems. Real-time data from IoT devices enables intelligent decision-making, such as adjusting HVAC systems, lighting, and energy-consuming equipment based on occupancy, weather conditions, and energy demand (Van et al. 2022).

- ***Precision Agriculture***: Precision agriculture utilizes smart technologies such as sensors, drones, and data analytics to optimize resource use in farming practices. By monitoring soil conditions, crop health, and weather patterns, precision agriculture enables targeted and efficient application of water, fertilizers, and pesticides, minimizing environmental impact and improving crop yields (Gebbers and Adamchuk 2010).
- ***Smart Buildings***: Smart building technologies integrate energy management systems, IoT devices, and automation to optimize energy consumption, indoor environmental quality, and operational efficiency. These technologies enable features such as intelligent lighting, occupancy sensors, and building automation systems to reduce energy waste and enhance occupant comfort (Priyambodo et al. 2022).
- ***Circular Economy and Waste Management***: Smart technologies can enhance waste management systems by enabling efficient collection, sorting, and recycling processes. IoT sensors and data analytics can optimize waste collection routes, monitor fill levels of containers, and track the flow of materials in the recycling chain, promoting a circular economy and reducing waste generation (Kharola et al. 2022).
- ***Smart Transportation and Mobility***: Smart technologies play a vital role in sustainable transportation solutions. Electric vehicles (EVs), intelligent traffic management systems, and smart public transportation systems can reduce carbon emissions, optimize traffic flow, and enhance mobility options, contributing to cleaner and more efficient transportation systems (Goh et al. 2021).
- ***Water Management***: Smart technologies can be employed for efficient water management, including smart irrigation systems, leak detection, and water quality monitoring. These technologies help conserve water resources, minimize water waste, and ensure the sustainable use of water in agriculture, industries, and urban areas (Fereres and Connor 2004).
- ***Smart Waste Water Treatment***: Smart technologies can optimize wastewater treatment processes through real-time monitoring, predictive analytics, and automation. These systems enhance energy efficiency, reduce chemical usage, and improve the overall effectiveness of wastewater treatment, promoting sustainable water management practices (Bong et al. 2018).

The integration of mart and sustainable technologies holds significant potential for creating more resource-efficient, environmentally friendly, and economically viable solutions across various sectors. By leveraging data, connectivity, and automation, these integrated systems enable better decision-making, optimization of resource use, and improved environmental performance.

11 Case Studies Showcasing Integrated Approaches

11.1 Case Study 1: WISErg: Smart Harvester System

WISErg, a technology company, developed the Smart Harvester system, an integrated approach that combines smart and sustainable agricultural technologies to address food waste and nutrient management challenges.

The Smart Harvester system collects and processes food scraps from grocery stores and restaurants, converting them into a nutrient-rich liquid fertilizer. The system uses sensors and data analytics to monitor and optimize the process, ensuring efficient decomposition of organic waste while capturing valuable nutrients. The collected food waste is processed in an anaerobic digester, which converts it into a liquid fertilizer called WISErganic. The system continuously monitors and adjusts the process parameters, such as temperature and pH, to optimize the decomposition and nutrient recovery.

The integrated technology enables real-time monitoring of the entire process, from waste collection to fertilizer production. Data analytics provide insights into waste generation patterns, nutrient content, and fertilizer quality. This information helps improve waste management strategies and enables farmers to make informed decisions about fertilizer application, reducing the need for synthetic fertilizers. By combining smart sensors, data analytics, and anaerobic digestion, the Smart Harvester system promotes sustainable waste management practices, reduces food waste, and provides a valuable nutrient resource for agricultural production (Otten et al. 2016).

11.2 Case Study 2: Saturas: Precision Irrigation System

Saturas, an Israeli agritech startup, developed a precision irrigation system that integrates smart sensing technology with sustainable water management practices.

The system utilizes stem-based sensors that are embedded in the trunks of trees or plants. These sensors measure the plant's water status in real-time, providing accurate information about its water needs. The data is transmitted wirelessly to a central system, where it is analyzed and translated into irrigation recommendations. By continuously monitoring the plant's water status, the precision irrigation system optimizes water use, reducing water waste and improving water efficiency. The system ensures that plants receive the right amount of water at the right time, preventing under or over-irrigation and minimizing water stress.

The integration of smart sensing technology with sustainable water management practices allows farmers to make data-driven decisions and implement precision irrigation strategies. This approach conserves water resources, enhances crop productivity, and reduces the environmental impact of irrigation (Brahmanand and Singh 2022).

11.3 Case Study 3: Philips: City Farming Solutions

Philips, a global technology company, has developed integrated city farming solutions that combine smart lighting, vertical farming, and data analytics to create sustainable urban agriculture systems.

The system utilizes LED lighting technologies that provide precise light spectra optimized for plant growth. The lighting can be dynamically controlled to adjust the intensity, color, and duration, simulating natural sunlight and maximizing photosynthetic efficiency. Vertical farming systems are employed, utilizing stackable trays or racks to grow crops in a controlled environment. The systems are designed for efficient use of space, water, and nutrients. Sensors monitor environmental conditions such as temperature, humidity, and carbon dioxide levels, ensuring optimal growing conditions.

Data analytics and machine learning algorithms analyze real-time data from sensors, optimizing crop growth parameters and resource utilization. The system provides insights into plant health, growth rates, and energy consumption, enabling continuous improvement and fine-tuning of farming practices. By integrating smart lighting, vertical farming, and data analytics, Philips' city farming solutions enable year-round production, reduce water and land requirements, and minimize the use of pesticides and fertilizers. These integrated technologies contribute to sustainable urban agriculture, food security, and reduced environmental impact (Nichols 2014).

These case studies highlight the successful integration of smart and sustainable agricultural technologies in addressing various challenges, including waste management, water efficiency, and urban agriculture. These integrated approaches demonstrate the potential for improved resource efficiency, productivity, and sustainability in modern agriculture.

12 Conclusion

Smart and sustainable food production technologies hold great potential in addressing the pressing challenges of global food security, environmental sustainability, and resource efficiency. These technologies encompass a range of innovative approaches that combine advanced systems, data analytics, and sustainable practices to transform the way we produce and consume food. By harnessing the power of automation, robotics, and artificial intelligence, smart food production technologies enable precise and efficient farming practices. Vertical farming, hydroponics, and aquaponics systems optimize space utilization and minimize water usage while maximizing crop yields. Automated processes and robotics streamline labor-intensive tasks, reducing costs and increasing productivity. Furthermore, these technologies promote sustainable agriculture by minimizing environmental impacts. Water management systems, such as drip irrigation and sensor-based monitoring, ensure optimal water usage, mitigating water scarcity concerns. Smart food production technologies also enhance food safety and traceability. Blockchain technology, for instance, enables transparent and secure tracking of food products from farm to fork, ensuring food quality, preventing fraud, and improving supply chain efficiency. Real-time monitoring systems can detect and address potential food safety risks, safeguarding public health.

Smart and sustainable food production technologies offer transformative solutions to the complex issues of food production, environmental conservation, and resource efficiency. By combining advanced technologies, data-driven approaches, and sustainable practices, we can create a future where food is produced efficiently, with minimal environmental impact, and in a manner that ensures the well-being of both people and the planet. Embracing these technologies is crucial for building a resilient and sustainable food system that can meet the needs of a growing global population while safeguarding our natural resources.

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Recent Trends in the Application of Essential Oils for Preserving Foods

Renu Garhwal, Karnam Sangwan, Yash Pal Sharma, Anuradha Bhardwaj, and Harish Kumar

Abstract The complex mixtures of volatile molecules that make up essential oils, also known as "*quinta essential*" are produced by the many oil-secreting glands that are present in the seeds, flowers, roots, barks, fruits, leaves, and general plant structures of plants. Additionally, essential oils are frequently used to treat a variety of diseases and conditions, including but not limited to cancer, oxidative stress, fungal infection, microbial infection, wound healing, and inflammation. Currently, there has been advancement in the use of essential oils for a variety of applications, notably in relation to human health, as a result of expanding knowledge of the chemical makeup and physiological impacts of these plants. These developments broaden the therapeutic applications of essential oils in the management of a variety of medical disorders. As a result, the market for essential oils is expanding quickly and becoming more significant every day. However, in order to ascertain the, it is essential to carry out additional scientific research and clinical trials.

Keywords Essential oils · Functional properties · Preservation · Microbial infections

1 Introduction

Essential oils, also known as *quinta essentia*, are complex combinations of volatile compounds derived from various oil-secreting glands found in various plant components, including seeds, flowers, roots, barks, fruits, leaves, and overall plant structures. In recent decades, there has been a noticeable upward trend emphasis on the

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significance of natural products in safeguarding against food spoilage. Consequently, there has been an increasing scholarly focus on essential oils, which are concentrated hydrophobic liquids comprising volatile chemical compounds derived from various plant sources such as buds, flowers, seeds, twigs, leaves, bark, fruits, herbs, roots, and wood. Essential oils, commonly known as ethereal volatile oils (Zheng et al. 2023), are a class of secondary metabolites synthesized by medicinal and aromatic plants. They constitute a minor proportion, accounting for less than 5% of the total composition of the plant's dry matter. Aromatic extracts derived from plants possess the characteristic of volatility, typically existing in a liquid state and devoid of colour when maintained at ambient temperature. The substances under investigation display a notable disparity in solubility between water and alcohol/organic solvents, with low solubility observed in the former and high solubility in the latter. Food preservatives that contain essential oils are frequently influenced by various factors in the food industry. These factors include the prevailing pH, physical structure of the food, chemical composition, oxygen concentrations, and storage temperature in the packaging. The biological activities of bioactive compounds derived from essential oils encompass a range of properties, such as antifungal, antimicrobial, antiviral, antiparasitic, antimycotic, antioxidant, and insecticidal effects (Falleh et al. 2020). The primary active constituents of these substances consist of terpenes and hydrocarbons, and it is plausible that the observed traits are associated with the role played by these active compounds.

Essential oils derived from citrus fruits, which consist of sesquiterpenes, oxygenated, and monoterpenes derivatives, have demonstrated potent inhibitory effects against the microorganisms, particularly pathogenic bacteria which have the potential to contaminate food matrices. The observed efficacy of these substances indicates their potential utility as food preservatives and flavour enhancers. In recent studies, the antimicrobial properties of essential oils derived from cinnamon, thyme, and oregano have garnered significant attention. These essential oils have demonstrated remarkable efficacy against various microorganisms, including *Listeria monocytogenes*, *Escherichia coli*, *Pseudomonas fluorescens*, and *Bacillus thermosphacta*. Furthermore, studies have demonstrated the antioxidant efficacy of edible plant extracts in vitro (Assogba Komlan et al. 2015). Hence, it is intriguing to assess the existing scientific knowledge in order to explore novel approaches for preserving and stabilising food matrices. The main objective of this chapter is to engage in a comprehensive discussion the antioxidant properties of essential oils and their constituents, specifically focusing on their potential applicability in the preservation of food products.

From a chemical perspective, the composition of these essential oils comprises a blend of aromatic molecules, either solely or in conjunction with nonaromatic molecules. The primary constituents of these substances consist of sesquiterpenes and monoterpenes, accompanied by a variety of carbohydrates, ethers, alcohols, ketones, and aldehydes. The compounds are secondary metabolites that play a pivotal role in the plants' defence mechanism. Consequently, they possess numerous biological properties. The essential oils consist of molecules that have historically held importance in various fields such as cosmetics, medicine, aromatherapy, and pharmacology. However, their utilisation has significantly advanced since the nineteenth century (Carpena et al. 2021). Additionally, according to reports, these substances have been found to demonstrate minimal adverse effects, as supported by the endorsement of the US FDA (Food and Drug Administration). The chemical compositions of these essential oils are analysed by considering factors such as the species, season, collection area, as well as solvents and extraction methods used (Carpena et al. 2021). Despite their extensive range of applications across various biological disciplines, the inherent instability and vulnerability of these substances to degradation when exposed to environmental stressors such as temperature, oxygen, and light pose significant challenges in fully harnessing their potential. In order to address these limitations, researchers are actively endeavouring to identify potential resolutions. One of the emerging results of these collective endeavours involves the technique of safeguarding these crucial molecules through their encapsulation within various colloidal structures, including nano-emulsions, nano-spheres, microcapsules, liposomes, and molecular inclusion complexes. This chapter focuses on the primary applications of essential oils, including their actions, emerging trends in the respective field, and the potential techniques employed to enhance their activities.

2 Essential Oils: Definition and Composition

Essential oils are substances derived exclusively through physical methods from raw plant materials and are commonly referred to as such. A range of physical methodologies are utilized for the extraction of essential oils, encompassing distillation techniques such as water distillation, steam distillation, and steam/water distillation. An alternative technique, commonly referred to as squeezing or cold pressing, which is specifically employed for the extraction of oils from citrus peels. Additionally, the dry distillation technique, also referred to as pyrolysis, is utilised for extracting oils from natural materials. The extraction operation is achieved through the process of distillation, which involves the physical separation of the essential oil from the aqueous phase. The volatile compounds possess the characteristic of being able to dissolve in fatty oils and fats, leading to their designation as “essential oils.” The term “oil” is employed to describe the viscous and hydrophobic nature, indicating its lack of solubility in water. Conversely, the term “essential” is utilised to signify the inherent essence and distinctive fragrance derived from the plant. The volatility of essential oils distinguishes them from fixed or vegetable oils, which primarily consist of lipids (Chémat and Fernandez 2012). Based on their respective applications, essential oils can undergo subsequent treatment processes aimed at partially or fully removing specific constituents or groups of constituents. Various methods are employed to acquire deterpenated, desesquiterpenated, rectified essential oils, or purified essential oils containing a specific compound. Essential oils are predominantly found within the realm of the vegetable kingdom. Certain families exhibit significant wealth, as exemplified by taxa such as *Lamiales, Asterales,* *Rutales, Laurales, Magnoliales*, and others. The chemical composition of essential oils may exhibit variations based on their specific anatomical localization within the plant. At the microscopic level, essential oils have the tendency to be found within specialised secretory cells, although they are typically present within secretory structures such as pockets, glands, channels, or hairs. The examination of essential oils within plant tissues is conducted through the utilisation of lipophilic dyes such as Sudan III. This particular dye imparts a red coloration to the oil droplets present in the plant's anatomical cuts.

The complexity and variability of essential oils are key characteristics that define their chemical composition. Essential oils are composed of a combination of compounds that can be categorised into two main groups. The first group consists of terpenes, which include monoterpenes, diterpenes, and sesquiterpenes. The hydrocarbon fraction of essential oils is comprised of these terpenes. The second group comprises oxygenated compounds, which encompass esters, ketones, aldehydes, alcohols, oxides, phenols, lactones, and acids. Nitrated or sulphur compounds may occasionally be observed. The chemical composition of essential oils is subject to various factors that can influence its makeup. These factors include the existence of chemo-types, environmental influences, the vegetative cycle, as well as the cultivation and extraction processes employed. Essential oils typically exhibit a liquid state at room temperature, possess volatility, emit an aromatic scent, and may display coloration. The of essential oils is typically lower than density of water, ranging between 0.850 and 0.950, with the exception of wintergreen, sassafras, clove, and cinnamon essential oils. These substances possess a high refractive index and are typically capable of exhibiting rotational properties. Essential oils exhibit solubility in alcohol, which is commonly preferred due to its widespread usage. Additionally, essential oils demonstrate solubility in a variety of organic solvents, with hexane being the preferred choice in laboratory settings. Furthermore, essential oils are soluble in fixed oils or/and their derivatives, such as grease. Although they possess limited water solubility, they effectively transmit their scent to it. Essential oils possess a well-established ability to penetrate the skin (Bruneton 1993). When examining the chemical properties, it is observed that sunflowers initially exhibit neutrality, but gradually develop an acidic reaction. These substances exhibit a high susceptibility to oxidation upon exposure to light, resulting in concurrent resinification through oxygen absorption. This process is accompanied by alterations in odour, elevation of boiling point, and reduction in solubility. Essential oils have the capacity to undergo absorption of chlorine, iodine, and bromine, accompanied by the liberation of heat. Additionally, they can engage in a chemical reaction with water, resulting in the formation of hydrates.

2.1 Sources of Essential Oil

Various parts of a plant species can serve as sources for the essential oil's extraction. The components primarily consist of leaves, flowers, bark, seeds, buds, and

Table 1 Parts of plants rich in essential oils

Parts of plant	Plants
Seeds	Almond, cardamom, anise, caraway, celery, carrot, coriander, nutmeg, cumin, fennel, parsley
Leaves	Basil, cinnamon, bay leaf, common sage, lemon grass, eucalyptus, citronella, mint, melaleuca, oregano, peppermint, patchouli, pine, spearmint, rosemary, tea tree, wintergreen, thyme, kaffir lime, savoury, laurel, tarragon, lantana, cajuput, lemon myrtle, niaouli, lemon, petitgrain, cypress laurel,
Bark	Cassia, sassafras, cinnamon, katrafay
Wood	Amyris, himalayan cedarwood, atlas cedarwood, camphor, sandalwood, rosewood, guaiac wood, myrtle
Resin	Frankincense, peru balsam, myrrh, elemi, gurjum, galbunum
Berries	Juniper, All spice
Peels	Bergamot, kaffir lime, grapefruit, lemon, orange, lime, mandarin, tangerine
Flowers	Blue tansy, clary sage, chamomile, clove, geranium, cumin, *Helichrysum hyssop*, lavender, jasmine, manuka, orange, marjoram, rose, palmarosa, baccharises, patchouli, *Rhododendron anthopogon*, ylang-ylang, *Rosalina*, ajowan, tarragon, marjoram sylvestris, neroli, immortelle
Fruits	Black pepper, *Xanthoxylum*, nutmeg
Roots	Ginger, turmeric, plai, valerian, spikenard, vetiver, angelica
Needles	Cypress, fir, palmarosa, scotch pine

Source (Tongnuanchan and Benjakul 2014)

other similar constituents (Table 1). Plant essential oils typically consist of a diverse blend of naturally occurring compounds, encompassing both non-polar and polar molecules. Typically, essential oils consist of terpenes (specifically sesquiterpenes and monoterpenes), aromatic compounds (such as methoxy derivatives, phenols, aldehydes, alcohols, etc.), and terpenoids (also known as isoprenoids) (Tongnuanchan and Benjakul 2014).

2.2 *Extraction of Essential Oil*

The predominant techniques employed for the extraction process of essential oils include steam distillation, hydro distillation, and solvent extraction. The utilised equipment is characterised by its simplicity, user-friendliness, and cost-effectiveness. Nevertheless, steam distillation has the potential to induce thermal degradation of the raw material, decomposition of heat-sensitive compounds, and hydrolysis of specific compounds. The objective of steam distillation is to disrupt the cellular composition of plant species through the application of heat, resulting in the liberation of essential oils (Locali-Pereira et al. 2020). Additionally, it has been documented that the degree of purity of essential oils acquired through solvent extraction method is diminished as a result of the concurrent extraction of other compounds, like resin. Moreover, it has been observed that the non-polar organic solvents commonly employed in various applications have been found to possess polluting properties (Nazem et al. 2019). In the contemporary era, a multitude of advancements have been unveiled with the aim of augmenting the caliber and efficacy of essential oil production. The primary extraction methods discussed include microwave hydro diffusion, microwave-assisted extraction, supercritical fluid extraction, and ultrasonic-assisted extraction. The benefits emphasised for these novel techniques include a decrease in the duration of the extraction process, an enhancement in the extraction efficiency, and a reduction in energy usage. Numerous studies have provided detailed accounts of the chemical compositions of various essential oils. The analysis of chemical composition is commonly conducted using GC and GC–MS (gas chromatography and gas chromatography-mass spectrometry) techniques (Salzer and Furia 1977). The determination of the components present in essential oils can also be accomplished by employing nuclear magnetic resonance (NMR) techniques, as demonstrated by (Tomi et al. 1995).

Intraspecies, the essential oil's chemical composition can exhibit variation, leading to the categorization of chemical races or chemotypes. The observed phenomenon can be classified as a chemical polymorphism, wherein a species exhibits homogeneity in its karyotype while simultaneously producing essential oils with varying compositions. The inhibitory effects of volatile plant extracts derived from *Cymbopogon citratus*, *Zataria multiflora Boiss*, *Cinnamomun zeylanicum* J.Presl., *Malaleuca alternifolia* (Maiden and Betche) Cheel, *Origanum vulgare L.*, *Thymus vulgaris L*, and their bioactive compounds such as carvacrol, menthol, anisaldehyde, and thymol have been scientifically demonstrated to effectively suppress the growth of moulds and their associated toxins (Donato et al. 2020). The antibacterial properties of terpenoid compounds present in the essential oil of C. citrus have been extensively investigated in prior studies. These compounds include citral, neral (β-citral), geranial (α-citral), cinnamaldehyde, 1,8-cineole, linalool, and eugenol. The compound myrcene exhibited no activity, but its presence enhanced the activity of neral and geranial. Essential oils are recognised for their inherent antiseptic and antimicrobial characteristics. Numerous entities possess properties that are antitoxic, antiparasitic, antioxidant, antiviral, and antivenomous in nature. In more recent times, it has been established that they also possess properties that exhibit anticancer effects. The biological efficacy of an essential oil is determined by its chemical composition and any potential synergistic interactions among its constituents. The value of the substance is attributed to its various components, rather than solely relying on its predominant compounds. As per the findings of (Wu et al. 2022), essential oils and their bioactive constituents exert their effects on microorganisms through various mechanisms. These include the inhibition of cell wall synthesis, induction of mitochondrial dysfunction, disruption of cell membrane integrity, suppression of efflux pumps, modulation of respiration and microbial energy metabolism, as well as interference with genetic material.

3 Applications in Food Products

3.1 *Essential Oil as Antimicrobials*

In recent decades, there has been a notable focus on the exploration, production, and examination of essential oils, as well as their utilization across various fields. The growing concern regarding the use of industrially synthesised food antimicrobials has sparked a surge in the exploration of naturally occurring compounds as potential alternatives. Consequently, there has been an emergence of literature discussing the utilisation of essential oils as natural antimicrobial agents for the preservation of food (Gyawali and Ibrahim 2014; Mahian and Sani 2016; Pandey et al. 2017). Bio preservatives have the potential to serve as substitutes for conventional chemical food additives in various food products, thereby enhancing their microbial stability. The utilisation of various verities of spices and herbs to enhance the longevity of food products is a well-established practise, rooted in the recognised antimicrobial properties exhibited by these natural substances. Therefore, it is plausible that essential oils and their constituents, which are presently employed as food flavourings, possess the potential to function as food preservatives owing to antimicrobial properties. This is especially significant considering that the majority of these substances are classified as Generally Recognised as Safe (GRAS) by the U.S. Code of Federal Regulations, 2016. Additionally, their utilisation in minute quantities is feasible owing to their exceptional efficacy.

Essential oils are recognised for their antimicrobial properties against a diverse range of microorganisms and are derived from the volatile and aromatic components of a plant's secondary metabolism. The antimicrobial properties exhibited by essential oils are intricately associated with the presence of their bioactive volatile constituents. Globally, there is an increasing requirement of natural food preservatives and advancements in the food packaging within the food industry. The utilization of essential oils and their constituents in a variety of food products, including dairy, bread, meat, and vegetable products, has been observed as a means to effectively combat foodborne pathogens. To date, a considerable number of recent review articles have concentrated on evaluating the effectiveness of essential oils in combating bacterial pathogens commonly found in food products (Mendonca et al. 2018; Pandey et al. 2017; Pisoschi et al. 2018). However, the food industry has implemented only a limited number of preservation applications that rely on the utilisation of essential oils thus far.

3.2 *Antioxidant Action of Essential Oils*

In the context of the food industry, an antioxidant can be defined as a compound possessing the capacity to engage with radicals or hinder the process of oxidation in substances that are prone to oxidation, such as polyunsaturated fats. These effects can be observed even when antioxidants are utilised in relatively low concentrations, ranging from 1 to 1000 mg/L. ROs (Reactive oxygen species) are implicated in the occurrence of oxidative stress, resulting in detrimental effects on various cellular components including DNA and cell membranes. As a result, the occurrence of reactive oxygen species (ROS) has been linked to the onset and progression of various diseases, including but not limited to Parkinson's disease, cardiovascular diseases, multiple sclerosis, Alzheimer's disease, cancer, and cardiac failure cognitive impairment. There has been an increasing inclination within the food industry to investigate natural and economically viable antioxidants sourced from plants. This interest stems from the desire to replace synthetic antioxidants such as tert-butyl hydroquinone, butylated hydroxyl toluene, propyl gallate, and butylated hydroxyl anisole due to their adverse health effects (Botterweck et al. 2000). The predominant types of natural antioxidants consist of terpenolic and phenolic compounds, with notable categories including flavonoids, phenolic acids, and tocopherols. The hydroxyl group in phenolics forms a covalent bond with the carbon atom of the aromatic ring. This hydroxyl group functions as a hydrogen donor to free radicals, consequently impeding the oxidation process of other compounds. Multiple studies have demonstrated that essential oils and their constituents possess inherent antioxidant properties, exhibiting diverse mechanisms of action including scavenging of free radicals, hindrance of chain initiation, acting as reducing agents, quenching of singlet oxygen, termination of peroxides, and binding of the metal ion catalysts. The predominant type of fats present in food is triglyceride, which serves as the primary substrate for oxidation. The process of oxidation deterioration, known as autoxidation, refers to the oxidative reactions between atmospheric oxygen and lipids in a spontaneous manner. This phenomenon is widely recognised as significant and prevalent in various contexts.

Oxidation is a significant factor in the deterioration of food, leading to unfavourable alterations in sensory characteristics, nutritional quality, food value, and the generation of potentially harmful compounds within food products. Food that has undergone significant oxidation exhibits significant flaws and lacks consumer acceptability. The occurrence of oxidation in food processing as well as storage can be observed through changes in appearance, alterations in colour, modifications in texture, and the development of undesirable flavours. However, the changes in the principal components of food, such as lipids, carbohydrates, and proteins, are not consistently evident. The oxidation process of the substance takes place through a radical-chain mechanism facilitated by peroxyl radicals, which is analogous to the autoxidation process observed in hydrocarbons.

Oxygenated monoterpenes, such as esters, ketones, and aldehydes, are present in high quantities in essential oils obtained from conventional plant sources, including *Ziziphora clinopodioides, Anethum rutifolia, Achillea filipendulina, Galagania fragrantissima, Mentha longifolia, Anethum graveolens,* and *Hyssopuss spp* (Bhavaniramya et al. 2019). Furthermore, the essential oils derived from Nigella sativa seeds exhibit potent antioxidant properties in laboratory settings, demonstrating remarkable efficacy in scavenging hydroxyl radicals. Kanuka (Kunzeaericoides), *Leptospermum petersonii*, and Manuka (*Leptospermum scoparium*) have been found to possess antimicrobial as well as antioxidant properties, as described by (Amorati et al. 2013). The essential oils derived from *Megalaima armillaris* exhibit a significant level of antioxidant activity. The activity of the subject is associated with the presence of phenolic acids, which possess significant redox properties and play crucial roles in the neutralisation of free radicals and the breakdown of peroxides.

3.3 Applications in Meat-Based Foodstuffs and Seafood Products

Meat products possess favourable characteristics that make them conducive to the growth and proliferation of food spoilage and pathogenic bacteria. These characteristics include a neutral pH, a nutrient-rich composition, and appropriate water activity. In contemporary times, the meat industry employs chemical additives during various meat processing procedures with the intention of inhibiting the proliferation of foodborne pathogens and prolonging the duration for which the meat can be stored under refrigeration. Considerable attention has been directed towards exploring the potential application of plant-derived essential oils as a more secure alternative for enhancing the preservation of meat products. Therefore, certain herbs and spices, including thyme, marjoram, oregano, and rosemary, have been employed as aromatic agents in the preparation of meats. According to (Bevilacqua et al. 2010), eugenol and oils derived from coriander, clove, oregano, and thyme have demonstrated significant efficacy in suppressing indigenous spoilage microorganisms and pathogens in meat and meat products applications. In a previous study conducted by (Lemay et al. 2002), the antimicrobial properties of natural preservatives in chicken meat were investigated. The study revealed that the utilization of essential oil derived from mustard led to a notable decrease in lactic acid bacteria and aerobic mesophilic bacteria in comparison to the control group, particularly following a storage duration of 2 days.

In their study, (Chouliara et al. 2007) examined the combined impact of essential oil of oregano, which is known for its high levels of carvacrol and thymol, and modified atmosphere packaging on the prolongation of the storage duration of fresh chicken meat. The meat samples were stored at 4 °C temperature. The growth of lactic acid bacteria, pseudomonads, yeasts, *Enterobacteriaceae,* and *Brochothrix thermosphacta* was observed to be reduced, resulting in an improvement in population control. A significantly limited level of lipid oxidation was observed. However, the results of sensory analyses indicated that the inclusion of 1% oregano oil resulted in a significantly intense taste in the product. On the other hand, samples consisting of 0.1% oregano oil exhibited a distinct and desirable aroma and taste in chicken meat, which closely resembled the flavour of cooked chicken. The study conducted by (Oussalah et al. 2006) revealed intriguing findings regarding the utilisation of oregano essential oil in minced beef. The incorporation of oregano essential oil was found to effectively preserve the microbiological quality of the meat and mitigate the oxidation of fat, even during extended periods of storage. In order to optimise the efficiency of essential oils, have implemented a method of stabilising the essential oils within edible polymers such as biofilm, coating, capsule, and emulsion. This technique facilitates the dispersion of the essential oils into the food product during the storage period. The utilisation of biofilms incorporating essential oils on meat slices resulted in a substantial reduction in the proliferation of pathogenic bacteria during storage periods exceeding one week.

In a study conducted by (Bukvički et al. 2014), the researchers examined the impact of *Saturejahorvatii* essential oils on a ground pork product. The findings revealed a noteworthy suppression of Listeria monocytogenes, which had been introduced into the meat. The assessment of the antimicrobial efficacy of bay leaf essential oil was conducted on fresh Tuscan sausage, which was stored at a temperature of 7 °C for a period of 14 days done by (Da Silveira et al. 2014). The efficacy of the essential oil was demonstrated in its ability to significantly decrease the population of total coliforms by approximately three logarithmic colony forming units per gramme (log CFU/g) and subsequently prolong the shelf-life of the product by a duration of two days. In the present study, the effects of essential oil on the sensory attributes of sausage were evaluated. Despite these effects, consumer satisfaction was observed, leading to the suggestion of incorporating essential oil into fresh Tuscan sausage. This incorporation serves the dual purpose of enhancing safety and prolonging the shelf-life of the product. The effectiveness of essential oils in combating bacteria that cause foodborne illnesses is contingent upon their interactions with various components present in food. (Singh et al. 2003) conducted a study which revealed that thyme oil exhibited a significant reduction in the bacterial population of L. *monocytogenes* in low-fat hotdogs but did not demonstrate the same effect in full-fat hotdogs. In a study conducted by (Bevilacqua et al. 2010), it was observed that the impact of oregano oil on *Photobacterium phosphoreum* was more pronounced when applied to cod fillets compared to salmon, which is classified as a fatty fish. The presence of a significant amount of fat has been observed to significantly diminish the efficacy of essential oils in fish and meat products.

3.4 Application in Milk and Dairy Products

Previous research has demonstrated the antioxidant properties of milk and its fractions. Essential oils can be incorporated into milk as well as dairy products through the addition of drops or by spray. For instance, (Ben Jemaa et al. 2017) demonstrated that the utilisation of essential oil extracted from *Thymus capitatus* or its nano emulsion resulted in enhanced oxidative capacity, improved physico-chemical and microbiological characteristics, and increased fermentation stability of UHT processed skimmed milk. Furthermore, the addition of essential oils such as oregano, Cordobes, and Criollo into cottage cheese has been found to result in a reduced level of chemical deterioration. This effect is particularly evident during the preservation and storage of polyunsaturated fatty acids, as they are protected from oxidation.

3.5 Fish and Fishery Products

These products exhibit a heightened susceptibility to oxidation, particularly in species that possess elevated concentrations of polyunsaturated fatty acids. The process of oxidation has been found to have an impact on the nutritional composition of food, leading to changes in taste, texture, and colour (Secci and Parisi 2016). A comprehensive review of literature has been undertaken to investigate the potential role of essential oils as antioxidants. Therefore, the efficacy of cinnamaldehyde at concentrations of 1 and 5 g/kg in the preservation and enhancement of white prawn quality at a temperature of 4 °C has been demonstrated. According to (Patel 2015), this particular molecule has the ability to decrease the remaining enzymatic activity of polyphenoloxidase, resulting in enhancement of the food's shelf life by a duration of eight days. Additionally, the molecule also enhances the sensory characteristics of the food, thereby improving its overall quality. In addition, the utilisation of laurel and oregano essential oils was found to decrease lipid oxidation in frozen chub mackerel burgers, as demonstrated by the study conducted by (Ozogul and Uçar 2013). Furthermore, (Veeck et al. 2013) discovered that the utilization of Lippie alba essential oil exhibited a favorable impact on the preservation of lipid stability in silver catfish fillets during storage at a temperature of –18 °C.

3.6 Application in Fruits and Vegetables

In contrast to meats, vegetables typically possess a relatively low-fat components, which has been suggested to play a role in the favourable outcomes observed with essential oils. In addition, it has been observed that reducing storage temperature and adjusting pH levels can augment the antimicrobial efficacy of essential oils. Numerous studies have been conducted on vegetables to investigate the effectiveness of essential oils and their constituents against the foodborne pathogens and natural spoilage flora. These studies have provided evidence of the efficacy of essential oils in combating these microorganisms. (Roller and Seedhar 2002) conducted a study wherein they demonstrated that the application of a 1 mM concentration of cinnamic or carvacrol acid effectively retards the spoilage process of fresh-cut melon and kiwifruit when subjected to freezing temperatures. Importantly, this treatment was found to have no negative impact on the sensory attributes of the fruits. According to a study conducted by (Raybaudi-Massilia et al. 2006), the efficacy of lemongrass and geraniol in combating *Salmonella sp., Listeria spp, and E. coli.* in pear, melon, and apple juices has been established. In a previous investigation, a comprehensive analysis was conducted to evaluate the antibacterial efficacy of 17 distinct plant essential oils and 9 oil compounds against the foodborne pathogens *S. enterica* and *E. coli* O157:H7 in apple juices. The compounds that exhibited the highest level of activity were oregano oil, carvacrol, geraniol, citral, lemon oil, cinnamon, and lemongrass oil. The enzymatic activity exhibited by *S. enterica* was found to be higher compared to that of *E. coli*. Furthermore, this activity was observed to increase with both the temperature of incubation and the duration of storage. Interestingly, the acidity levels of the juices did not have any significant impact on the enzymatic activity. The antifungal activity of essential oils derived from summer savoury, thyme, and clove was assessed by various researchers. The evaluation was conducted over a period of two months, and the target fungus was *Aspergillus flavus*. The essential oils exhibited antifungal properties, effectively impeding the growth of mould. Notably, thyme oil and summer savoury demonstrated particularly strong inhibitory effects. A taste panel evaluation, conducted using a tomato ketchup base, received positive acceptance from the panellists.

3.7 Application in Cereal Products

Essential oils possess the capacity to serve as a viable means of food preservation in the context of cereals. Cereal crops are susceptible to infection by various fungal pathogens. This research study aimed to investigate the effectiveness of essential oils obtained from a diverse range of five distinct species of food and medicinal plants. The efficacy of these essential oils was evaluated against five pathogenic fungal species that are recognized for their ability to induce diseases in cereal crops, with a particular impact on the stems, leaves, and ears. The present study employed essential oils derived from *Thymus vulgaris*, *Pimpinella anisum, Pelargonium odoratissimum, Foeniculum vulgare*, and *Rosmarinus officinalis*. These Essential oils were subsequently administered to the fungal species *Microdochiumnivale, Oculimaculayallundae, Zymoseptoriatritici, Fusarium culmorum,* and *Pyrenophora teres*. The application of various essential oils had an impact on the growth of the fungi under investigation. Among the essential oils tested, it was found that *T. vulgaris* exhibited the most potent antifungal activity. Due to the adverse consequences associated with the extensive utilisation of pesticides, such as the emergence of toxicity concerns, pest resistance, and detrimental impacts on the environment as well as human health, the adoption of botanical pesticides seems to present a viable substitute. The utilisation of essential oils derived from plants presents a potential solution for replacing chemical fungicides in order to safeguard cereal crops.

3.8 Aromatherapy

The utilisation of essential oils as a prominent therapeutic modality for the management of diverse medical conditions constitutes the fundamental concept of aromatherapy, a practise that is experiencing significant global expansion. This product provides relief from stress and pain associated with indigestion, depression, muscular pain, headaches, and various skin ailments. The utilisation of these oils is increasingly prevalent in the management of sleep disorders and cancer. The market for aromatic cleaning products in the realm of personal care and hygiene is experiencing growth. These products include soaps, perfumes, cosmetics, room fresheners, and air fresheners. Among the various options available, peppermint, tea tree oil, rosemary, lemon, and lavender are widely recognised as the most popular choices worldwide. The utilization of rosemary and lavender essential oils is prevalent within the realm of aromatherapy (Lizarraga-Valderrama 2021). Aromatherapy is a therapeutic practise that involves the utilisation of the fragrances or smells of essential oils for the treatment of serval diseases. The act of soothing an individual's body, soul, and mind is an inherent and instinctive practise. The historical origins of this technique can be attributed to ancient civilizations, including India, China, and Egypt, where it was extensively utilized as a prominent modality for fostering equilibrium and alternative forms of healing. Subsequently, the resurgence of interest in this practise occurred following the re-evaluation of the antiseptic qualities of essential oils by scientific researchers. Essential oils are commonly utilised in aromatherapy through inhalation, topical application, and incorporation in baths. These methods facilitate the absorption of the oil into the surface of the human skin. Upon the introduction of oil into the system, it undergoes a process of self-modulation in order to exhibit desirable behaviour at the designated location or over the affected region. The primary location where these essential oils exert their effects is the brain, which elicits a dynamic response via the olfactory nerves (Lai et al. 2011). According to (Ali et al. 2015), these substances possess a high level of potency and concentration, enabling them to directly target pressure points and facilitate rejuvenation. The stimulating action of these substances is derived from their structural similarity to natural hormones (Ali et al. 2015). Their effects are diverse and difficult to ascertain due to their intricate composition (Lizarraga-Valderrama 2021).

The utilization of essential oils as inhalants, such as eucalyptus oil, has been recognized for its potential benefits. Peppermint oil can be taken orally, while rosemary oil, lavender oil, and thymol oil can be used as gargles or mouth rinses. These oils are also employed as aromatherapeutic agents. These are also employed as a cognitive enhancer in the field of psycho-aromatherapy. There are various oils that possess properties that induce relaxation and soothe, while others have stimulating effects that can aid in the reduction of anxiety. According to (Pearson et al. 2019), the act of inhaling essential oils has been associated with enhanced emotional well-being, increased serenity, relaxation, and revitalization of the human body. Furthermore, research has indicated that the utilisation of grape seed, almond, or jojoba oil during massage therapy has demonstrated remarkable results. The incorporation of essential oils in facial cosmetics has the potential to contribute to the improvement of skin health. This therapeutic approach involves the utilisation of essential oils in skincare products, including those designed for the body, face, and hair, to perform various functions such as cleansing, moisturising, toning, and drying (Pearson et al. 2019). The practise of cosmetic aromatherapy encompasses the utilisation of essential oils in cosmetic formulations designed for the enhancement and maintenance of the skin, hair, body, and face. These oils serve as effective components in various cosmetic products used for cleansing, toning, and moisturising purposes. A small quantity of the suitable oil has been found to offer a rejuvenating and revitalising experience for the entire body. According to (Chang 2008), the incorporation of grape seed, almond, jojoba, or other pure vegetable oils during massage therapy is believed to have a therapeutic effect. Aromatherapy in the medical field is a contemporary practise that involves the utilisation of essential oils for the purpose of massaging patients during surgical procedures and for the treatment of medically diagnosed ailment. The efficacy of these essential oils in the management of diverse neurologic disorders, mood disorders, and pain has been established. Essential oils have the potential to effectively alleviate pain in vulnerable patients who experience numerous side effects from alternative medications. Olfactory aromatherapy refers to the practise of inhaling essential oils in order to promote emotional well-being, induce relaxation, foster a sense of calmness, or facilitate rejuvenation of the human body. The alleviation of stress is also associated with pleasurable aromas. In the field of psycho-aromatherapy, it is possible to modify moods and emotions through the use of essential oils, thereby inducing sensations of relaxation, invigoration, or evoking pleasant memories. The medical practitioners administered a solution within the confines of the patients' room, intended for inhalation, which resulted in a direct impact on their cognitive faculties. The following is a compilation of several commonly utilised plant species in the practise of aromatherapy.

4 Other Applications in Food Industry

In addition to its extensive utilisation as an antioxidant agent, essential oil finds application in various other capacities within the realm of food products, such as flavouring, fragrance enhancement, and as a crucial component of active packaging.

- ***The utilisation of essential oils in the preparation of savoury dishes***

Thyme, rosemary, oregano, asafoetida, and marjoram essential oil are commonly employed in the culinary preparation of curries, meatballs, pickles, and other savoury dishes with the intention of enhancing their umami flavour.

- ***The utilisation of essential oils in the context of organic food processing***

The essential oils derived from oregano, cinnamon, and thymus possess antibacterial and antioxidant properties, making them potentially valuable for application in the meat industry. These oils can be used in products such as cooked gammon, minced beef, and dry-cured sausage. Additionally, lavender and bergamot essential oils are utilised as flavouring agents in chocolate and also in chocolate coating, specifically in candy melts (Muriel-Galet et al. 2012).

- ***The utilisation of essential oils as additives in food products***

The incorporation of citrus, Chinese cinnamon, and turmeric essential oils has been employed as supplementary components in the production of biodegradable coatings and films for the purpose of active food packaging. The antimicrobial and antioxidant properties of coatings and films are contingent upon their composition and interactions with the polymer matrix.

- ***The utilisation of essential oils in the baking industry***

Peppermint and clove essential oils possess a highly potent aroma and are employed as a flavouring agent within the baking industry, specifically in the production of candies, cakes, and baked goods.

- ***The utilisation of essential oils in active food packaging***

Polymers with biodegradable and edible coatings have the capability to encapsulate essential oils, allowing for a controlled and gradual release onto the surface of food materials to be packed such as fruits, meats, and fish. This methodology enhances the stability of volatile constituents, thereby safeguarding them against potential interactions with the food matrix, while also augmenting their antimicrobial efficacy.

- ***The incorporation of essential oils into beverages***

Lemon-lime sodas incorporate essential oils derived from lime, lemon, orange, and neroli as primary flavourings. Additionally, vanilla essential oils are employed as flavouring agents in soft beverages. *Stevia rebaudiana*, commonly known as stevia, is a plant species that possesses leaves containing a variety of essential oils with a sweet taste, which can be utilised for the purpose of sweetening beverages. Essential oils derived from various plant species are commonly employed as flavouring agents in the food and beverage industry.

5 Essential Oil-Based Pesticides for Food Plant Production

Food products, including fruits, grains, and other materials containing cellulose, are susceptible to infestation by pests, particularly arthropods. However, it is possible to protect these products by inhibiting the detrimental actions of these insects and arthropods. The present study aims to explore the burgeoning interest in essential oils as a result of their remarkable pesticidal properties, which encompass antifungal, antibacterial, antiviral, insect repellent, insecticidal, and deterrent activities (Pisoschi et al. 2018). Due to their inherent hydrophobic and lipophilic properties, these substances disrupt fundamental metabolic, biochemical, behavioural, and physiological processes in insects. Essential oils are frequently utilised through inhalation, ingestion, or skin absorption by insects, resulting in their efficient transmission across cell membranes' lipid bilayer. The present study investigates the impact of a specific transmission of ion transport, cellular material leakage, proton motive force-mediated electron flow, and the subsequent demise of the pest. The diverse range of bioefficacy and detoxifying properties exhibited by essential oils has led to the exploration of their potential as pesticides. Fumigants, granular formulations, and direct sprays are among the applications for these substances. They exhibit a range of effects on insects, including high repellence, deterrence, and toxicity. The literature study has demonstrated the effectiveness of essential oils derived from various plant species, including Mentha, Thymus, Rosmarinus, Artemisia, Salvia, Limnophila, and others, in combating numerous arthropod species such as bihar hairy caterpillars, aphids, cabbage looper, leaf rollers, diamondback moth, silverleaf whitefly, and others. These arthropods pose a significant threat to horticultural crops and stored grain.

6 Conclusion

The essential oils possess significant antioxidant potential, which could potentially support their utilisation as natural preservatives within the food industry, thereby replacing synthetic chemical preservatives. Essential oils possess extensive utility within various sectors, including the food, pharmaceutical, incense, perfume, and cosmetic industries. The utilization of diverse essential oils and their unique bioactive phytoconstituents has gained significant attention in the field of natural antimicrobial agents, antioxidants, preservatives, and insect repellents to mitigate the deleterious effects of oxidative degradation, microbial contamination, pathogenic organisms, and insect infestation in food commodities. Topically applied essential oils are commonly utilised for pain relief purposes. Moreover, essential oils are widely utilized for the treatment of diverse ailments and conditions, including but not limited to anxiety, oxidative stress, inflammation, wound healing, depression, cancer, microbial as well as parasitic infection, and fungal infection. Currently, the growing understanding and recognition of the chemical composition and physiological effects of essential oils, leading to advancements in their utilization for a range of purposes, particularly in relation to human health. These advancements expand the therapeutic uses of essential oils in the treatment and control of a wide range of medical conditions. Hence, the market for essential oils is experiencing rapid growth and increasing in significance on a daily basis. However, it is imperative to conduct additional scientific research and clinical studies in order to determine the optimal dosage, actual effectiveness, toxicology and safety, of various essential oils.

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A Novel Sustainable Approach for Extraction of Pectin from Citrus and Dairy Waste

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Abstract Pectin is a food hydrocolloid utilized in the food and pharmaceutical industries as a gelling, emulsifying, thickening, and stabilizing agent. It has therapeutic purposes, and the soluble fiber is used to treat conditions including high blood pressure, digestive issues, high cholesterol, and others. Peels from citrus fruits are a key source of pectin. The goal of the study was to investigate the biotechnological pathway for pectin extraction from lemon peels and whey, a byproduct of the dairy sector. Whey was applied to dried, defatted lemon peel powder under three distinct settings: pH, temperature, and time. The conditions were 10, 24, and 40 °C at pH, 3.5, 4.5, and 5.5, and 4, 12, and 24 h, respectively. At pH 4.5, 24 °C, and 4 h of soaking, the maximum methyl concentration of 7.8% was attained. Additionally, sterile whey and water were used for the extraction, which was then contrasted with the acid hydrolysis procedure. The amount of yield, equivalent weight, percent methoxyl content, molecular weight, anhydrouronic acid, ash, and moisture were all measured for the pectin that was produced utilizing these procedures. The outcomes demonstrated that whey or sterile whey can be used to extract pectin of high grade. The study may open the door for pectin manufacture using affordable green technology.

Keywords Pectin · Citrus waste · Whey · Methoxyl content · Acid hydrolysis method

1 Introduction

India is recognized as the largest producer of milk and 2nd largest producer of fruits and producer of vegetables in the world (MoFPI 2023). This has been achieved because of varied soil and climatic conditions from temperate to subtropical and tropical. Its share to world production of milk is 24%, fruits is 10.9% and that of vegetables is 8.6% (FAO 2023). In 2021–22, India produced 210 MMT of milk, 107.24 MMT of fruits and 204.84 MMT of vegetables. Mango, banana, papaya, orange,

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mosambi (sweet orange), guava, grapes, apples, pineapple, sapota, ber, pomegranate, strawberry and litchi, etc. are the major fruits grown in India. Fruits and vegetables processing industry contribute a major share in fruit processing industry at global level. Although India is the world's largest producer of fruits, less than 3% of the production is commercially processed.

Food processing industrial operations produce big volumes of solid and liquid wastes. These wastes pose increasing disposal and potentially severe pollution problems and represent a loss of valuable biomass and nutrients (Khedkar and Singh 2018). Sustainable industrial development needs due consideration to proper utilization and disposal of solid waste.

2 Holistic Concept for Utilization of Fruit &Vegetables Processing

Environmental concerns can be addressed through the concept of 4-R, comprising of reduce, reuse, recycle and recover in industrial waste management. The holistic concept of food production includes product quality, production efficiency and environmental protection (Fig. 1). The recycling of residues for value addition has got importance to make the units sustainable. The goal of green productivity could 'be achieved through zero discharge, zero emission, zero pollution, cost effective processing and application of clean production technology.

Fruits and vegetables are highly perishable in nature. Their production is increasing globally due to increasing demand of the rising population. Huge amount of wastage occurs during the production, harvesting, processing, distribution and consumption of these fruits and vegetables. After processing of fruits and vegetables, around 10–60% of the produce is wasted as non-edible part such as peels, seeds, pods, skin etc. The waste is rich in organic matter and bioactive compounds having medicinal properties and industrial uses. The by -products of the fruit and vegetable waste can be utilized for the production of natural colours (Thakur and Modi 2022), pectin, essential oil, feed and fodder etc. They can also be used in the processes for manufacture of organic acids, enzymes, ethanol (Khedkar and Zahid 2022). Composting, biogas, developing functional foods are some of the strategies for reusing and recycling of the waste (Khedkar and Singh 2014) (Fig. 2).

3 Citrus Fruit Production

Globally, the production of citrus fruits has experienced steady growth in the last decades of twentieth century. Total annual citrus production was estimated at over 161.8 million tons in the period 2021 (Gonzato and Santos 2023). Oranges make up the bulk of citrus fruit production, accounting for around 50% of global citrus

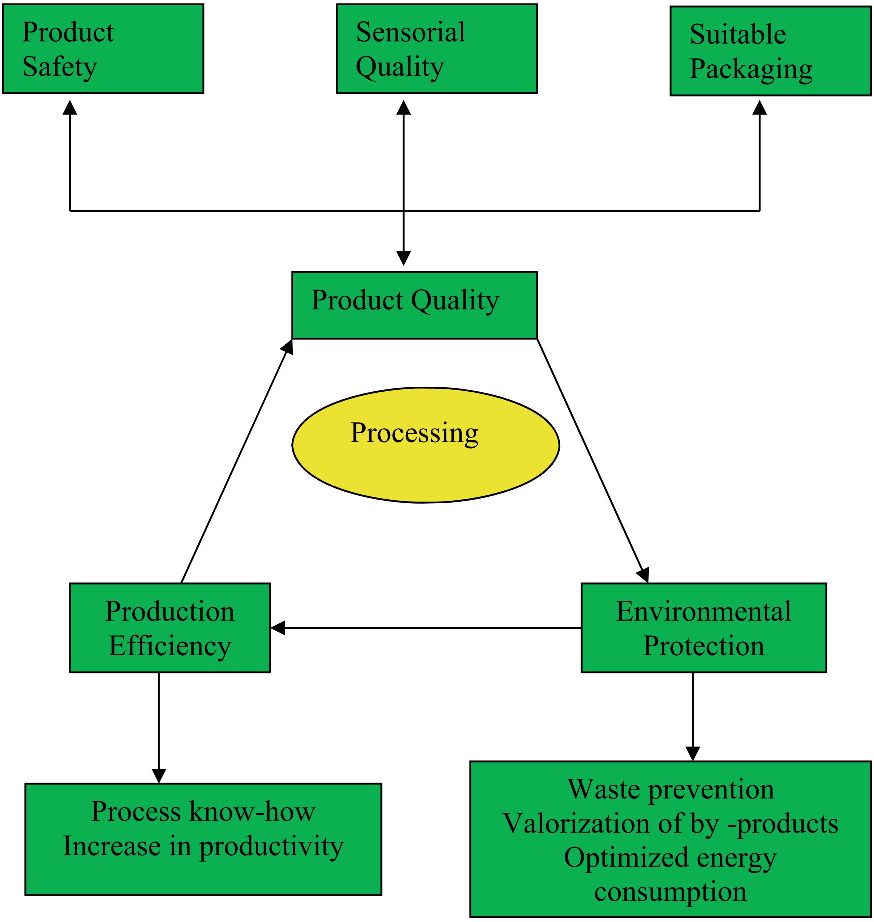


Fig. 1 Holistic concept of fruit and vegetable processing industries

production in 2020. The global increase in citrus production is nearly 5.5 times in last 60 years. Increase in the cultivation area and changing consumer preferences for healthier and convenient food coupled with rising income is mainly responsible for the rise in citrus fruit production. Citrus production in India was 14.8 million tons in 2021. India produces a number of varieties of citrus fruit including sweet oranges, Santra, kinnow, lemon, lime, Galgal, and Mosambi. Citrus fruits occupy 3rd position in volume after mango and banana in the production of fruits.

Lemon is the third most widely produced and traded citrus fruit in the world after oranges and tangerines. Global lemon and lime production amounted to 20.83 million metric tons and India is the largest producer with 3.4 million metric tons in 2021 (Statista 2021).

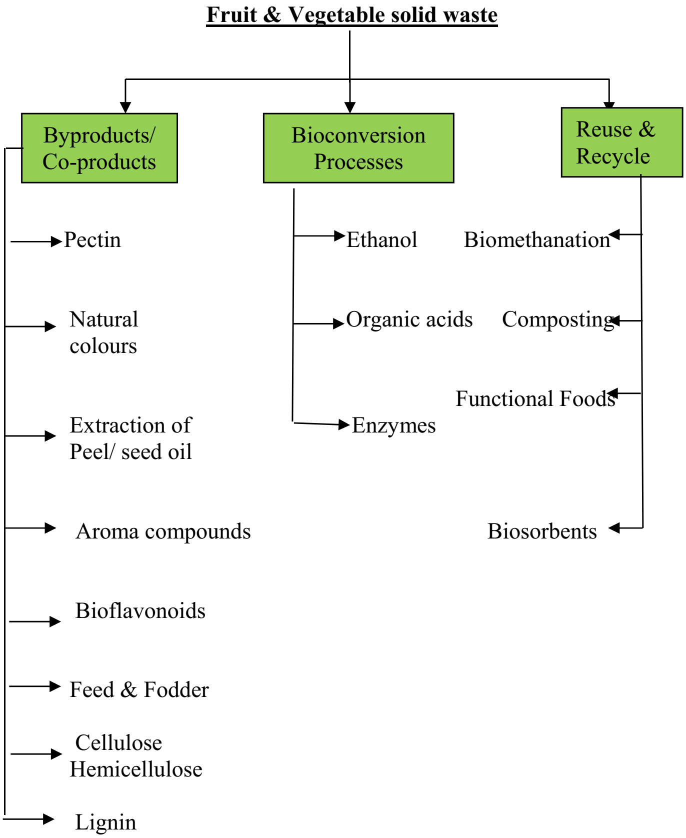


Fig. 2 Strategies for utilization of fruits and vegetable waste

3.1 Structure of Citrus Fruit

The mature citrus fruit has three clearly distinguishable parts shown in Fig. 3.

- Flavedo (7–8%): Flavedo is the outermost layer of the peel.
- Albedo (25–30%): Albedo is the cellulosic spongy layer under the flavedo.
- Segments (60–65%): The segments are the sacks containing the pulp.

3.2 Citrus Waste

Citrus peel is the by-product of lemon and orange juice processing. The peels constitute a valuable source of essential oils and pectin. The inner white spongy portion of the peel, the albedo is rich in pectin and the outer colored portion, the flavedo has glands containing essential oil. Oil content varies between 1.8 and 9.7 kg/ton of the

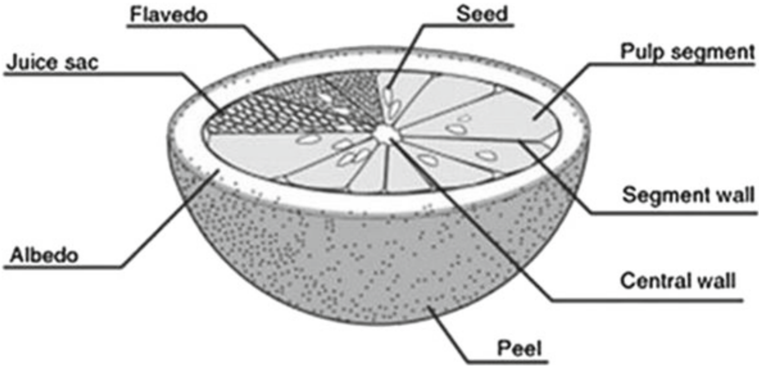


Fig. 3 Structure of citrus fruit (Mamma and Christakopoulos 2014)

peel. Flavonoids are also present in this part. Bitter orange peels contain hesperidin, isohesperidin, aurantiamarin-a crystalline acid and an amorphous resinous body. The bitter principle is mainly concentrated in the spongy portion from the juice of citrus-the limonin. A glycoside citrin has been obtained which appears to be a mixture of hesperidin, eriobictyol glycoside and quercitrin. Hesperidine chalcone is said to afford protection against capillary fragility. The peels of citrus reticulata, and citrus sinensis contain a water-soluble pigment, a carotenoid, phytosterolin and phytosterols. Palmitic, stearic, oleic, linolic and linolenic acids are also present. (The Wealth of India 1990). Citrus waste is a rich source of antioxidants such as flavonoids, ascorbic acid, phenolic compounds and pectin. These bioactive compounds offer health benefits to human population (Mhgub et al. 2018).

4 Dairy Waste

Whey, a waste from cheese-making and casein industry, exerts a substantial burden on waste disposal plants due to its high BOD but it also contains high nutritional value. Globally, around 180 to 190 × 10^6 tons per year whey is produced. Whey treatment is a serious problem due to its high chemical oxygen demand (COD) of 100, 000 $mgO_2\ L^{-1}$. Whey contains around half of the solids present in the milk, which includes whey proteins, lactose, minerals and water-soluble vitamins. About 50% of total world cheese-whey production is now treated and transformed into various food products, of which, in the EEC, about 45% has been reported to be directly in liquid form, 30% in the form of powdered cheese-whey, 15% as lactose and delactosed byproducts, and the rest as cheese-whey protein concentrate (Marwah and Kennedy 1988; Baldasso et al. 2011). Continuing research in the field of whey utilization has resulted in a variety of new whey products. The valuable characteristics of whey has made it possible to use it for biotechnologies for production of biofuels and biochemicals of importance.

Donaghy and McKay (1994) used sweet whey as a complete medium for the production of polygalacturonase by the yeast *K. fragilis.* The polygalacturonase was used for pectin extraction from orange peel. Higher extraction of pectin was obtained at 37 °C as compared to 25°Cover a 24 h period. It was observed that pectin liberation was reduced when the water: peel ratio was less than 12:1.

5 Pectin

Pectin is a water soluble anionic biopolymer of commercial importance. The global pectin market estimated at $1 billion in 2019 is expected to reach $1.5billion in 2025 (Pectin Market 2019). Pectin is a safe, non-toxic product with easy availability and low cost and therefore, has wide applications in food and pharmaceutical industry. It is a gelling, thickening, emulsifying, stabilizing and texturizing agent used in making of jams, jellies, fruit juices, desserts and dairy products. In the food industry, pectin is also used to produce packaging materials and edible coatings (Freitas et al. 2021; Khedkar and Khedkar 2020; Khedkar and Zahid 2021).

5.1 Presence of Pectin in Plants

Cell walls of many higher plants is constituted with a large proportion of complex carbohydrates called pectin which plays a main role in growth, development and senescence. Pectin was first discovered by Bracannot in 1825 (Pectin 2023). Pectic substances fill the intercellular spaces in the middle lamella of plant tissue. In young tissues, especially in fruits, pectins are often formed in such large amounts that they form wide channels, pushing apart the cells.

5.2 Structure of Pectin

Pectic substances are high molecular weight, negatively charged, acidic, complex glycosidic macromolecules. The basic building block of these pectic substances is D-Galacturonic acid. Pectin is composed of several structural elements rich in homogalacturonans (HGs) (65%) and rhamnogalacturonans I (RGs-I) (20–35%) while rhamnogalacturonan II (RG-II) (<10%) is present in lesser amounts. HG is made of $(1 \rightarrow 4)$ linked α-D-Galacturonic acid residues that can be partly methyl esterified at C-6 and at times acetyl-esterified at O-2 and/or O-3 to produce low methoxylated (<50%) and high methoxylated (>50%) pectin (Schols and Voragen 2003). The degree of methylation (DM) and degree of acetylation (DAc) are defined as the percentage of GalA units esterified with methanol or acetic acid, respectively. RG-I is constituted of a repeating disaccharide unit [$\rightarrow$2)-α-L-Rhap -$(1 \rightarrow 4)$-α-D-GalpA-

(1 →] n. Rhamnosyl residues often carry neutral sugars side –chains. RG-II is HG backbone composed of GalA units having complex branches of monomers of rare sugars as apiose, fucose, aceric acid, DHA (Freitas et al. 2021).

The pectic substances are classified into **protopectin, pectic acid, pectinic acid & pectin** on the basis of the modifications of the backbone chain.

- ***Protopectin*:**—The main pectic substance occurring in plants is the water insoluble protopectin. On restricted hydrolysis, it produces pectin or pectinic acid (Fig. 4).
- ***Pectinic acid or Pectin*:**—These are the galacturonans (polygalacturonic acids) constituted of various amounts of methoxyl groups. The normal or acid salts of pectinic acids are called pectinates. Pectinic acid alone has the unique property of forming a gel with sugar and acid or, if suitably low in methyl content, with certain other compounds such as calcium salts and are also called pectins. The general term pectin is defined as those water soluble pectinic acids of differing methyl ester content and degree of neutralization and are capable of gel formation with sugar and acids under suitable conditions. Pectin used in food products is a polymer containing at least 65% galacturonic acid units. The acid groups may either be free, combined as a methyl ester or as sodium, potassium, calcium or ammonium salts and in some pectins amide groups may also be present (Alkorta et al. 1998).
- ***Pectic acid*:**—The galacturonans which are free from methyl ester groups. Pectates are the normal or acid salts of pectic acid.

Pectic substances are present in almost all plants but commercial manufacture of pectin has been possible only from few limited sources, which produce pectins having desirable yields and jellying characteristics. Pectic substances constitute around 0.5–4.0% of the fresh weight of plant material (Table 1).

Conventional sources—Citrus peels (85%) and apple pomace (14%). Table 1 shows the pectin content in different fruits and vegetables.

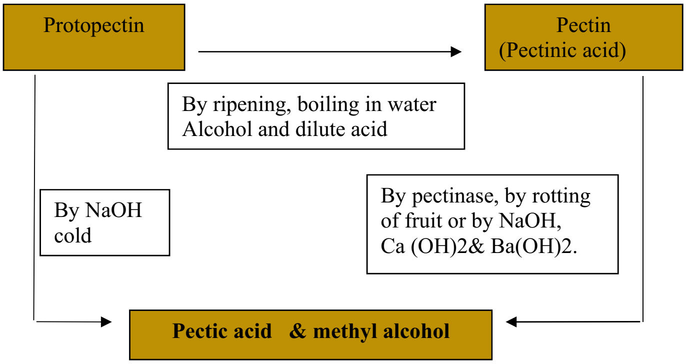


Fig. 4 Pectic substances from protopectin

Table 1 Pectin content in different fruits &vegetables (Sakai et al. 1993)

Fruits/vegetables	Tissue	Pectic substance (%)
Apple	Fresh	0.5–1.6
Banana	Fresh	0.7–1.2
Peaches	Fresh	0.1–0.9
Strawberries	Fresh	0.6–0.7
Cherries	Fresh	0.2–0.5
Peas	Fresh	0.9–1.4
Carrots	Dry matter	6.9–18.6
Orange pulp	Dry matter	12.4–28.0
Potatoes	Dry matter	1.8–3.3
Tomatoes	Dry matter	2.4–4.6
Sugarbeet pulp	Dry matter	10.0–30.0
Lime/Lemon peel	Dry matter	30–55
Papaya	Dry matter	10–13
Mango	Dry matter	12–16
Guava	Fresh	1.5–4.0

Unconventional sources—sugar beet, sunflower, guava, papaya, jackfruit, wood apple, passion fruit.

5.3 Functional Properties of Pectin

- Pectin molecules are long, easily entwine with each other and cause thickening. So, pectin is used for improving the texture of low sugar drinks.
- When sufficient quantity of sugar is added to bring down water availability for dissolution of pectin, the molecules cling to the smooth regions with ester groups for formation of gel network. This property is used in the preparation of high sugar jams.
- Changes in the acidity (pH) changes the amount of charge on the pectin chains as the acid groups are weak. Pectins, which can join together under acid conditions, repel each other at lower acidity or higher pH. So, it requires both sugar and acid for setting a jam or jelly.
- The calcium ions having two positive charges can join two acid anion groups in pectin with negative charges. If enough negative groups are present, as in low ester pectins, they link with pectin molecules together in a gel network without the need of so much sugar. Low ester pectins are used in the making of jams with low sugar, and many other fruit preparations for use in the food industry.
- Pectin molecules with a negative charge can stick to proteins with a positive charge and avert them from coagulating on heating. Pectins can prevent the milk

protein in yoghurt from curdling when heated, so ultra heat treated (UHT) long life yoghurt drinks can be prepared (Ciurzynska et al. 2016).

Functionality of pectins depends on the functional groups of pectins namely-carboxyl, methoxyl and amide groups, the molecular mass or length, distribution of the functional groups and degree of methylation. The physico-chemical properties of various citrus peel pectins have been presented in Table 2. Low ester pectins, which have a degree of esterification <50%, are able to form gels in the presence of small amounts of divalent cations, even though the percent of solids is very low. Low ester pectins do not require the presence of sugar for the formation of a gel as do the high ester pectins. They are used in the preparation of low solid salads and desserts, in pharmaceuticals, and also in dietetic foods, to reduce the calorie content and increase fibre content of desserts and sweets (Vanitha and Khan 2019).

Over the years the positive public connotation of pectin has proven helpful in its widespread use, and this may be a contributing factor to the growing interest in investigating pectin for possible direct health benefits and thus applications in regulated non-food segment as well as in functional foods and nutraceuticals. Pectin also finds medical and pharmaceutical applications.

Pectin has many medicinal benefits such as lowering cholesterol in blood, removal of heavy metal ions from the body, stabilizing the blood pressure and for improving the intestinal function (Ptichkina et al. 2008). It is also a source of dietary fiber. Pectin with clay kaolin (hydrated aluminum silicate) is used in the management of diarrhea. Pectin is used as a component in the adhesive part of ostomy rings and is also marketed as a nutritional supplement for the management of elevated cholesterol.

Different types of commercial pectins, according to their applications are given in Table 3.

Table 2 Physico-chemical Properties of citrus peel pectin (Shastri 2001)

Characteristics	Lime	Orange	Sweet orange	Grapefruit
Yield (%)	17.2	15.3	17.8	14.5
Moisture (%)	10.1	9.9	8.6	10.6
Ash (%)	2.82	2.97	2.85	3.2
Jelly grade	225	205	180	200
Setting time (min.)	1.0	5.0	5.0	4.0
Degee of esterification (%)	63.2	56.1	57.0	57.1
Equivalent weight	1452	969	859	940
Methoxyl (%)	8.62	7.60	7.73	7.40
Anhydrouronic content (%)	77.4	73.9	76.9	73.6
Acetyl (%)	0.32	0.46	0.35	0
Molecular wt	92,600	78,000	67,000	72,700
Intrinsic viscosity (cp)	4.4	3.7	3.2	3.4
Viscosity 0.5% Soln.(cp)	19.2	10.7	7.2	9.4

Table 3 Types of pectin and their applications (*Source* Technical Information 2023)

Type of pectin	Applications
Rapid set pectin	Jams and marmalades
Slow set pectin	Jellies and for some jams and preserves when using vacuum cooking at low temperature, bakery and biscuit jams, sugar confectionery
Stabilizing pectin	Yoghurts, whey and soya drinks
Low methyl ester and amidated pectin	Low sugar products, sugar preserves, fruit preparations for yoghurts, dessert gels and toppings, sauces, marinades, preserves containing low acid fruits (figs, bananas) and confectionery

6 Production of Pectin

Pectin can be produced by using the process of conventional acid hydrolysis. But this process is energy intensive and releases environmentally hazardous waste. Novel techniques of pectin production including Ultrasound Assisted extraction (UAE), Microwave assisted extraction (MAE), High Pressure Assisted Extraction (HPAE), Enzyme Assisted Extraction (EAE) and Microbial extraction of pectin have the potential to be less energy intensive and more environmentally friendly (Singhal and Swami Hulle 2022).

6.1 Conventional Acid Hydrolysis Method

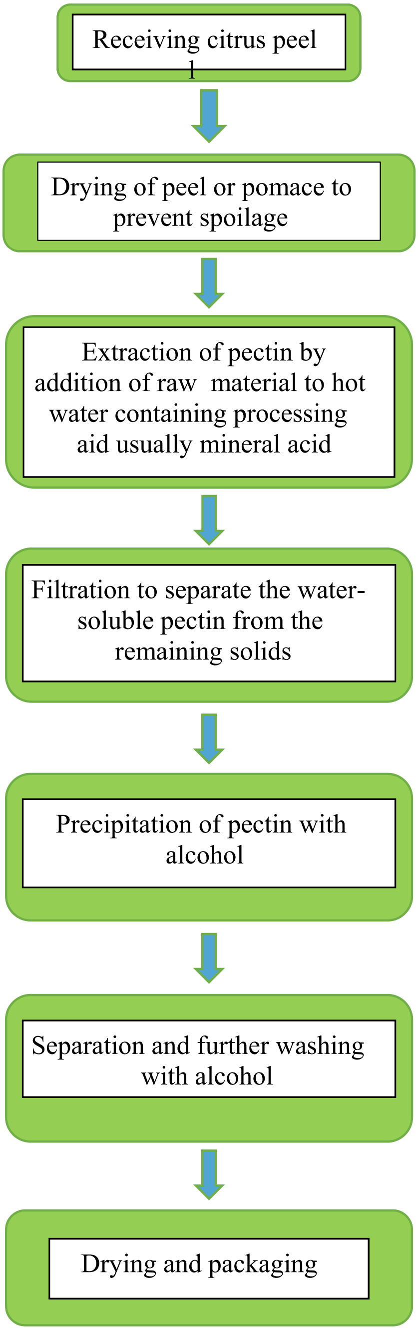
Process details vary between different companies, but the general process of pectin extraction using acid hydrolysis is as follows (Anonymous 2023, Fig. 5):

However, this process has many drawbacks including the need for maceration of the pulp, difficult filtration of the residue and corrosion of the equipment. Also, this physicochemical method of acid hydrolysis is energy intensive and produces large amount of industrial waste.

6.2 Biotechnological Pathway for Production of Pectin

Pectic substances are important structural constituents of cell wall in non-woody tissues. They exist as insoluble pectin so called ‘protopectin’ and contribute for construction of plant tissue and highly affect the texture of vegetables and fruits. Important changes of protopectin are observed during ripening as they become soft during the solubilization of protopectin. The enzyme originally named protopectinases (PPase), which catalyzes the solubilization was assumed to be not existent

Fig. 5 Process for extraction of pectin by acid hydrolysis



(Sakai and Takao 2000). Earlier it was assumed that PPase was an enzyme that only macerate plant tissues and little was known about its ability to liberate highly polymerized pectin. Sakai (1980) and his colleagues researched and produced pectin from citrus peel by microbial method. The microorganism producing protopectin solubilizing enzyme was isolated and identified as a variety of *Trichosporon penicillatum.* Citrus (*C. unshiu*) peel was suspended in water (1:2, wt./vol.), the organism was added to it and fermentation was allowed to proceed over 15–20 h at 30 °C. The pectin in the peel was completely extracted during fermentation without macerating the peel. This method yielded 20–25 g of pectin per kg of peel. The pectin contained neutral sugars at high levels.

Sakai et al. (1993) used *Geotrichum penicillatum* fungi as the source of protopectinase to liberate pectin from sugarbeet pulp. They studied the effect of carbon source, pH and inoculum size on the yield of pectin. It was seen that 5 g/lt. of glucose gave the highest protopectinase activity while at pH 2.0 the yield of pectin is maximum (1.90 g/10 g pulp). The minimum inoculum size was found to be 3%. Khodzhaeva (1996) studied beet pectin produced in solid state fermentation (SSF) of various fungi, e.g. *Flamulina Velutipes, Phanerochaete chrysosporium, Pleurotus ostreatus, A. ustus and Penicillium notatum.*

Jona Roberto (1997) compared the chemical and enzymic extraction of pectic substances of two fruits, one climacteric and the other non-climacteric. He found that both protocols remove the same amount of pectin but the relative amount of cellulosic and hemicellulosic polymers were dependent upon the method of extraction. Ramos et al. (2021) studied the extraction of pectin from waste generated during processing of cocoa beans using cellulases. For a pectin yield of 10.20 g/100 g feedstock, 52.06 g galacturonic acid/100 g pectin, and a yield of 5.31 g galacturonic acid/100 g feedstock, the parameters were 6.0% feedstock concentration, 40 μL g^{-1} of enzyme, and 18.54 h. The enzymatic extraction was compared with chemical extraction and using the chemical extraction method, a yield of 8.08 g pectin/100 g feedstock and a galacturonic acid content of 60.97 g/100 g pectin were obtained. Using assisted sonication, a pectin yield of 8.28 g/100 g feedstock and a galacturonic acid content of 42.77 g/100 g pectin were obtained. It was noted that enzymatically optimized pectin has rheological and physicochemical features typical of this biomaterial.

Abou-Elasaoud et al. (2021) extracted pectin from sugar beet pulp, Xylanase, cellulase, and their mixtures. The mixed enzymes mixtures resulted in significantly higher yield than using the enzymes separately. Ultrasonic pretreatment remarkably helped in increasing the yield at the shorter enzymatic treatment time (1 and 2 h).

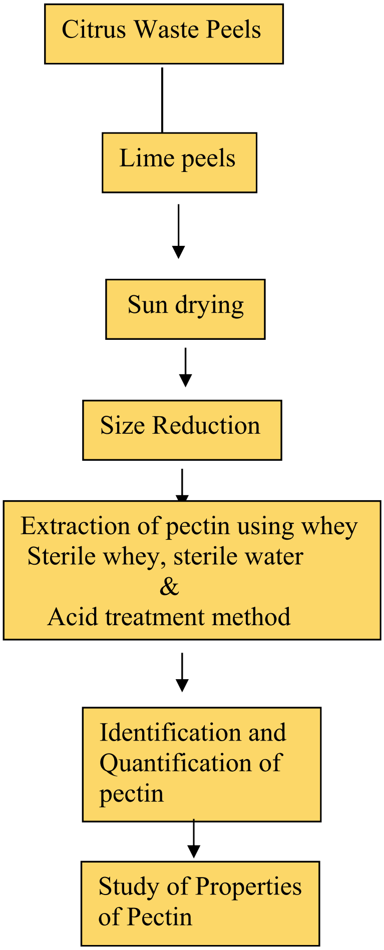


Fig. 6 Biotechnological pathway to produce pectin using lemon peel and whey

7 Research Work for Extraction of Pectin using Whey & Lemon Peels

This research work aims to develop a process to utilize biotechnological pathway to produce pectin using lemon peel and whey (byproduct of cheese-making industry) and compare it with the conventional energy intensive process of acid hydrolysis.

7.1 Materials and Methods: The Methodology for the Research Plan is Presented in Fig. 6

7.1.1 Materials Required

1. ***Lemon Peels***: The lemon peels were brought from the juice vendors and dried in sunlight for 7 days and ground to 1cm size. The dried ground peels were then defatted by solvent extraction method using hexane. The defatted peels were used for pectin extraction.

2. ***Whey****:* Mother culture for whey preparation was collected from the Govt. Milk Scheme, Nagpur. Curd was prepared using the mother culture at 32°C for 4hours and then it was filtered through muslin cloth to separate the whey. The pH of the whey was kept between 4.0 and 4.5. The mother culture was stored at −4 °C for subsequent whey preparation.

7.2 Analysis of Raw Material

Proximate Analysis of lemon peels: The proximate analysis including the moisture content, ash content, crude fat and crude fibre was carried out on the lemon peels (Ranganna 2001).

Analysis of whey: The proximate and the microbial analysis of whey was conducted as per AOAC (2000).

7.3 Extraction of Pectin from Lemon Peel

7.3.1 Optimization of Extraction of Pectin from Lemon Peel Using Whey at Different Conditions of Time, Temperature and pH

25 g of lime peel was soaked in whey/sterile whey/sterile water (1:6) at different conditions of temperature, time and pH. After the desired time, it was heated for 20 min and filtered through muslin cloth. The filtrate was cooled rapidly and equal volumes of ethanol was poured (till the precipitate appeared) into it. It was centrifuged and the precipitate was separated which was subjected to repeated alcohol washings and drying in the oven below 50 °C (Fig. 7).

Enzymatic/Microbial extraction of pectin using citrus peels and whey:

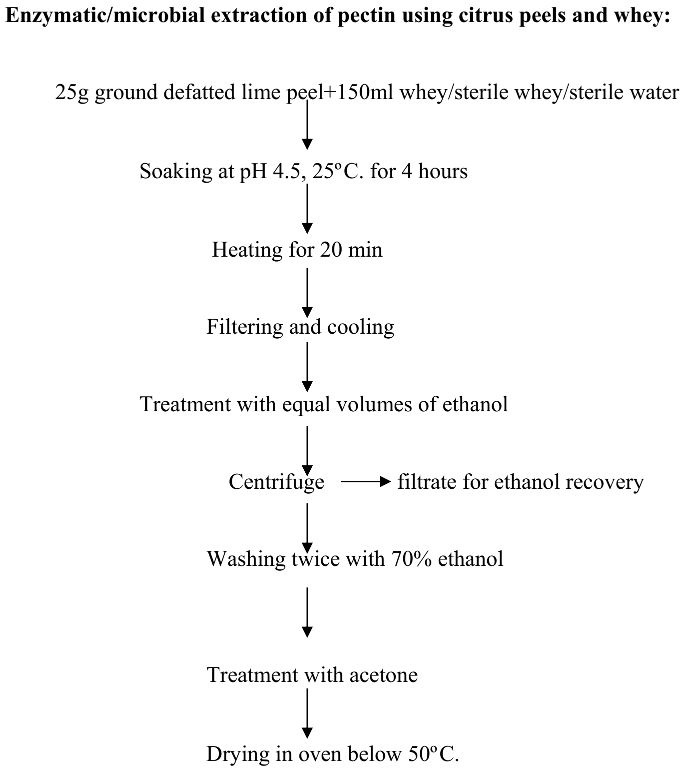


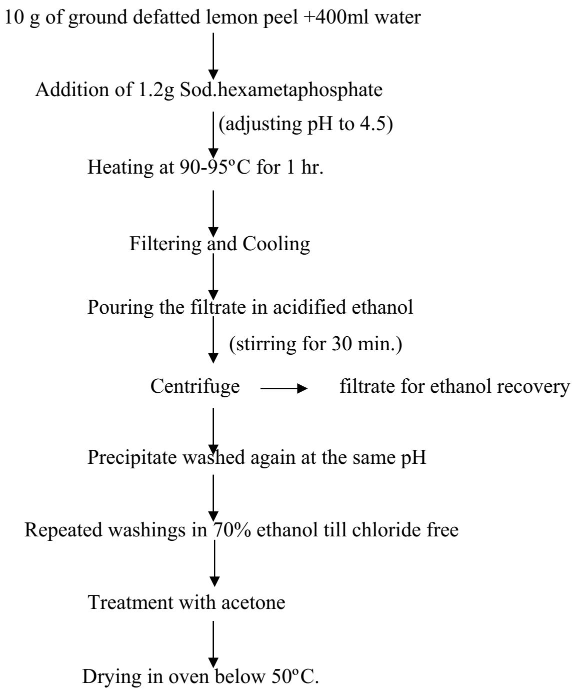
Fig. 7 Process for enzymatic/microbial extraction of pectin using lemon peels and whey

7.3.2 Acid Hydrolysis

10 g of ground, dried and defatted lime peel was taken in a 1000 ml beaker containing 400 ml water. 1.2 g of freshly ground sodium hexametaphosphate was added to it and the pH was adjusted to 4.5. It was heated with stirring at 90–95 °C for 1 h. The water lost by evaporation was replaced at 15 min intervals. It was filtered through muslin cloth while hot and the filtrate was cooled rapidly (Fig. 8).

The filtrate was then poured in 3 volumes of ethanol containing 0.5 M HCl. The pH of the slurry was kept between 0.7 and 1.0. It was then stirred for 30 min and centrifuged. The precipitate was separated and washed at the same pH to remove the traces of ash. The precipitate was again subjected to repeated washings with 70% ethanol until the precipitate was chloride ion free. The precipitate was dehydrated with acetone and dried in an oven below 50 °C. The precipitate was used for further analysis.

Fig. 8 Extraction of pectin from lemon peels using acid hydrolysis



7.3.3 Identification of Pectin

One gm of each sample extracted by the above method was heated with 9ml of water on a water bath until a solution was formed. The water lost by evaporation was replaced. A stiff gel was formed on cooling. This confirms that the sample is pectin.

7.3.4 Analysis of Pectin

The pectin obtained by the conventional acid hydrolysis method, whey, sterile whey and sterile water was characterized using following parameters as described by Ranganna (2001) for % Moisture, % Ash, Equivalent weight, % Methoxyl content, % Anhydrouronic acid content, Molecular weight & Relative viscosity.

Moisture:—Weigh 1 g of sample of pectin, ground to pass 80-mesh, into a tared metal dish (5 cm in diameter with cover). Dry *in vacuo* (5–20 mm of Hg) for 4 h at 100 °C. Cool in a dessicator over phosphorus pentoxide. Weigh again.

Ash: —Weigh 1 to 2 g of pectic substance ground to pass 80-mesh into a tared crucible. Ignite slowly, then heat for 3–4 h at 600 °C. Cool the crucible to room temperature in a dessicator and weigh. To determine the alkalinity of the ash, dissolve the ash in 25 ml of 0.1 N HCl. Heat gently to boiling and cool. Titrate with 0.1 N NaOH using phenolphthalein as indicator.

$$\text{Ash }\% = \frac{\text{Wt of ash } \times 100}{\text{Wt of pectin}}$$

$$\text{Alkalinity }\%\text{ as carbonate} = \frac{\text{Titer} \times \text{normality of NaOH}}{\text{Wt. of ash} \times 1000}$$

$$\text{Carbonate free ash}\% = \text{Ash }\% - \text{ Carbonate }\%$$

Equivalent Weight:—Weigh 0.5 g of pectic substance into a 250 ml conical flask. Moisten with 5 ml ethanol. Add 1 g of sodium chloride to sharpen the end point. Add 100 ml of carbon dioxide free distilled water and 6 drops of phenol red. Make sure that all the pectic substance has dissolved and that no lumps are retained on the sides of the flask Titrate slowly with 0.1 N NaOH until the colour of the indicator changes (pH7.5); the colour change should persist for at least 30 s. Hinton's indicator gives a magenta end point. The neutralized solution can be used for methoxyl determination.

$$\text{Equivalent weight} = \text{Wt. of sample} \times 1000\,\text{ml of the alkali} \times \text{Normality of alkali}$$

Methoxyl content:—To the neutral solution titrated for equivalent weight, containing 0.5 g of pectic substance, 25 ml of 0.25 N sodium hydroxide was added and shaken thoroughly, and allowed to stand for 30 min at room temperature in a stoppered flask. 25 ml of 0.25 N HCl was added to it and was titrated with 0.1N NaOH to the same end point as before.

$$\text{Methoxyl content }\% = \frac{\text{ml of alkali} \times \text{Normality of alkali} \times 3.1}{\text{Wt of sample}}$$

Anhydrouronic Acid:—Making use of the equivalent weight, methoxyl content and the alkalinity of the ash data, the anhydrouronic acid was calculated from the expression given below.

$$\text{Anhydrouronic } 176(\text{m.e.Alkali for m.e.Alkali for} + \text{m.e.Titratable}) \times 100 \text{ Acid}$$
$$= \text{free acid saponification ash}$$

Wt. of sample (mg)

Molecular Weight and relative viscosity:—Pectin sample equivalent to 0.1 g on ash- and moisture-free basis was weighed in a 50 ml beaker. The sample was wetted with a few drops of alcohol and dissolved in about 50 ml of 1% sodium hexametaphosphate solution with warming. Cooled, transferred to a 100 ml volumetric flask, and made up to volume using 1% sodium hexametaphosphate solution. The solution was filtered through Whatman filter paper. 20 ml of pectin solution was taken in a Ostwald-Cannon-Fenske viscometer and the viscosity was measured by noting the time required for the solution to flow from the mark at the neck of the bulb to the bottom mark. The viscosity of the solvent (i.e. 1% sodium hexametaphosphate solution only) was also determined. The molecular weight was calculated using the

Table 4 Proximate composition of whey

Fat (%w/v)	0.1
SNF (%w/v)	8.26
Acidity (%)	0.68
Protein (%w/v)	0.48
Lactose (%w/v)	4.16
pH	4.19
TPC	9×10^3/ml

following formula.

$$\text{Molecular weight} = \frac{(h_r^{1/p} - -1) \times p}{CK}$$

where η_r = relative viscosity

C = concentration in terms of grams of galacturonic acid/100ml

P = any number when the deviation of the intrinsic viscosity is
Minimum, which has been found to be equal to 6

$K = 4.7 \times 10^{-5}$ (constant)

7.4 Results of the Extraction of Pectin from Whey & Lemon Peels

The proximate composition of whey is presented in Table 4. The pH of the whey was found to be 4.19 whereas the SPC was found to be 9×10^3/ml. The fat, protein, lactose, SNF, acidity in the whey was found to be 0.1%, 0.48%, 4.16%, 8.26% and 0.68% respectively. Bylund (2003) reported the values of fat (0.04%), protein (0.55–0.75%) and lactose (4.2–4.9% (w/v)) in the whey.

Pectin was extracted from the lemon peels using the conventional method of acid hydrolysis and the enzymic/microbial method of extraction. The liberated pectin was characterized and the results were compared.

7.5 Pectin Extraction from Lemon Peel

The moisture, ash, fat content, crude fibre and crude protein of the dried lemon peel was found to be 2.2, 3.6, 3.0,8.6 and 6.7% respectively. Carbohydrate content was found to be 84.5%. Mhgub et al. (2018) reported the proximate composition of lemon peel as crude protein (7.8%), ash (5.3%), crude fibre (15.4%), fat (2.5%) and carbohydrates (68.91%). Pectin was extracted from the lemon peel at the temperature of 10 °C, 25 °C and 40 °C respectively. The yield of pectin with respect to the methoxyl content was compared and it was observed that maximum methoxyl content was obtained at 25 °C as seen from Table 5. The yield of pectin at 40 °C was lower than that of 10 °C and 25 °C. It maybe due to the decrease in protopectinase activity at high temperatures as is reported by Sakai (1980).

The effect of pH on the liberation of pectin from the lemon peel was observed. The pH range of 3.5 to 5.5 was selected. The maximum yield of pectin was obtained at pH 3.5 Part of this pectin could be liberated chemically, by acid extraction (Johan Hallaert et al.1993). However, pectin extracted at pH 4.5 showed higher methoxyl content (7.96%). Pectin was extracted at the time intervals of 4 h, 12 h and 24 h. It was observed that the optimum yield of pectin was obtained after 4 h of incubation. This pectin also showed higher methoxyl content (7.8%). Therefore, the extraction conditions selected for further studies were 25 °C, pH 4.5 and 4 h. of incubation (Fig. 9).

Lemon pectin extracted by different methods at the optimum conditions was characterized and compared in Table 6. It was observed that the yield of pectin obtained by using whey/sterile whey/sterile water was comparable to that from the acid treatment method. The relative viscosity of 0.1% sol. was almost same in the case of whey/sterile whey and the acid treatment. The Eq, Wt. and the methoxyl content obtained by the acid treatment method was (1136 mg, 10.08%) and by using whey (1362 mg, 7.31%)/sterile whey (1250 mg, 9.92%). Siddiqui et al. (2021) reported the Equivalent weight and methoxyl content in pectin extracted from sweet lime to be 740.3 mg and 7.1% respectively. The Methoxyl content is an important parameter for the gelling property of the pectin.The Mol.wts. of pectin from the acid treatment method (94794g/mol), whey method (117110g/mol), sterile whey (98298g/mol) and by using sterile water (87777g/mol) could be compared with the results reported by Mhgub et al.(2018). They observed the moleculer weight of pectin obtained from citrus peels to be between 2.6×10^2–4.3×10^6 g/mol.

In order to ascertain the effect of organisms present in whey (i.e. lactic acid organisms) and the surface organisms of peel, the study was conducted for extraction

Table 5 Optimization of extraction of pectin from lemon peel using whey at different conditions of time, temperature and pH

	Conditions	%Yield of pectin	% Methoxyl content
Temp (°C)	10	7.4	5.9
	25	6.3	7.8
	40	6.1	2.5
pH	3.5	6.5	3.1
	4.5	4.2	7.96
	5.5	3.1	3.41
Time(hr)	4	6.3	7.8
	12	4.4	2.8
	24	3.6	2.2

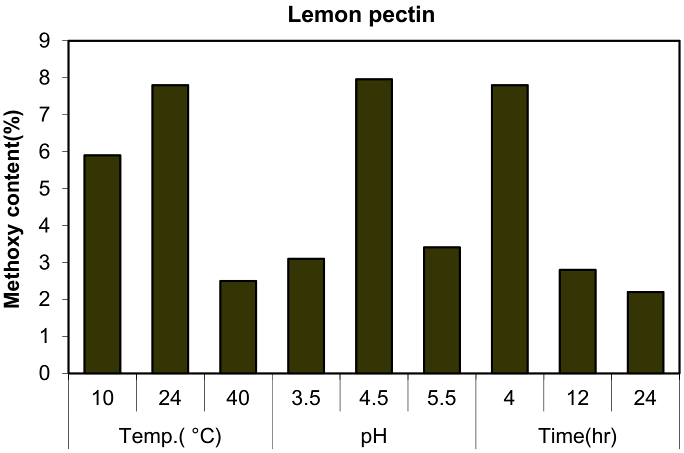


Fig. 9 Methoxyl content of lemon pectin at different temp., pH and time

Table 6 Characterization of lemon pectin

	Acid hydrolysis	Whey	Sterile whey	Sterile water
Yield (%)	12.5	8.48	9.2	10.01
Moisture (%)	3.01	3.2	2.72	2.54
Ash (%)	5.28	8.45	16.57	10.37
Eq. Wt. (mg)	1136	1362	1250	3125
Methoxyl content (%)	10.08	7.8	9.92	10.85
Anhydrouronic acid (%)	81.26	63.16	65.57	63.26
Mol. Wt. (g/mol)	94,794	117,110	98,298	87,777
Relative viscosity(0.1%)	1.41	1.39	1.39	1.29

of pectin by using whey/sterile whey/sterile water. It was observed from Table 6 that pectin yield and methoxyl content was found to be maximum in the sterile water method followed by sterile whey and whey in the decreasing order.

From these results it can be concluded that the organisms present on the peels are responsible for protopectinase activity that results in higher concentration of pectin and also the esterase activity that results in higher values of methoxyl content. Further we can conclude that the lactic acid bacteria has lesser role to play than the surface microorganisms in pectin extraction from lemon peels.

8 Conclusion

Citrus peels and apple pomace are good sources of pectin. Pectins are extracted from these sources by acid hydrolysis at higher temperatures on industrial scale. These processes are energy intensive. In order to save energy, alternative methods are to be exploited, especially through biotechnological methods. In the present study, pectin is extracted from lemon peels using the waste from dairy/cheese industry i.e. whey. The conditions are optimized for the better yield of pectin using whey/sterile whey/sterile water. The experimental results showed that, pectin could be extracted using whey at 25 °C, pH 4.5, and 4 h. of incubation to get optimum yield and better physicochemical characteristics. It was observed that, lemon peel is the good source of pectin for pectin extraction through biotechnological approach. Though the yield of pectin using whey was less as compared to conventional acid hydrolysis method, its physico-chemical properties are comparable to the existing methods. The colour of pectin from the whey method is lighter and brighter than the other methods. From the studies of citrus pectin by the above methods, it is also seen that the lactic acid bacteria have lesser role to play than the surface organisms of peels in the extraction of pectin. The process is less energy intensive as compared to the acid hydrolysis method. Also, there is no corrosion. The process of extracting pectin from citrus peels using whey shows that an integrated approach towards utilization of wastes from citrus processing industry and dairy industry can yield value added product like pectin. This is also a step towards **zero waste, zero pollution**.

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Sustainable Extraction and Utilization of Underulised Plant Purslane (*Portulaca Oleracea*) in Food Product Formulations

Niharika Shanker

Abstract Green leafy vegetables (GLV) have been utilized for generations as a blessing for a secure and healthy life. To meet our daily nutrient needs, green leafy vegetables are a vital part of our diet. Depending on personal preferences, they can be utilized in a variety of ways, including salad and cooked or processed form. Because of the growing consciousness about eating organic or natural foods, people are becoming more and more aware of GLV. GLV holds a significant/high position in the food pyramid, which is a crucial component of a balanced diet. GLV are the best for weight management because they have a low calorie value. They are very nutrient-dense because to their high dietary fiber content, low fat content, and abundance in a range of vitamins and minerals. Low glycemic index nutrition profiles reduce the risk of cancer, cardiovascular disease, and type 2 diabetes. GLV also have a healthy level of polyphenols and antioxidants, which contribute to their therapeutic effect. Due to a lack of understanding on the part of the population regarding their eating habits, purslane (*Portulaca oleracea*) is one of the underutilized green leafy vegetables growing in India. An effort was made in this chapter to raise awareness of this plant and its applications. By promoting the use of GLVs in food and food products, the load associated with synthetic chemicals can be lessened.

Keywords Green leafy vegetables (GLV) · *Portulaca oleracea* · Vitamins · Minerals

1 Introduction

In field of crops and lawns, purslane (*Portulaca oleracea* L.) grows as a weed naturally. Purslane is a plant that is found all over the world and is widely used as a culinary herb in many parts of Europe, Asia, and the Mediterranean area. Mucilaginous compounds found in this plant have therapeutic use. It has a high potassium content (494 mg/100 g), is a good source of magnesium (68 mg/100 g), and is a good

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source of calcium (65 mg/100 g). It also has the potential to be used as a vegetable source of omega-3 fatty acids. Of all green leafy vegetables, it is a very good source of alpha-linolenic acid (ALA) and gamma-linolenic acid (LNA, 18:3 w3) (4 mg/g fresh weight). It had the highest concentration (22.2 mg and 130 mg per 100 g)of alpha-tocopherol and ascorbic acid (26.6 mg and 506 mg per 100 g of fresh and dry weight, resp.). The oxalate content of purslane leaves was reported as 671–869 mg/ 100 g fresh weight. The antioxidant content and nutritional value of purslane are important for human consumption. It revealed tremendous nutritional potential and has indicated the potential use of this herb for the future (Thakur and Modi 2020).

2 Botany of Purslane

There are a number of fleshy plants in the purslane family, *P. oleracea* is an annual herbaceous succulent that can reach a height of 10–30 cm and prefers warm, sandy soil. Its invasive growth characteristics have led some people to label it a weed. The plant has alternate wedge-shaped leaves, reddish-brown stems, clusters of summer-blooming yellow flowers with 4–6 petals, and a lot of black, shiny, gritty seeds. The botanical name is derived from the Latin words potare, which means "to carry," and lac, which refers to the plant's milky sap. *Portulaca neglecta* Mack. & Bush and *Portulaca retusa* Engelm. *P. oleracea*, sometimes referred to as small hogweed, are synonyms (Rashed et al. 2003). They also possess antimicrobial activity and can be used in different food products to extend storage life.

3 Miracle Benefits of Purslane

Purslane is a rich source of vital phytochemicals like flavonoids, alkaloids (including oleraceins, dopa, dopamine, and noradrenaline), terpenoids, proteins, carbohydrates, vitamins A, B, C, and E, carotenoids, and minerals like phosphorus, calcium, magnesium, and zinc, according to numerous studies. Omega-3 fatty acids, particularly alpha-, gamma-, and linolenic acids, which are not typically produced by terrestrial plants, are found in significant proportions in purslane (Kumar et al. 2021). Additionally, there are antioxidants such tocopherol, ascorbic acid, beta carotene, and glutathione. The amount of alpha-linolenic acid varies depending on the cultivar, region, and environment, with the leaves having a higher concentration than the seeds and stems (Teixeira et al. 2010). The food sector is interested in purslane because of its vivid yellow blossoms since they contain betalain, which contains nitrogen (Wang et al. 2010).

Purslane also contains lipids, glycosides, sterols, coumarins, and triterpenes. Phenolic constituents of purslane include scopoletin, bergapten, isopimpinellin, lonchocarpic acid, robustin, genistein, and others. Amino acids in the leaves of the Portulaca species include phenylalanine, alanine, tyrosine, and aspartate. Plant acids include isoleucine, proline, leucine, lysine, phenylalanine, methionine, cystine, valine, threonine, and tyrosine.

4 Health Benefit of Green Leafy Vegetable & Importance of GLV in Life

Future problems will focus on the health and nutrition of the growing global population, especially in developing nations. In addition to providing energy, minerals, and nutrients necessary for health, plant foods also contain phytochemicals that have additional health advantages like glycemic management, immune activation, or antioxidant activity. Every person should consume about 50 g of green leafy vegetables per day, according to the Expert Committee of the Indian Council of Medical Research (ICMR 2010), which advised this taking into account nutrient requirements (NIN 2011). The critical micronutrients found in fruits and vegetables are crucial for both nutrition and wellness. Fruit and vegetable output in India ranks either first or second. Micronutrient deficits and widespread anemia are caused by low vegetable consumption. Increasing vegetable consumption to improve micronutrient status through nutrition education. They also looked into culturally relevant ways to convey the educational concepts that go along with the information about how iron intake affects academic performance. Due of their improved understanding of the foods to eat to boost their iron intake, the adolescents who received the interventions consumed more iron overall each day, increasing their intake of heme–iron in the process. The most desirable and long-lasting strategy for reducing micronutrient deficiency is one that is focused on nutrition. These strategies aim to enhance dietary consumption of micronutrients. Changes in behavior that result in an increase in the selection of iron-containing foods and a meal pattern that is conducive to enhanced bioavailability are the major objectives of dietary modification in order to improve and maintain the iron status of a population. Such dietary adjustments, however occasionally challenging to implement, have the potential to significantly and sustainably enhance both iron status and nutrition in general. Such adjustments must be based on issues that consider education, food security, and actual availability. For the prevention and management of nutritional deficiencies, a variety of strategies, such as nutrient supplementation, food fortification, diversification, and public health interventions, have been proposed. The most sensible and long-lasting method of preventing micronutrient deficits is diet improvement. Since it helps to enhance ones overall nutritional state, improving one's diet is of utmost importance. Extraction fortification and dietary supplementation with foods high in micronutrients to combact the micronutrient deficiency.

The standard of living of individuals around the world has improved significantly over the past ten years. The growing industrialization and innovation in every industry are mostly to blame. Due to the quick pace of life, where consumers prioritize convenience and quick access to wholesome, palatable meals, the fast food industry has likewise rapidly expanded. As a result, there was a dramatic rise in the demand for ready-to-eat items like extruded snack food.

5 Extraction of Omega-3 and Protein Concentrates From Purslane

Food processing operations require antioxidants that can sustain in various temperature, and provide protection to finished products. According to the study, soybean oil was mixed with an ethanolic extract of purslane leaves at three distinct concentrations (T1, T2, and T3): 500, 1000, and 1500 ppm. These concentrations were compared to the control. The sample that had 100 ppm of TBHQ added to it served as the positive control. By calculating the total phenolic content, loss of -carotene, and antioxidant activity of the ethanolic extract of purslane leaves, antioxidant activity was evaluated. It was determined how well soybean oil combined with purslane leaf extract heated (173.2 °C for 24 h; 8-h heating cycles each day) in terms of peroxide value, free fatty acid, total polar material, and fatty acids composition.

The thermal stability of the oils was evaluated using differential scanning calorimeter. The poori was ready to assess the oil's suitability. According to the results, a purslane leaf extract (1500 ppm) may be used to produce soybean oil with reasonable thermal stability and acceptable sensory properties. Even while TBHQ and the purslane leaf extract (1500 ppm) demonstrated nearly same thermal stability, natural anti-oxidants are still chosen over synthetic ones. The purslane leaf ethanolic extract shown remarkable antioxidant action with goodness of omega-3 fatty acids in soybean oil under rapid oxidation during heating in a dose-dependent manner. The existence of strong anti-oxidative compounds with high thermal stability was highlighted in order to highlight the great antioxidant activity of LEP in soybean oil. As a result, purslane leaf extract can be utilized as a substitute source of natural antioxidants to improve the stability of oils and meals that include oils. As a result, the research indicated that purslane has a good chance of being investigated as a source of natural antioxidant (Niharika et al. 2019).

The current way of life, which includes a high-fat diet and little exercise, significantly increases the risk of hypercholesterolemia and cardiovascular diseases. Reactive oxygen species (ROS) that induce oxidative stress are a major factor in the pathogenesis of many diseases, including atherosclerosis and coronary heart disease. One of the risk factors for coronary heart disorders is hyperlipidemia. The reduction of coronary heart disease complications by polyphenolic chemicals present in fruit, vegetables, and other plant material is supported by epidemiological research. According to studies, plant phenolics, flavonoids, flavonolignans, and phenolic acids operate as antioxidants at the molecular level and have health-promoting characteristics. Furthermore, findings point to phenolics' potential to modify and have a favorable impact on lipoprotein metabolism. Additionally, studies show that plant-based phenolics may help reduce coronary heart disease. Therefore, general practice for treatments based on herbs. Nutraceuticals that can lower complications brought on by hyperlipidemia or control serum cholesterol and triacylglycerol levels have become increasingly important over time. (Makni et al. 2008) studied the hypolipidemic and hepato-protective effect of n-3 and n-6 fatty acid-rich flax and pumpkin seed lipids in hypercholesterolemic rats. Plant extracts contain phenolics, which are possible candidates, but they frequently contain complexes of other compounds that have pro-oxidants and antioxidant characteristics. For this reason, the trial looked into the possibility for hypolipidemic effects of purslane extract. Treatment for atherosclerosis that is effective includes lowering plasma cholesterol levels. Fibrates and statins are two chemical medications that have the ability to decrease cholesterol.

6 Utilization of Purslane Leaves in Various Food Product

Approximately 97% of Americans get an average of 24% of their calories from snack items, according to a USDA research (USDA 2010). On the other hand, due to the advantages they hold, a range of junk foods have also been observed holding a significant part of the diet. These are highly caloric processed foods that are mostly made of starch and fat and lack sufficient fiber. According to epidemiological study, those who consume a diet that is mostly deficient in fiber frequently suffer from gastrointestinal and cardiovascular problems (Kumari and Grewal 2007). A unique array of plant meals, such as those found in fruits and vegetables, provide not just energy and nutrition but also a sizable amount of fiber. According to the National Horticulture Database, which was released by the National Horticulture Board (Oxford University Press 2016), India is the world's second-largest producer of fruits and vegetables, behind China. Despite the fact that vegetables are produced in large quantities, the majority of modern civilizations choose to restrict their diet to a variety of vegetables while avoiding specific green leafy vegetables, such as purslane leaves, which have superior nutritional qualities to major cultivatable vegetables. It is well known that it contains more fatty acids, including alpha-linolenic acid, than any other vegetable. Additionally, because of its outstanding nutritional qualities, purslane is regarded as a "power food" and may be used to a variety of snack meals. It would add extra nutrients to the diet that support the maintenance of our health and wellbeing (McDonald and Nicholson 2006). By incorporating the micro and macronutrients necessary for human health, a supplement improves the nutrient profile of a typical diet. Herbal remedies have historically been used to treat a wide range of issues, including disease, fever, wounds and infections, CVD, constipation, weight management, immune-modulators, and memory loss, among others. Despite having a high quantity of antioxidants, minerals, and omega-3 fatty acids, purslane is considered to be a wild plant and is hence underused. As a result, it is getting more and harder to use natural resources to support the health care system. Additionally, it has been discovered that the demand for nutraceuticals rises as consumers become more conscious of the link between their diet and health. In order to allow improved nutrient absorption, it is crucial to incorporate these active substances with the current food formulations. So, it is essential to integrate these active ingredients with the current food formulations to facilitate enhanced nourishment with an added advantage to the consumers in relation to health. The consumer's viewpoint on food production and consumption has significantly evolved during the past few decades. Customers are more conscious of how much food affects their health and happiness (Mollet and Rowland 2002). Consumers today consume food not just to satisfy their hunger but also to gain important nutrients, to prevent diseases related to nutrition, and to improve their physical and mental health. According to (Pathania et al. 2017), traditional cuisines from several nations, including India, are recognized to be more nutrient-dense than popular junk food. Functional foods can be quite effective in reducing the symptoms of lifestyle disorders. Due to rising healthcare costs, longer life expectancies, and consumer demand for better eating, these foods have received a lot of appeal and attention (Kotilainen et al. 2006).

The majority of the populace in developing nations consumes vegetarian food. Many families cannot afford to buy meat more frequently than once a week due to its high cost. Only a small portion of the world's edible plants are used to produce food for people. In addition, only 20 crops account for 90% of the world's plant food production. In actuality, only 6 crops are exported or imported from/to a number of nations. According to the Food and Nutrition Board, food plants that provide protein equal to or greater than 12% of their calorific value are regarded to be good sources of protein. Given that they contain a significant amount of the vegetative component, the leaves are frequently taken into consideration for the creation of high-value recombinant proteins (Shanker and Debnath 2015).

Due to its high nutritional and antioxidant content, it is said to be the superfood of the future. It is marketed in stores in the United Arab Emirates and Oman and is regarded as a vegetable in China for long life. It is employed as a herbal skin remedy in traditional Chinese medicine. Purslane has a wide range of other pharmacological actions, including antibacterial, analgesic, anti-inflammatory, and wound-healing properties. Purslane extracts have been demonstrated to have antidiabetic effects when used as an alternative to streptozotocin in diabetic rat models. Numerous organs, including the liver, heart, and kidney, have been shown to experience oxidative stress as a result of hypercholesterolemia. It has been demonstrated that plant bio-active antioxidants have a greater ability to shield people from a wide range of ailments, including cardiovascular diseases. It has also been claimed that purslane has a variety of biological effects, such as hypoxia, hepatoprotective qualities, and an anti-hypertension impact; however, there is no evidence in the literature to support these claims. According to clinical investigations, dyslipidaemia is one of the main risk factors for coronary disease. Preclinical investigations have shown that high cholesterol encourages the buildup of low-density lipoprotein in the artery wall, endothelial cell dysfunction, and the progression of atherosclerosis (Takahashi et al. 2005).

7 Conclusion

Traditional medical practices have employed purslane to treat, manage, and/or control hypertension and diabetes mellitus. Purslane can be used to manage or control hyperlipidemia because research showing that its leaves can be used to prevent hyperglycemia also shows that the plant's leaf aqueous extract has hypolipidemic capabilities. Purslane's effect on lipid metabolism needs to be further confirmed, nevertheless, by dietary research. Additionally, purslane can be utilized as a convenient supply of natural antioxidants.

In light of this, an effort was made to use purslane greens to create inexpensive, fiber-rich goods for consumers who are deficient in micronutrients and to evaluate the sensory quality of such products.

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Circular Strategies for Recovery and Valorization

Effect of Ultrasonication on the Recovery of Essential Bioactive Compounds from Tomato Waste

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Abstract The tomato processing industry causes high amount of waste mainly skin and seeds that creates the environmental problem. These residues are major source of bioactive compounds and valuable pigments. Hence the purpose of this study was to extract the lycopene content from tomato pomace using conventional organic solvent extraction (COSE) and ultrasonication assisted extraction (UAE) methods. The effect of operating conditions was determined by varying extraction treatment time, solid liquid ratio and power variation in UAE. The maximum yield of lycopene was obtained in UAE (160 V for ratio 50:1 for 15 min) as compared to COSE. FTIR analysis was performed for lycopene Extract. Beta carotene was also obtained in the lycopene enriched alcoholic extract and maximum yield was found to be in UAE at 50: 1 for 20 and 30 min at 180 V. Tomato oil was isolated from dried tomato seeds obtained from tomato pomace. GC analysis was performed to study fatty acid profile.

Keywords *Solanum lycopersicon* · Lycopene · Bioactive compounds · Ultrasonication

1 Introduction

Tomato (*Solanum lycopersicon* Mill.) is one of the most edible and nutritious vegetable. Lycopersicon esculentum L is a member of Solanaceae family with the production of 126 tons worldwide and it is a excellent source of primary and secondary metabolites which are necessary for human health such as vitamins, carbohydrate, fiber, and minerals with the enrichment of B-carotene, lycopene, flavonoids, phenolics and chlorophyll (Raiola et al. 2014; Bhuvaneswari and Nagini 2005; Elbadrawy and Sello 2016). Consumption of tomato is associated with the reduced risk of inflammatory processes, cancer, and chronic non communicable diseases (CNCD) including cardiovascular diseases (CVD), diabetes and obesity (Raiola et al. 2014; Rao and Agarwal 1999).

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Tomatoes are principal carotenoid and red pigment in tomatoes and are industrial processed to obtain juice, ketchup, paste, dried or canned tomatoes and dried tomato powder. These products have high demand on global scale (Silva et al. 2019; Eh and Teoh 2012; Sadler et al. 1990). It is a protein food containing essential amino acids having emerging antioxidants properties (Bhuvaneswari and Nagini 2005; Vilkhu et al. 2008). Processing of tomatoes mainly has pomace as a main residue i.e. skin and seeds with a fraction of pulp. Tomato pomace has no industrial value hence it is decomposed landfill or act as animal feed. Silva et al. (2019), Zuorro et al. (2013). This decomposable feed contains nutrients and valuable phenol and several bioactive compounds such as carotenoids and particularly abundant source of lycopene (Bhuvaneswari and Nagini 2005).

Lycopene is C40 poly-isoprenoid, *tetrapic* hydrocarbon with 13 carbon double bonds and found to be efficient singlet oxygen quencher and responsible for bright red color in tomatoes whereas seeds are used as a source of vegetable oil (Cuccolini et al. 2013; Zuorro et al. 2013; Montesano et al. 2008). Tomato seed oil contains saturated fatty acids, mono-di-poly unsaturated fatty acid and antioxidants (Ezz et al. 2018). It is clearly stated a concern regarding safety towards environment and economy gain an interest towards green and reliable extraction techniques for byproducts from waste (Yi et al. 2009). Lycopene is extracted from tomato peels (Yi et al. 2009; Cuccolini et al. 2013; Kumcuoglu et al. 2014; Naviglio et al. 2008; MacHmudah et al. 2012; Choudhari and Ananthanarayan 2007; Rozzi et al. 2002) and health oriented tomato oil from tomato seeds (Giuffrè et al. 2017; Botineştean et al. 2014).

Montesano et al. (2008) extracts lycopene by innovative low-cost extraction method for high purity lycopene from tomato. The results shows 95% pure all trans lycopene detected by DAD HPLC with mass spectrometer. Sabio et al. (2003) also extracts the lycopene and b carotene content from tomato waste by using super critical extraction at 300 bar and 80 °C gives yield of 80 lycopene and 88% beta-carotene using 130 g of co2 per gram of matrix (Hassen et al. 2019) studied the effect of pre heating and different combinations on processing waste of tomato to study lycopene content. Hot bread, normal break and cold break method was treated to tomato paste. Naviglio et al. (2008) studied the extraction of lycopene by using high pressure extraction approach. The extract was characterized by UV-spectrophotometer, H-NMR, C-NMR and electrospray ionization mass spectroscopy.

The objective of the study is to determine the recovery of essential bioactive compounds especially lycopene from tomato waste peel by different extraction methods. COSE and UAE methods are used to obtain the lycopene rich alcoholic extract. Comparing yields with antioxidant activities for lycopene rich extract associated with variation in the time of treatment, solid liquid ratio and power. In addition, the effect of b-carotene content on the extraction's conditions have also been studied. Tomato oil was obtained from dried tomato seeds with further determination of presence of fatty acid profile were also studied.

2 Material and Methods

2.1 Material

Tomato waste (seeds and peels) were brought from NOGA industry, MIDC Hingna, Nagpur, Maharashtra, India. Pomace was collected in plastic container immediately after being processed and transported to the laboratory. Seeds were removed from the pomace by rinsing with water multiple times at different interval. Peels were dried mostly by using hot air oven and were grinded by using grinder. Peel powder was stored in zip-lock plastic bags for longer storage. Hexane, ethanol, acetone, BHT, ascorbic acid, ethanol, gallic acid (3,4,5-trihydroxybenzoic acid), folic Cialteau reagent, Na_2CO_3 was obtained from Himedia limited, Mumbai, India. ABTS (2,2'-azinobis ((3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt), DPPH (2,2-diphenyl-1-picrylhydrazyl), were also obtained from HIMEDI, India.

2.2 Methods

2.2.1 Extraction of Lycopene and Oil from Tomato Waste

Conventional method of Lycopene extraction was carried out as mentioned in (Kumcuoglu et al. 2014). Solid liquid ratios of 1:10 (w/v) were taken. Mixture of hexane: ethanol: acetone was taken as a liquid containing 0.004% of BHT to minimize oxidation. The suspension was mixed and homogenized by using shaker at room temperature. By adding cold distilled water two liquids i.e., polar layer and non-polar layer are seen in separating funnel. Polar layer is used for the determination of lycopene and b-carotene. Ultrasonication was also used for the extraction of lycopene from tomato pomace. High intensity probe system ultrasonicator was used. Solid- liquid mixture was taken at different variations in the UAE process. Time and Power were also varied in the experiment (Jerman et al. 2010; Wang et al. 2008; Eller et al. 2010; Arabani et al. 2014).Tomato oil was extracted by Maceration method from dried powder of tomato seeds. Petroleum ether was used as a extracting media (Fig. 1).

2.2.2 Determination by UV Visible Spectroscopy

Determination of lycopene content was done as per procedure described in (Kumcuoglu et al. 2014). Polar and non-polar layer form after adding water in the mixture of solvent (hexane: acetone: ethanol). UV Spectro photometer was available at the department of food technology in LIT, RTMNU, Nagpur. Measurement of optical density at 503 nm in a spectrophotometer was recorded. Values were finally expressed as mg/kg fresh weight (fw). Beta carotene is present in polar layer in

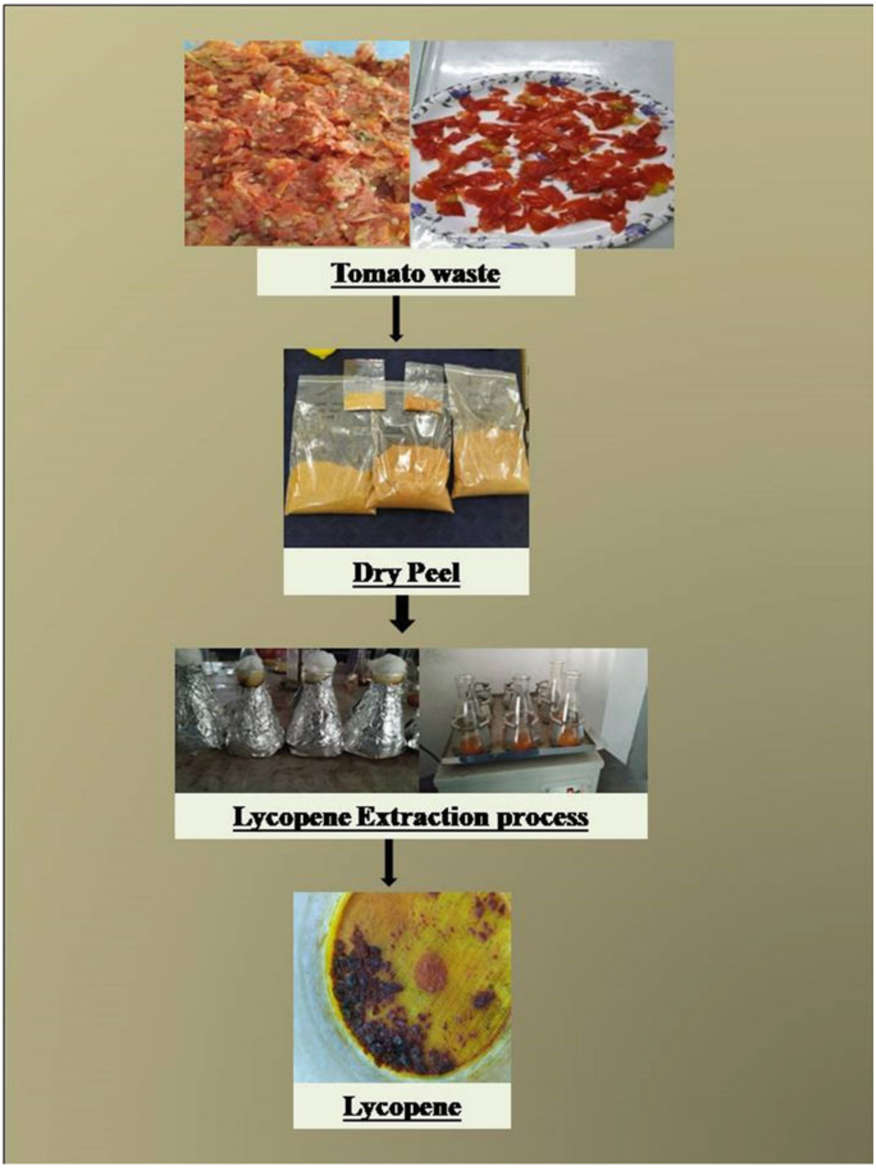


Fig. 1 Schematic representation of extraction of lycopene from tomato waste

solvent mixture. It is a provitamin A and known for a strong antioxidant. Optical density at wavelengths 663, 645, 505, and 453 nm was measured by taking polar form and blank as solvent mixture (hexane: acetone: ethanol) in ratio 2:1:1. Content of beta-carotene is determined by using formula.

β-Carotene (mg 100/mL of extract) = $0.216 \times A663 - 1.22 \times A645 - 0.304 \times A505 + 0.452 \times A453$.

2.2.3 Antioxidant Activity

Antioxidant capacity of industrial tomato pomace, alcoholic lycopene rich extract and tomato seeds was evaluated. DPPH (2,2-diphenyl-1-picrylhydrazyl), total phenol compound including soluble and insoluble-bound phenol compounds were determined. The antioxidant capacity is defined by the potential to donate electrons to normalize the DPPH radical. An aliquot of ethanol (50%) of sample was added to DPPH solution and absorbance was measured at 515 nm (Periago et al. 2002). The inhibition percentage was calculated of DPPH radical by equation given (Silva et al. 2019).

% Inhibition DPPH = (A control—A sample/A control) * 100

Total phenol content was determined according to the method of Durante et al. (2017) alcoholic extract were mixed with 50 μL of Folin-Ciocalteu's phenol reagent and 450 μL distilled water. Further addition of 500 μL of 7% (w/v) Na2CO3 and make up to 1250 μL with distilled water. Mixture was then measured at 750 nm using a spectrophotometer after keeping the mixture at room temperature for 90 min. Gallic acid was taken as standard for calibration in between 0–12 μg GA/100 μL in 80% ethanol. The final values were expressed as gallic acid equivalent per gram of seeds (Shah and Thakur 2015; Sayeed and Thakur 2019; Sayeed and Thakur 2019; Singh et al. 2022).

2.2.4 Characteristics Properties of Tomato Oil

Free fatty acids, saponification value, acid value, peroxide values and iodine values were determined in tomato oil. Free fatty acids were measure by titration of oil by 0.1 N NaOH whereas PV (peroxide value) was measure by titrating oil with 0.01 N sodium thiosulfate solution. Oil was saponified with strong reflux by alcoholic KOH solution. Saponification value is the amount of alkali required for titration with HCL as a standard solution. Physio chemical analysis including iodine value was determined according the official method of AOAC 920.18 It is expresses as g i2/100 g oil. Fatty acid profile was determined as per the method given by (Durante et al. 2017). Procedure was performed on the Agilent 5977A Series GC. Temperature of the column was 50 °C after injection for nearly 1 min. Programming at 25 °C/min to 200 °C, at 3 °C/min to 230 °C for 23 min and then maintained for a constant temperature of 250 °C. Head pressure of the column sets to 40 psi for 0.4 min with constant pressure at 20 psi. Split ratio of 5:1 with flow rate of 1.0 ml/min was set. Carrier gas of pure helium was used spectrum data was collected at interval of 0.5 s whereas solvent cut time was set to 2 min with retention time of 40 min to separate fatty acids. A single tomato oil replication was performed.

2.2.5 Statistical Analysis

All analysis was performed in triplicate and is expressed as triplicate + standard deviation. For antioxidants activity, calibration curves of linear regression were obtained by graph pad prism software. ANOVA (one way analysis) was performed to mark the difference between the batches taken when significant differences were found. Statistical tests were performed by using graph pad prism software. Tukey test was performed at confidence level at 5% through r (pearson correlation coefficient) and to establish the difference between means ($p < 0.05$).

3 Results and Discussion

3.1 Extraction Efficiency of Ultrasonication and Conventional Extraction Method on Alcoholic Extract

Conventional organic solvent extraction (COSE) method and ultrasonication assisted extraction (UAE) was used for the extraction of alcoholic extract. Effect of different processing methods were studied on bioactive compounds rich alcoholic extract (Jerman et al. 2010). Liquid solvent Ratios of 10:1, 35:1 and 50:1 was taken with the extraction treatment of time of 10, 20, 30 and 40 min. Power variation in the ultrasound assisted extraction was also considered. UAE consist of high intensity probe that penetrates to the inner part of cell gives effective extraction and higher efficiency Whereas Conventionally, there is no heating of liquid hence less degradation of bioactive compounds (Kumcuoglu et al. 2014).

Traditionally more amounts of solvent and high extraction time are needed for greater efficiency hence Decreasing the solvent amount and extraction time enhances extraction yield which gives high quality of extracts which can be processed by new techniques such as ultrasound assisted, microwave assisted, pulsed electric field, high pressure process and supercritical extraction (Luengo et al. 2014; Rozzi et al. 2002; Naviglio et al. 2008). Though content of lycopene and B-carotene was measured using UV spectrophotometer at 472 nm shown in below Tables 1, 2 and 3.

Table 1 T lycopene (mg/kg) content of alcoholic extract by COSE

	Lycopene (Mg/Kg)		
	Liquid solvent ratio		
Extraction time (min)	10:1	35:1	50:1
10	68.243 ± 1.240	37.289 ± 0.792	28.690 ± 1.074
20	68.120 ± 0.772	44.632 ± 0.990	30.890 ± 0.554
30	68.410 ± 0.275	38.744 ± 1.054	33.457 ± 0.334
40	67.500 ± 0.702	61.262 ± 1.052	30.500 ± 0.235

Table 2 B-carotene (mg/kg) of alcoholic extract by COSE

	B-Carotene (mg/ml)		
	Liquid solvent ratio		
Extraction time (min)	10:1	35:1	50:1
10	Nd	36.777 ± 0.240	28.760 ± 0.219
20	Nd	44.404 ± 0.690	31.257 ± 0.172
30	Nd	37.347 ± 0.465	33.261 ± 0.189
40	Nd	60.162 ± 0.049	30.657 ± 0.205

The extraction efficiencies were determined by comparing the recovery yields of lycopene and β carotene content from tomato peel extracts. Extraction was performed by at room temperature with the highest efficiency of lycopene in UAE is for 15 min at 160 V for ratio 35:1 and b-carotene at 20 min (180 V) for solid liquid ratio of 50:1. In COSE, higher yield is to be seen for the extraction time of 30 min at 10:1 ratio of solid liquid (Table 1) (Wang et al. 2008).

Fourier- Transform spectroscopy (FTIR) is nondestructive technique for analyzing and offers spectral bands. Spectr typical bands arise from amide and lipid groups strong and broad absorption bands of water are also shown. Intense bands of various carbohydrates and acids present in tomato enriched lycopene extract is represented (Fig. 2) (Raduly et al. 2011).

All the readings are taken in triplicate form and the values are expressed as average ± standard deviation of triplicate and the values followed by the same letter do not statically differ ($P < 0.05$).

Table 3 Lycopene and B-carotene content in alcoholic extract of UAE method

Power (Volt)	Ratio	Time (min)	Lycopene (Mg/Kg)	B-Carotene (mg/ml)
120	35:1	10	0	0.00
		15	99.203 ± 0.640	0.683 ± 0.031
		20	25.490 ± 0.121	0.330 ± 0.080
		30	48.420 ± 0.104	0.333 ± 0.263
	50:1	10	0	Nd
		15	84.487 ± 0.219	Nd
		20	81.563 ± 0.306	Nd
		30	65.610 ± 0.248	Nd
160	35:1	10	0	0.350 ± 0.030
		15	104.527 ± 0.031	0.347 ± 0.021
		20	20.510 ± 0.062	−0.477 ± 0.031
		30	7.580 ± 0.284	Nd
	50:1	10	0	0.399 ± 0.020
		15	112.297 ± 0.271	0.333 ± 0.025
		20	102.467 ± 0.451	−0.514 ± 0.010
		30	–	Nd
180	35:1	10	0	0.387 ± 0.006
		15	57.280 ± 0.053	0.428 ± 0.007
		20	51.637 ± 0.133	0.533 ± 0.021
		30	102.320 ± 0.302	Nd
	50:1	10	0	0.442 ± 0.009
		15	48.130 ± 0.125	0.667 ± 0.019
		20	74.473 ± 0.214	0.697 ± 0.012
		30	78.393 ± 0.348	Nd

3.2 *Effect of Liquid Solid Ratio on the Extraction of Alcoholic Extract*

Different variations of solid liquid ratio were taken to determine the lycopene and B carotene content in the alcoholic extract obtained from COSE and UAE. In comparison, liquid–solid ratio of 35:1 yields better efficiency for lycopene content of 44.632 ± 0.990 mg/kg and at ratio of 35:1 gives yield of 60.162 ± 0.049 mg/kg for B carotene at 40 min. According to observations in the study as the amount of liquid increased the content of lycopene decreases. Dilution of solid into liquid gives rise to reduction of lycopene was observed (Wang et al. 2008).

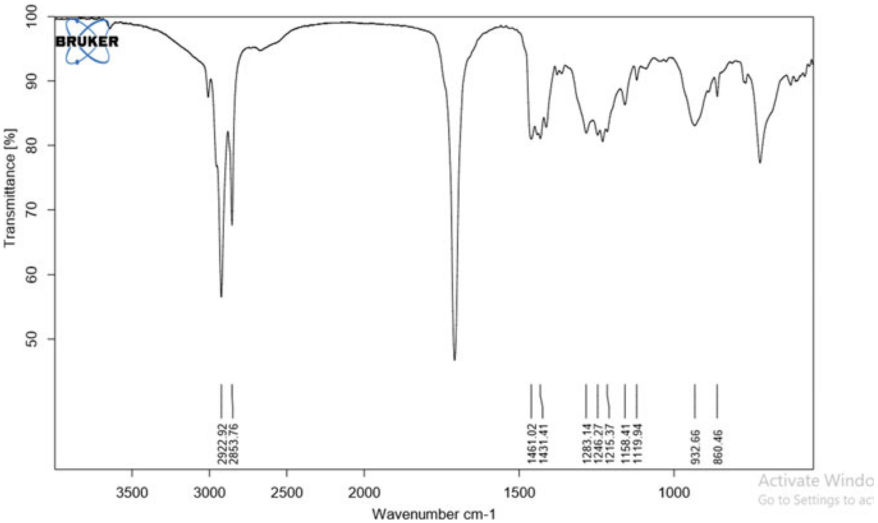


Fig. 2 FTIR analysis of alcoholic extract of lycopene

In this study highest yield in UAE determines bioactive compounds including lycopene and b-carotene actively of 112.297 ± 0.271 mg/kg at treatment of 160 V for 15 min and 0.683 ± 0.031 mg/ml at 120 V for 35:1 duration for 15 min. Previous study undertaken by (Kunthakudee et al. 2020) extracts lycopene from tomato by using environmentally benign solvents with optimum conditions of solvent/ratio of 50:1 with extraction time of 45 min with temperature of 45 Degree C. Ethanol was used to increase the yield. Some readings are estimated as Nd that is not determined due to degradation of compounds. Factors responsible are like high temperature, low liquid for extraction or high power in UAE etc.

3.3 Effect of Variation in the Time of Treatment on the Extraction of Alcoholic Extract

COSE and UAE extractions were performed with different measuring parameters. Variations in the time of treatment of 10, 20, 30 and 40 min has been taken into considerations to study the effect of processes on the extract in terms of time (Nobre et al. 2012). Lycopene content was measured by using spectrophotometer in this ratio of COSE extraction, high amount of lycopene (68.410 ± 0.275 mg/kg) was measured at 30 min of extraction for liquid solid ratio of 10:1. a pattern was observed in the liq-solid ratio of 35:1, in which extraction time of 40 min yields highest b carotene content of 60.162 ± 0.049 mg/kg.

In this study In UAE, 15 min of time of treatment has been effective among all the time considered. 99.203 ± 0.640 mg/kg 35:1 at 120 V, 112.297 ± 0.271 mg/kg at 160 V for 50:1 yields highest amount of lycopene. More time of treatment degrades the lycopene content as it is sensitive to heat. Initially lycopene content was increased afterwards gradually decrement was observed in the lycopene content (Kumcuoglu et al. 2014). In the previous study of Eh and Teoh (2012) lycopene was extracted from tomatoes by Ultrasound extraction with enhanced efficiency of lycopene at 40 min at 40 °C and noted that enhancement of recovery is due to low temperature and extraction time.

3.4 Effect of UAE on the Extraction of Lycopene Enriched Alcoholic Extract

In ultrasound assisted extraction, three different powers were used for different extraction time and ratio (Jerman et al. 2010). At power of 120 V, for the liq-solid ratio of 35:1 for 10 min of treatment lycopene compound was not observed due to less extraction time. In the whole extraction of 120 V, in liquid-solvent ratio [35:1] extraction time of 40 min and in ratio of 50:1 at time of 30 min gives highest lycopene content. Turbidity was also observed which increasing with the extraction time whereas amount of polar layer decreases with extraction time and increase with the liquid solvent ratio. Power was increased to 160 V on the ultrasonicator to check the difference between the lycopene extracted by increasing the power. Same liq-solid ratio (35:1 & 50:1) was maintained with the same extraction time. At 35:1 ratio decreasing content of lycopene pattern was followed with increasing the extraction time. After 15 min of extraction 104.527 ± 0.031 mg/kg of lycopene was determined. Here lycopene gets suddenly decreased due to the more dilution of solid with solvent; Kumcuoglu et al. (2014).

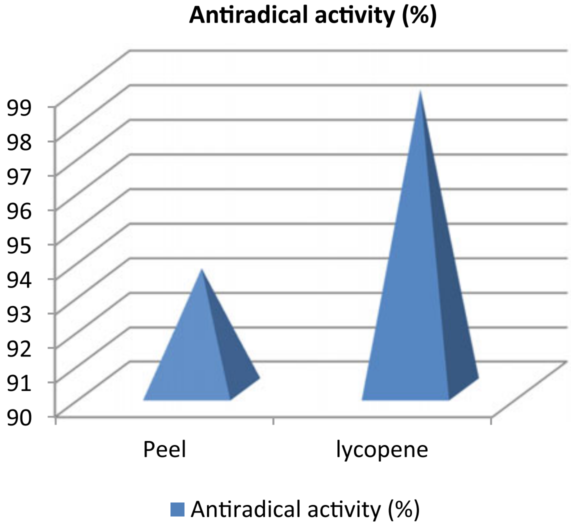
By increasing the extraction time for 30 min 102.320 ± 0.302 mg/kg lycopene was obtained hence 30 min gives the highest yield. (Lianfu and Zelong 2008) compares ultrasound and microwave assisted extraction from tomatoes for lycopene extraction. Temperature of 56.4 °C and for 29.1 min at ratio of 8:1 was optimized to get highest lycopene of 89.4%. (Li et al. 2014) optimized the processing papaya waste for extraction of lycopene by using ultrasound extraction process with optimal conditions of 42.28% ethanol for time 26.09 min at 50.12 °C with maximum extraction of 189.8 ug/g fresh weight which was marked higher as compared to traditional process (153.9 ug/g).

3.5 Effect of DPPH Free Scavenging Radical Activity and Phenol Compounds in Bioactive Enriched Alcoholic Extract

Scavenging activity was studied to evaluate the stability of DPPH radical to determine antioxidant activity. The colorimetric technique is used to determine antioxidant activity using free radical. The absorbance is measured at 515 nm. The degree of discoloration specifies the activity of scavenging potential of antioxidant in the extract. DPPH radical activity of raw peel and lycopene has shown in the graph represented. Raw peel showed the antioxidant activity of 93.53 ± 3.6% where as in lycopene extract 98.70 ± 2.3%. All the extracts were prepared in ethanol. This indicates that peel has the lowest scavenging free radical activity than lycopene. It is associated that scavenging activity is related to alteration of hydroxyl groups in the aromatic ring of phenolics, thus emerging their denoting ability of hydrogen (Elbadrawy and Sello 2016; Periago et al. 2002). Insoluble and soluble phenolics compounds are determined by considering gallic acid as a standard. Phenolic compounds are majorly found in fruits and vegetables. It is one of the phytochemicals play a major role in physiological and morphological activities and contributes the sensory characteristics of plants. They have the vital role of antioxidants along with carotenoids and vitamins. Soluble and insoluble phenols have studied had represented graphically as shown Fig. 3.

Silva et al. (2019) characterized tomato processing byproduct for determination of antioxidant activity of DPPH, TEAC, FRAP and TPC. The phenol content was varied between 0.08 ± 0.18 and 22.75 ± 2.36 mg Gallic acid equivalent (GAE)0.100g1 of dry weight. (Periago et al. 2002) studied the phenol and antioxidant, lycopene content

Fig. 3 Anti-oxidant activity of peel and lycopene



in different tomato species. (Nour et al. 2015) studied the incorporation of lycopene in bread and its antioxidant activity of phenolic content of 865.77 mg GAE/kg.

3.6 Effect of Extraction of Tomato Oil on the Fatty Acid Profile

Fatty acid profile was studied of tomato oil extracted by maceration method by using hexane represented in Fig. 4 and tabulated in Table 4. It is clearly stated that linoleic acid represents the major fatty acid with the percentage of 54.2% of all fatty acids followed by oleic acid (19.6), palmitic acid (14.6) and stearic acid (5.3). Elbadrawy and Sello, 2016) estimates the similar value extracted of lycopene peel oil. Saturated fatty acids were found in tomato seeds oil was 24.8% with maximum amount of polyunsaturated (54.59) fatty acids was observed. High level of omega 6 fatty acids were obtained in oil 54.59 which is essential fatty acids and protect from cardio vascular disease (Table 4) (Elbadrawy and Sello 2016; Botineştean et al. 2014). Zuorro et al. (2013) produced tomato seed oil by using enzymes with the production of 25 kg/ton oleoresin with lycopene of 6.8%. Arabani et al. (2014) studied the tomato extraction hot water using pre-treatments of using ultrasound and microwave extraction process from tomato seeds. GC analysis of fatty acids are determined with saponification and iodine value.

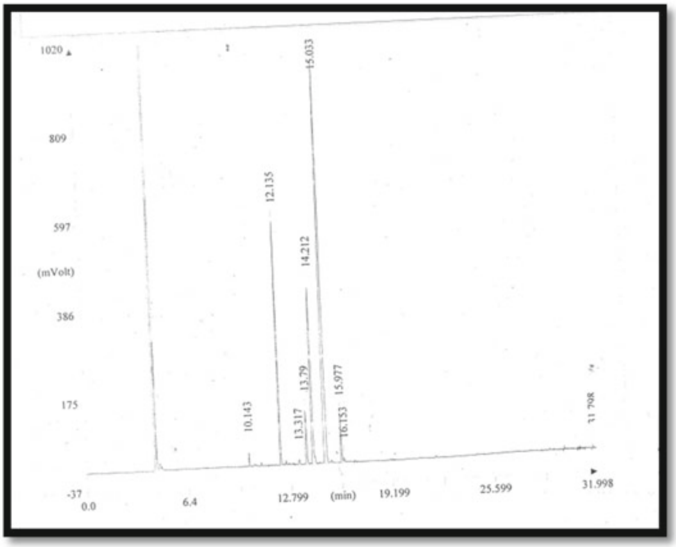


Fig. 4 GC analysis of tomato seed oil

Table 4 Fatty acid profile to tomato seed oil

Components	%	Components	%
Stearic acid (C18:0)	5.3	Saturated fatty acids	24.8
Tridecyl acid (C13:0)	0.9	Mono-unsaturated fatty acids	20.3
Palmitic acid (C16:0)	14.6	Poly-unsaturated fatty acids	54.59
Heptadeconoic acid (C17:0)	0.7	Trans fatty acids	0
Oleic acid (C18:1)	19.6	Omega-3	0
Linoleic acid (C18:2)	54.2	Omega-6	54.59
Arachidic acid (C20:0)	4		
Linolenic (C18:3)	0.4		

3.7 Effect of Antioxidant Activity on Isolated Tomato Oil

Tomato seeds recovered from industrial tomato waste after extraction of juice from fresh fruits for extraction of tomato seeds oil. Total phenols, soluble and insoluble phenols was studied as phenol compounds are present in both soluble and insoluble form exits in vacuoles and plant matrix respectively. In all assayed sample of tomato oil was measured spectrophotometrically for DPPH radical scavenging activity and total phenolic content is graphically represented (Figs. 5 and 6). Measurement was taken in three replicates (Durante et al. 2017). Giuffrè et al. (2017) worked on tomato seed to obtain edible oil. fatty acid methyl ester profile, free acidity, peroxide value, spectrophotometric characteristics, phenol content, and radical scavenging activity (DPPH) values were determined for edible tomato oil. Botineştean et al. (2014) determines the physiochemical properties of The FA composition of tomato seed edible oil, by gas chromatography results in linoleic acid (20.8–39.9 mg/mL), arachidic acid (0.08–0.4 mg/mL), palmitic acid (6.3–19.3 mg/mL), stearic acid (0.1–0.8 mg/mL), linolenic acid (0.7–4.9 mg/mL), palmitoleic acid (0.03–0.5 mg/mL), myristic acid (0.05–0.2 mg/mL) and oleic acid (2.5–14.2 mg/mL), margaric acid (0.02–0.11 mg/mL). The oil content of tomato seeds was registered in the range of 13.3–19.3%.

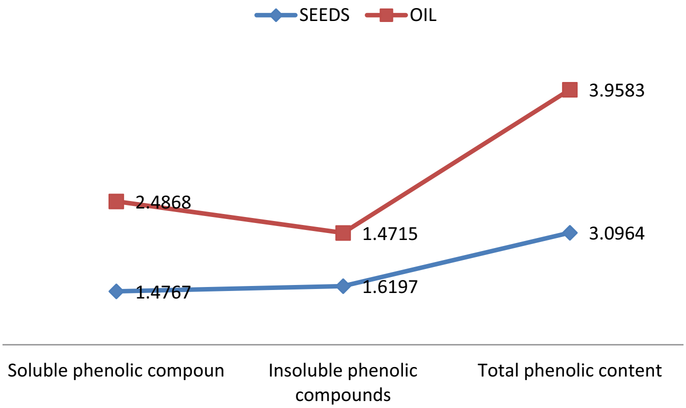


Fig. 5 Total phenolic compounds of tomato seed and oil extracted

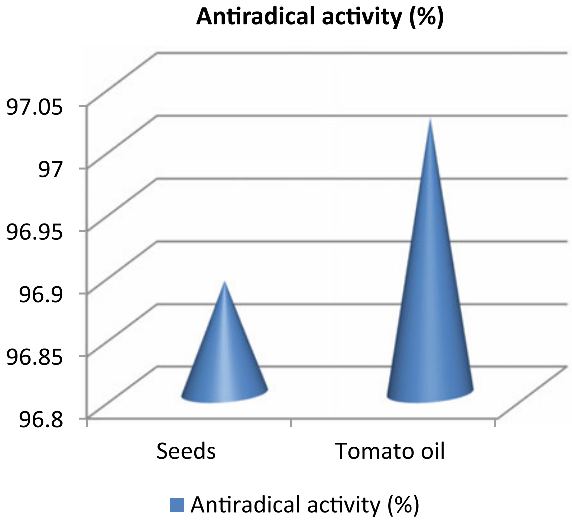


Fig. 6 Antiradical activity of tomato seed and oil

4 Conclusion

Lycopene was extracted from two different methods of COSE and UAE from tomato pomace by using solvent. From these two methods highest amount of lycopene was extracted in UAE at 160 V for ratio 50:1 for 15 min. High content of Beta carotene was found in UAE at 50: 1 for 20 and 30 min at 180 V. These readings showed the wise efficiency of UAE as compared to COSE. FTIR examines the purity of lycopene and quantifies its compounds. Antioxidant activity such as DPPH (2,2-diphenyl-1picrylhydrazyl) and total phenolic compound was performed. Lycopene shows the highest antiradical activity in comparable to tomato dried peel. Extracted lycopene can be incorporated at various food products for human consumption. Due to red dark bright colour and appearance of tomato oil was of great influence to eyes. Its antiradical activity determines its antioxidants potential. Peroxide value, acid value, iodine value, free fatty acids allows its edibility so can be further used for human consumption for the beneficial of human society.

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Sustainable Valorization of Waste from Mango Processing Sector

Jyoti Nishad and Aaruni Jaiswal

Abstract Mango has high demand in processing industries. Tremendous expansion of mango processing has contributed significant amount of biowaste mainly in the form of skin and kernel. Accumulation of this agro-industrial waste pose a serious economical and environmental burden. Mango biowaste is a potential source of numerous functional and bioactive compounds including pectin, dietary fiber, polyphenols, carotenoids, etc. Presently with the advent of new sustainable technologies, value addition of biowaste has gaining popularity and playing a vital role in the growth of the food industry. Many green extraction techniques are now available for significant extraction of bioactive compounds. These compounds have promising commercial applications in food, biotechnology, pharmaceutical and cosmetic industries. Further, biowaste streams can be properly managed by using biorefinery for development of value added products such as bioenergy, biofuel, etc. This book chapter highlights the valuable mango by-products and the recent sustainable approaches for conversion of biowaste into diverse value-added products for their management.

Keywords Bioenergy · Biofuel · Mango biowaste · Polyphenols · Bioactive compounds

1 Introduction

With increase in global population and demand for processed, healthy and nutritious food there is tremendous increase in food processing industries worldwide. In the developing countries like India these industries are swiftly evolving and providing more market opportunities to farmers. This has had a significant impact

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on the massive amount of biowaste, which is primarily produced by the fruits and vegetable processing industries due to the variety of processed food products. Mango (*Mangifera indica*) is one of the important tropical fruits with 58.3 million metric tons global production (Mango Production by Country 2023). Mango has gained high demand in food processing industries due to large market potential of mango products and around 16% of the mango production is utilized for processing.

A tremendous quantity of waste is produced during mango processing and value addition, primarily in the form of peels and seeds, sometimes known as stones (Cheok et al. 2018; Jahurul et al. 2015). Depending upon the mango variety the peel weight may vary from 7–24% and seed around 20–60%. Thus, in general, the processing of mangoes produces millions of tonnes of solid waste, which corresponds to 30–50% of the raw material. The standard waste disposal system is comprised of 3 R's- reduce, reuse, and recycling. This mango industry waste can be reused using sustainable approaches. Mango kernel and peels are enriched with various bioactive compounds including polyphenols, carotenoids and dietary fibers, edible oil, various vitamins, and enzymes. The antioxidant, anti-microbial and anti-inflammatory properties of these compounds have been well established. Thus, valorization of mango processing waste into value added and functional products is a new avenue for food industries, pharmaceuticals, and cosmetic industries. Besides, these can serve as a raw material for biofuel and bioenergy production, alleviating the energy crisis from non-renewable sources. Various extraction methods have been implemented for extraction of bioactive compounds from waste which has numerous applications in supplementations of foods such as pasta, bakery products, dairy products, beverages, breakfast cereals, and ice cream (Owino and Ambuko 2021). Mango peel has substantial amount of aromatic compounds which can be reused in the processed mango products as flavoring agents and perfumeries (Oliver-Simancas et al. 2020).

Mango kernel is a potential source of edible oil (15%) with low peroxide value and free fatty acids. Blend of mango kernel oil and palm oil yields a unique combination of palmitic, stearic and oleic acid which is comparable to cocoa butter. Thus, it can be exploited as an alternative to cocoa butter in chocolate making (Mwaurah et al. 2020). This review concentrates on current mango processing and value addition trends that are relevant to micro, small, and medium-sized food processing businesses.

2 Mango Fruit Structure and Composition

Mango fruit is a complete large drupe developed from the ovary post fertilization. The mango fruit may be oval, ovoid-oblong and round, most of the times accompanied by a beak at the apex. Generally, it contains a minimally thick, leathery, aromatic skin ranging from light–dark green to clear yellow and reddish-yellow, when fully ripe. The fruit when mature develops a characteristic fragrance and a smooth, thin skin. The flesh of mango broadly rich in vitamin A, C and D is considerably juicy with fibres originating from a solitary, ovoid-oblong seed enclosed in a stiff, fibrous endocarp and accounts for 50–60% of the fruit. The energy value for 100 g of the pulp ranges from 60 to 190 kcal (250–795 kJ), entitled to be a paramount fruit for the human diet (Diczbalis et al. 1997; Boudon et al. 2020). However, there are a large number of variations in the form, size, shape, color and quality of fruits. The pericarp of fruit comprises of the following—exocarp, mesocarp and endocarp. The exocarp has a cuticle, single-celled epidermal layer and definite thick cell wall layers (Khadivi et al. 2022). The vital polysaccharide in mesocarp of immature mango fruit is starch. These granules of starch disappear during fruit ripening owing to distinguished levels of hydrolysis. Interstitial void is another distinguished structural change during ripening. The pectin available in the middle lamella functions as a cementing agent thereby joining the cells together via calcium ions. On esterification (or during ripening) the integrity of cells alleviates and softens (Wakabayashi, 2000; Han et al. 2006; Preethi et al. 2014; Khadivi et al. 2022). Due to the presence of vital components mango fruit has a great nutritional value thereby providing immense health benefits. These components are segregated as macronutrients- 53.34–76.81% of carbohydrates such as sugars namely glucose, fructose, sucrose and others include cellulose and pectin, fatty acid, lipid, organic acids and 5.20–10.48% of proteins comparatively in low quantity with respect to other macronutrients; micronutrients comprised of vitamins which includes all B-complex vitamins except for biotin and minerals and phytochemical constituents (phenolic, pigments, polyphenol and volatile). The phytochemicals possess a high antioxidant, anticancer, antimicrobial and antidiabetic properties and are known to be found in mango kernels in excessively large quantities (Lebaka et al. 2021; Khadivi et al. 2022). Mango pulp have low quantities of lipids and fatty acids but on the contrary mango seeds are a rich source of lipid. The substantial amino acid encompasses arginine, cysteine, leucine, lysine, methionine, phenylalanine and valine. The composition of lipid aggravates during ripening especially the omega-3 and omega-6 fatty acids. The indispensable pigments accountable for change in color and metabolism of mango fruit are chlorophyll and carotenoids. The crucial organic acids involved for conferring fruit acidity are citric and malic acid. However, the nutritional composition of mango depends particularly on its type/variety, its locality and the climatic conditions and moreover on the maturity of fruit (Lebaka et al. 2021). Tables 1 and 2 depicts the proximate composition of mango kernel and mango peel, respectively.

Table 1 Proximate composition of Mango Kernel (*Source* Sagar et al. 2022)

Constituents	Proximate composition (%)
Moisture	27.5
Carbohydrate	36.36
Protein	5.24
Crude fiber	1.50
Ash	1
Total fat	7.84
Energy content (KJ/100 g)	236.96

Table 2 Proximate composition of Mango Peel (*Source* Reddy et al. 2011)

Constituents	Proximate composition (%)	
	Fresh Mango Peel	Dried Mango Peel
Moisture	70 ± 5	10 ± 1.2
Total solids	25.6 ± 4.6	70.5 ± 2.7
Reducing sugars	7.0 ± 1.8	30 ± 2.5
Non-reducing sugars	5.9 ± 0.4	4.3 ± 0.5
Protein	3.5 ± 0.5	4.0 ± 0.8
Cellulose and Lignin	25.2 ± 2.0	23 ± 1.2

3 Mango Fruit Processing Industry and Products

Owing to several factors such as the rapid drift of urbanization, and an increase in health consciousness amidst consumers, a sudden switch towards nutritious food custom particularly manufactured using natural ingredients is observed (Owino and Ambuko 2021). The chief fruit mango widely cultivated in the tropical and subtropical regions where India contributes to around 50% of the world production. The fruit has a pronounced caliber and is generally not only consumed in its natural state but also processed at two phases of its maturity into several nutritious and shelf-stable products. The particularly unripe fruits are used in the formulation of products like chutney, curry, pickles and various other parched commodities whereas ripe ones are processed into purée, canned and frozen slices and juices (Salvi et al. 2017; Evans et al. 2017). Such processing practice enables evolution of a diverse range of products deftly and renders the seasonal fruit available to the consumers all year long. Since the consumers all over the world are gradually getting aware of such essentialities therefore the processed mango product market is on high rise (Zafar and Sidhu 2017). On the basis of the type of cultivar the mango flesh constitutes about 40–60% of the total weight of fresh fruit and contributes to the consumable portion of the fruit that contains functional and nutritional compound (Akin-Idowu et al. 2020). The mango pulp is prepared from certain fresh varieties of the mango fruit that are fully mature. They are washed, blanched, deseeded, pulped, homogenized, centrifuged, concentrated, thermally-processed and aseptically packed, sealed and retorted in a sterile environment. However, the process is executed in a controlled manner to avoid any loss of natural flavor and aroma (Zafar and Sidhu 2017; Lebaka et al. 2021). Mango pulp is a base ingredient used for the processing of mango juice (Adedeji and Ezekiel 2020); mango juice concentrates (Sakhale et al. 2016); mango squash (Muslim et al. 2021); cordial, mango leather, jam and jellies (Salvi et al. 2017); mango nectar (Kumar et al. 2019); probiotic drink, mango wine, pickles (Owino and Ambuko, 2021); and mango powder (Tonin et al. 2018).

4 Mango Processing Waste

Amongst the most cultivated tropical fruits in the world, mango, is one such recurring fruit with a restricted shelf-life since the quality of fruit declines post ripening (Gurumeenakshi et al. 2019). Also, tonnes and quintals of the mango by-products (peel, seed, kernel) are generated subsequent to the processing and augmented values leading to acute complications of dumping that would perhaps be a hazard to the nature causing asphyxiation, greenhouse gas emission, microbial growth, malodor, floral harm, soil contamination, and water contamination (Siddiq et al. 2017). The nutritional, physiochemical and bioactive rich by-products normally include peels and seeds which are generally rich in multiple compounds such as fibers, calories, vitamins, mineral, polyphenols, carotenoids, fatty acids, etc. and are expected to be restored via efficacious mechanical techniques so as to obtain a sustainable valorization strategy that is economically safe and environmentally attainable. A number of such biologically active components have the aptitude to recycle effluent stream into elemental components for utility purpose (Jahurul et al. 2015; Sharma et al. 2016; Cheok et al. 2018). Table 3 revealed the various applications of different mango waste.

Depending on the kind of diverseness, the peels adds up to 7–24% of the weight of fruit containing reminiscent mass of moisture, mangiferin, beta carotene, cellulose,

Table 3 Mango waste valorization

Part of mango	Component used	Application	References
Peels	Carotenoids	Antioxidant in edible oils	del Pilar Sanchez-Camargo et al. (2019)
	Polyphenols	Antioxidant in edible oils, pharmaceuticals, cosmetics	Safdar et al. (2017)
	Ethanol	Active-film packaging	Widsten et al. (2017)
	Resorcinol and mangiferin	Functional foods, pharmaceuticals, cosmetics	Espinosa-Espinosa et al. (2022)
Kernel	Tannins	Leather industry	Correa et al. (2019)
	Starch	Packaging Food industries (bakery products, beverages, soups) Pharmaceuticals	Adilah et al. (2018), Torres-León et al. (2016)
	Kernel oil	Cosmetic industry Food industry	Wu et al. (2015), Nadeem et al. (2016)
Husk	Cellulose and Hemicellulose	Adsorbent material (activated carbon), Bioenergy	Elizalde-González and Hernández-Montoya (2007), Arora et al. (2018)

hemicelluloses, protein, and protocatechuic acid; the seed constitutes about 20–60% of the weight of the fruit and conversely the kernel constitutes 45–75% of the mass of seed whilst being a storehouse of macro- and micronutrients and producing storage resistant products with consummate organoleptic, nutritional and various quality attributes (Sharma et al. 2016; Sagar et al. 2018). It has been delineated that the mango seed is the ascendant agro-industrial leftovers approximately about 50% of the raw material and is quite biological oxygen demanding (Sagar et al. 2018). Therefore, aggravating the overall cost of production due to the added high-cost transportation, waste disposal and doubtful landfills vacancy. Nevertheless, these challenges are directed by formulating value added products or incorporating it in the currently available commodity and enhancing its efficiency (Sharma et al. 2016; Wall-Medrano et al. 2020). The oil obtained from the mango kernel measures approximately 15% of the edible oil and is examined to be avant-garde, economical and feasible due to its phytochemical as well as physicochemical possessions.

The by products are accumulated and conveyed to biogas plant for the production of marsh gas and the treated compounds are further utilized as manure and other organic fertilizers (Jahurul et al. 2015; Serna-Cock et al. 2016; Mutua et al. 2017). The starch present in the mango kernel has certain amylose content and its swelling capacity portends it application in personal hygiene and other selfcare/grooming manufactures. Pectin procured from the peel is used as an alternative to thickening agents and preferred over gelatin and such products are even labeled as “vegan” (Gupta et al. 2022). The outer fibrous portion of mango seeds, the husks are fabricated of cellulose and hemicellulose can serve as an alternative source of activated carbon and derivatives such as nanocrystals and nanowhiskers (Zuin et al. 2020). Despite it being quite challenging to recover and completely re-harness the organic compounds from the discarded parts of the mango fruit, the relevant mango by-products have major suitable applications in the packaging, cosmetic, food and pharmaceutical industries (Cheok et al. 2018; Gurumeenakshi et al. 2019).

5 Different Waste Valorization Approaches: Bioactive Extract, Pectin Extract and Other Components

The secondary metabolites obtained from fruits, vegetables, grains and nuts in compact proportions are particularly bioactive compounds that exhibit certain wholesome properties such as anticarcinogenic, anti-inflammatory, antimicrobial and antioxidant properties designated to provide definite health aid (Aggarwal et al. 2017; Rodriguez Garcia and Raghavan 2022). A number of possible applications of mango peel and kernel extracts are pertained to the prior given factors, however keeping in mind the variety (Okino Delgado and Fleuri 2016).

5.1 *Valorization of Mango Peel*

5.1.1 Production of Ethanol

Direct fermentation on supplementing nutrients such as yeast extract, peptone and wheat bran yields the final ethanol yield of approximately 7.14% (w/v). Yeasts particularly including the thermotolerant and alcohol tolerant yeasts (capable of growing at 40 °C) are exploited for producing ethanol from mango peels and the ultimate ethanol concentration of 13 g/L was estimated within 120 h (Reddy et al. 2011; Somda et al. 2011). The bioethanol obtained is economically and environmentally viable enough to alternate petrol. The ethanolic peels of mango are used with polymers such as polyvinyl alcohol (PVA), cyclodextrin and gelatin as constituents of manufacturing process in the film packaging industry considering the perishable and semi-perishable food products and extend its shelf life provided, they are kept under refrigeration (Mok et al. 2014).

5.1.2 Mango Wine Fermentation

Mango processing wastes can acclimate as potential feedstock for wine manufacturing and correspondingly alternate for dumping polluting residues. Mango wine fermentation via yeast-mango peel immobilized biocatalyst system has been recorded in the recent years (Sadineni et al. 2012). The operational stability of the biocatalyst system was found appropriate for winemaking at low temperature (Mok et al. 2014).

5.1.3 Lactic Acid Fermentation

The production of lactic acid from the discarded peels of mango has been efficaciously determined (Jawad et al. 2013). Direct fermentation of mango peel using bacteria capable of producing both amylolytic and lactic acid has been reported. On statistically optimizing the fermenting conditions, the maximal lactic acid produced was approximately 17.484 g/L while in the other case mango peels when fermented by *Lactobacillus casei,* the lactic acid concentration was found to be 63.33 g/L (Mudaliyar et al. 2012). The variation in the two is by virtue of the pretreatment via steam explosion succeeded by acid hydrolysis of the scrap prior fermentation. Such treatments tends to increase the amount of fermentable sugar in the medium therefore eliciting the overall yield of lactic acid.

5.1.4 Pectinase Production

The competency of mango peel as a low cost substrate for pectin production has been recorded. They are known to be a storehouse of pectin and microbes (efficient enough to degrade pectin such as the filamentous fungi). The pectin restored via solid–liquid extraction also generates a true value as a thickener, gelling and stabilizing agent in the agri-food continuum and cosmetic industry (Kumar et al. 2012 and Mok et al. 2014).

5.1.5 Animal Feed

The discarded mango peels generated as domestic waste are also used as a feed to animals owing not only for its extreme energy value and excessive sugar content but also for its application in alleviating greenhouse gas (Sruamsiri and Silman 2009; Geerkens et al. 2013). The below par non-fermented agro-products when ameliorate post fermentation with certain fungi render an appreciable nutritious animal feed (Mok et al. 2014).

5.1.6 Phenolic Antioxidants

Polyphenols are known to exhibit antioxidant, antiviral, antibacterial and anti-inflammatory activity (Aggarwal et al. 2017; Ekorong Akouan Anta et al., 2018). The mango peels are significant sources of phenolic compounds such as syringic acid, quercetin, mangiferin pentoside and ellagic acids. The peels are also used as immunity enhancer due to components such as mangiferin, phenol and resorcinol that portends antioxidant and anti-inflammatory activities (Ajila and Rao 2013; Okino Delgado and Fleuri 2016). A latest study was undertaken wherein phenolic compounds from mango peels were adequately extracted employing subcritical water (SCW) and the procured solvent was reviewed to be sustainable in expressing bioactive compounds and consequently be pertinent for the food industry (Tunchaiyaphum et al. 2013).

5.1.7 Rich Source of Carotenoids

It is even contemplated that the bioactive compounds present in the agro-industrial mango waste has gained high functional values due to the presence of carotenoids in excessive quantities that is known to possess substantial vitamin A activity due to high beta-carotene (Mercadante and Rodriguez-Amaya 1998). The carotenoid content is more in peel on account of advanced physiological ripening when in contrast with the peel with partial ripening (Ajila et al. 2007; Varakumar et al. 2011). While the carotenoids in chloroplasts and chromoplast of fruits and vegetables are pigments (red, orange, yellow) and used as colorants in cosmetic as well as food products (del Pilar Sanchez-Camargo 2019).

5.2 Valorization of Mango Kernel

5.2.1 Active Packaging Industry

Mango kernels are also treated with binate fusion of ethanol and water to extract antioxidants. The key compounds identified in the mango kernel were gallic acid, caffeic acid, rutin, and penta-O-galloyl-β-D-glucose (Lim et al. 2019). Due to the presence of such components the mango kernel determines its key potential applications in active packaging via mixing the kernel starch, kernel fat and phenolic extract. The omnipresence of the mango kernel extract aggrevates certain physical attributes of the film such as its antioxidant activity, tensile strength and thickness (Melo et al. 2019).

5.2.2 Functional Food Ingredient

Hereupon, the presence of starch in mango kernels impart the latter with commendable functional properties and are used as a food additive (as soup pre-mixes and considered to be an alternative for cornflour provided there were minor differences in their storage life and sensory properties), food thickener and stabilizers (Zuin et al. 2020). Furthermore, the seed kernel is a repository of phytochemicals that boosts human health and averts the maturation of pathogenic organisms.

5.2.3 Production of Mango Kernel Oil

It is customarily determined that the discarded mango kernels churn out a fine quality edible oil (extracted by hexane) with distinguished functional and oxidative stability (Kittiphoom and Sutasinee, 2013). Mango kernel oil obtained is a pale-yellow commercial oil containing lower content of carotenoids and higher phenolic compounds like mangiferin, chlorogenic acid, quercetin and caffeic acid. Mango kernel oil also finds its application in the cosmetics industry in soaps, shampoos and lotions (cocoa butter alternative) because of a rich source of phenolic compounds and microelements such as selenium, copper and zinc (Kittiphoom and Sutasinee 2013; Melo et al. 2019). Besides, its use in the cosmetic industry it is also used as an ingredient in the food industry in formulating nutrition rich food such as in preparing muffins and biscuits.

6 Conclusion

Biowaste from mango processing industry has tremendous commercial value and require a sustainable approach for its utilization. Substantial amount of several bioactive compounds are present in the processing waste having promising anti-oxidative, anti-inflammatory, anti-carcinogenic, and antimicrobial properties. Green extraction of these bioactives is being a researchable topic in past many years and several sustainable technologies have been successfully implemented for extraction. Polyphenols from mango waste have found wide applications in pharmaceutical, cosmetics and food industries. Comprehensive utilization of kernel and peel powder, and extract in the production and supplementation of food and non-food products is also a hotspot in research. Recent studies have also revealed potential application of functional compounds from mango waste in active packaging where antimicrobial activity of polyphenols enhance the product shelf life. These biowastes are also a potential raw material for energy generation which satisfy both economic and environmental concerns. Further research is needed for effective utilization of waste in developing pomace-based products with commercial applicability and by channelizing the bioactive compounds in functionalization of different products.

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Sustainability in Production of Enzymes From Fruit and Vegetable Waste

Anila Zahid and Renu Khedkar

Abstract The management of waste has become a significant economic and environmental challenge as a result of the massive increase in waste generation throughout the world. According to the Food and Agricultural Organization of the United Nations, 14% of the world's food, valued at $400 billion annually, is lost between harvest and the retail market, while 17% of food is wasted at the retail and consumer levels. There are a number of by-products in the large amount of fruit and vegetables wastes that are useful for a diverse range of industries. Various food and vegetable wastes can be used to produce a wide variety of industrial enzymes. The extracted enzymes, is utilized in food research, pharmaceutical, cosmetic, organic acid, and chemical industries. This chapter mainly focuses on the sustainable utilization of fruits and vegetables waste to produce a number of crucial enzymes for food industry, including phytase, pectinase, amylase, cellulase, pectinase, protease, organic acids like acetic acid, lactic acid, etc. are produced using a variety of microorganisms that have been isolated from various dietary wastes.

Keywords Enzymes · Waste · Bioactive compound · Organic acid · Sustainability

1 Introduction

With the growing population across the world, researchers are working towards the rising of yield of food materials especially fruits and vegetables and cereals to meet the demand. During 2021–22, India produced 107.24 million metric tonnes of fruits and 204.84 million metric tonnes of vegetables. Fruits were grown on an area of 7.05 million hectares, while vegetables were grown on an area of 11.35 million hectares (APEDA 2023). India ranks second in the world with a global output share of 10% and 14% for fruits and vegetables, respectively (Das and Mondal 2013; Ingale et al. 2014). Out of the total fruits and vegetable production, in India around, 30–40% of the product is lost at the supplier, retail, consumer, post-harvest, and processing levels.

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We suffer tremendous economic losses as a result of inadequate postharvest management methods, but increased awareness about the benefits of processing perishable commodities has led to an increase in agricultural commodity processing globally (Zahid and Khedkar 2021; Thakur et al. 2020). This results in a massive amount of horticulture residues or waste. The estimated value of these wastes is around USD 483.9 million (Sridevi and Ramanujam 2012). These fruits and vegetables are high in organic matter, phytochemicals, and nutraceutical components. The lack of enough infrastructure to handle a high amount of biodegradable material (biomass) causes environmental contamination (Sharma et al. 2016). The decomposition causes an unpleasant foul odor and the proliferation of diseases since there is organic matter present and there is a lot of moisture (Singh et al. 2011). The majority of these wastes are generally decomposed on land or may be used for landfilling but get spoiled and not only cause only detrimental effect to environment as well as attracts birds or animals etc., which may lead to various illnesses because they include biodegradable material. It consists of skin, moldy peel, shells, seeds, and more. As a result, the researcher's attention is now moving towards utilization of fruits and vegetables on a worldwide scale. Innovative technologies are designed to convert these wastes in the production of enzymes, organic acids, etc. (Thakur and Modi 2020; Zahid and Khedkar 2021).

However, according to the United Nations Food and Agricultural Organization (FAO), the major losses somewhat around 20% were reported production and processing level. The food industry processes large amounts of fruits and vegetables to make pickles, sauces, purees, juice, etc. 30–50% of the input raw material is made up of industrial leftovers from processing industries (Di Donato et al. 2011). Additionally, it is a big worry that vast amounts of fruit and vegetable waste are dumped, as this contaminates the soil and water. The amount of greenhouse gas released by the food wastes is estimated to be 4.14 t of CO_2 equivalent per ton of discarded food (Oelofse and Nahman 2013).

It is well recognized that fruit and vegetable wastes (FVW) can be successfully converted into products including enzymes, organic acids, flavoring compounds, food colorants, bioethanol, and biomethane by microbial processing (Laufenberg et al. 2003). Some scientists have created genetically altered microbes by introducing the desired genes for excessive production of such compounds. The enzymes, organic acids, colorants, biofuels, and other biological products have been successfully overexpressed through the use of modifications to biochemical pathways, protoplast fusion, and metabolic engineering.

The objective of this chapter is to examine the significant methods for using fruit and vegetable wastes to produce various and necessary enzymes, including amylases, lignocellulases, pectinases, tannases, proteases, and lipases, through microbial processing and its applications in different food industries. Several different technologies i.e., the metabolic engineering of microorganisms for enhanced bioproduction have been incorporated in the production of enzymes through fruit and vegetable wastes. However, this review will exclusively focus on the upscaling procedures of producing enzymes from fruit and vegetable wastes.

2 Microbial Processing

Microbial processing, also abbreviated as microbial bioprocessing or biodegradation, i.e., the use of microorganisms to break down organic matter or pollutants into simpler and often harmless substances. This natural process plays a critical role in various ecosystems and has been harnessed by humans for a wide range of applications, including waste management, bioremediation, and the creation of items with value-addition. It is known that several types of microorganisms are employed in the transformation of fruit and vegetable waste into novel bio-products by using different micro-organisms such as *E.Coli, Lactobacillus species (spp.), Streptococcus spp., Saccharomyces spp., Pediococcus spp., Saccharomyces cerevisiae e*tc. For instance, *Saccharomyces cerevisiae* is commonly known as "brewer's yeast" as it produces alcohol by fermentation of different malted cereals and fruit juices (Walker and Stewart 2016), and vinegar is a food product made by acetic acid bacteria that can ferment the alcohol in alcoholic liquids to acetic acid (Raspor and Goranovic 2008). Additionally, by using bioprocessing technology, *Saccharomyces cerevisiae* is utilized to bioenrich fruit and vegetable wastes with protein to prepare feed (Correia et al. 2007). Similarly, *Aspergillus species* is responsible for the production of organic acids such as citric and lactic acid from fruits and vegetable wastes and the popular strain like *Bacillus species* is utilized for the production of enzymes including cellulase, amylase, and protease (Mussatto et al. 2012). Depending on the physical condition of fruit and vegetable wastes, different microbial technologies are adopted for the synthesis of enzymes. These microbiological processing methods can be broadly divided into two categories: (i) solid state fermentation (SSF), and (ii) submerged fermentation (SmF) (Ray and Ward 2006).

3 Enzyme Production

Enzymes serve as biological catalysts for a variety of chemical reactions within living organisms. Usually, they are proteins, although some enzymes may contain RNA molecules (known as ribozymes) that also exhibit catalytic activity. Enzymes play a crucial role in the metabolism of cells, helping to accelerate the rates of specific biochemical reactions that are essential for life. Enzymes are responsible for performing various metabolic functions of the body (Chapman-Smith and Cronan 1999). Some enzymes require the amino acid sequence and either a co-factor (one or more inorganic ions) or a co-enzyme (organic or metallo-organic molecule) in order to function (Lehninger et al. 2005). In today's scenario, there are several industries that use enzymes in their processes. For instance, pectinases and amylases are used in industries such as bakery, beverage, etc. Tannases are used to lower the amount of tannic acid in tannery effluent while cellulases are utilized in the biofuel industry. The applications of enzymes in different industries have been presented in Table 1.

They have been employed in a variety of industries including bakery, meat, brewing, textile, and dairy (Saini et al. 2017).

Enzymes are the biomolecules that support a number food processing industry. For instance, amylases are widely employed in industries for the production of syrups, cheese, fruit juices, and chocolate cakes (Laufenberg et al. 2009; Toumi et al. 2016; Sagar et al. 2018). The most common fruit and vegetable wastes used for production of amylases are banana peel (Oshoma et al. 2019), orange peel (Uygut and Tanyildizi

Table 1 Application of fruit and vegetable wastes (FVWs) to produce enzymes

S.No	Enzymes	Purpose	(FVWs) for Enzyme Production
1	Amylases	Production of cheese, chocolate pastries, fruit liquids (Toumi et al. 2016; Saini et al. 2017); brewing, textile, and pharmaceutical industries (Saini et al. 2017)	Banana waste (Oshoma et al. 2019); orange peel (Uygut and Tanyildizi 2018); potato waste (Pereira et al. 2017); date waste (Acourene et al. 2014; Sagar et al. 2018), rice bran (Almanaa et al. 2019); mango waste (Kumar et al. 2013; Sagar et al. 2018)
2	Invertase	Production of chocolates, lactic acid, glycerol, sweets, artificial sweeteners, invert sugar, and confectionary (Sagar et al. 2018; Veana et al. 2018; Mashetty and Biradar 2019), pharmaceutical product creation and rise in product shell life (Kumar and Kesavapillai 2012; Panda et al. 2016; Sagar et al. 2018)	Pineapple waste (Oyedeji et al. 2017); pomegranate waste (Uma et al. 2012); papaya waste (Chelliappan and Madhanasundareswari 2013)
3	Pectinase	Production of fruit juices and wine (New et al. 2018; Nighojkar et al. 2019); extraction of pigments (Munde et al. 2017) and essential oils from leftover fruit and vegetables (Castilho et al. 2000; Sagar et al. 2018); the process of making superior paper (Ahlawat et al. 2008), for the treatment of pectic waste and the brewing of coffee and tea (Kashyap et al. 2001)	Citrus peel (Ahmed et al. 2016); banana waste (Sethi et al. 2016); mango shell (Kuvvet et al 2019); sugarcane peel (Biz et al. 2016), pineapple waste (Kavuthodi and Sebastian, 2018)
4	Cellulases	Detergent manufacturing, the food sector (Imran et al. 2016); and biotechnology at industrial level (Bajaj and Mahjan 2019)	Potato waste (Taher et al. 2017); orange peel (Srivastava et al. 2017); Pineapple waste (Oyedeji and Ojekunle 2018); cucumber, banana waste (Viswanath et al. 2018)
5	Xylanases	Creating paper, biofuels, food, and textiles, as well as enhancing animal feed (Kumar et al. 2018)	Banana waste (Zehra et al. 2020); passion fruit wastes (Martins et al. 2018); cassava waste (Olanbiwoninu and Odunfa, 2016); orange waste (Silva et al. 2018)

2018), potato peels (Pereira et al. 2017), date wastes (Acourene et al. 2014; Sagar et al. 2018), rice bran, wheat bran (Almanaa et al. 2019), and mango kernels (Kumar et al. 2013; Sagar et al. 2018). 'Invertase' is the name given to the enzymes employed in the synthesis of invert sugar, artificial sweeteners, chocolates, lactic acid, glycerol, sweets, and confectionery (Sagar et al. 2018; Veana et al. 2018; Mashetty and Biradar 2019). Sucrose, lactose, and fructose must all be present in the fruit and vegetable wastes that are used to make these enzymes (Sagar et al. 2018). FVW that has been so far used is pineapple peel (Oyedeji et al. 2017); pomegranate peel (Uma et al. 2012); papaya peel (Chelliappan and Madhanasundareswari 2013). Apart from their roles in food industries, it is used for production of pharmaceutical products and extension of shell life of products (Kumar and Kesavapillai 2012; Panda et al. 2016). Similarly, pectinase is used in brewing industry i.e., used in the synthesis of wine and fruit juices (New et al. 2018; Nighojkar et al. 2019). This enzyme is also responsible for the extraction of pigments (Munde et al. 2017), and essential oils from fruit and vegetable wastes (Sagar et al. 2018; Castilho et al. 2000). Additionally, it is consumed in the synthesis of good quality paper (Ahlawat et al. 2008; Rebello et al. 2017). Also, utilized on the treatment of pectic waste during the fermentation of tea and coffee (Kashyap et al. 2001; Rebello et al. 2017). The citrus peels (Ahmed et al. 2016); banana waste (Sethi et al. 2016); mango waste (Kuvvet et al. 2019); sugarcane bagasse (Biz et al. 2016), pineapple stem (Kavuthodi and Sebastian 2018), have been used for the production of pectinases.

The researchers have developed the technologies for the production and stability of enzymes via residual or inexpensive substrates. The current section highlights the fruits and vegetables wastes utilization for obtaining quality product as well as their microbial processing to create beneficial enzymes that can be widely commercialized. Some importante enzymes produced using microbial processing are described in Table 2.

The following are the enzymes which are majorly used in the food industries and produced by the utilization of fruit and vegetable wastes:

3.1 Amylases

Amylases are starch-degrading enzymes that aid in the hydrolysis of internal alpha 1–4 glycosidic linkages in polysaccharides while preserving the end products' alpha anomeric structure (Saini et al. 2017; Takata et al. 1992). Amylases are a group of enzymes that play a crucial role in the breakdown of complex carbohydrates into simpler sugars. They are part of the larger family of enzymes called hydrolases, which catalyze the hydrolysis of chemical bonds using water. Amylases are found in various living organisms, including animals, plants, and microorganisms, and they serve essential functions in biological processes and industrial applications. Plants store their carbohydrates mostly as starch, whereas mammals and fungi store their glucose as glycogen. By cleaving the glycosidic bonds between glucose units, amylases convert starch and glycogen into smaller, soluble molecules like maltose,

Table 2 Enzymes production from fruit and vegetable wastes (FVWs) via microbial processing

S.No	Enzymes	Substrate	Microbes	References
1	Starch degrading enzymes	Loquat waste, Mango waste, Cassava waste, Banana waste, Date wastes, Potato waste	*Fusarium solani, P. expansum, Rhizopus stolonifera, Bacillus subtilis, and Aspergillus niger, Candida guilliermondii* CGL-A10, *B. licheniformis Bacillus subtilis*	Erdal and Taskin (2010), Kumar et al. (2013), Pothiraj et al. (2006), Unakal et al. (2012), Kokab et al. (2003), Acourene and Ammouche (2012), Shukla and Kar (2006)
2	Lignocellulosic waste degrading enzymes	Banana waste, orange bagasse, banana waste, palm oil fiber, and kinnow fruit waste, Sapota waste	*Trichoderma reesei, P. fleuroscence, P. putida, B. megaterium, Thermoascus aurantiacus*	Norsalwani and Norulaini (2012), Oberoi et al. (2010), Silva et al. (2005), Dabhi et al. (2014), Saravanan et al. (2012)
3	Pectin degrading enzymes	Pineapple waste, Orange waste, Apple peels, cashew waste, Date waste; Jack fruit peel	*A. niger, P. chrysogenum, A. foetidus, A. oryzae, Eupencillium javanicum, B. subtilis* EFRL 01	Okafor et al. (2010), Mrudula and Anitharaj (2011), Venkatesh et al. (2009), Akbar and Prasuna (2012), Rao et al. (2014), Patil and Deshmukh (2015), Dhillon et al. (2004), Tao et al. (2011), Qureshi et al. (2012)
4	Tannase	Cherry waste, Cashew waste, apple peel, bagasse, Grape waste	*A. species, P. species, Trichoderma viride*	Lima et al. (2014), Prommajak et al. (2014), Paranthaman et al. (2009)
5	Protease	Outer covering of bean, Pomegranate peel, Karat peel, Potato peel	*A. species, B. subtilis*	Radha et al. (2012), Oyeleke et al. (2011)
6	Lipase	Coconut waste, Mahua waste, Lemon waste	*Chaloropsis thielarioides, Lasiodiplodia theobromae, Aspergillus niger*	Venkatesagowda et al. (2014), Kumar and Kanwar (2012), Parihar (2012)

(continued)

Table 2 (continued)

S.No	Enzymes	Substrate	Microbes	References
7	Invertase	Pineapple peel, Banana waste, Chikku, Orange, Pineapple waste, Pomegranate waste	*A. niger, A. flavus*	Mehta and Duhan (2014), Uma et al. (2010)
8	Carboxymethyl cellulase (CMCase)	Mango waste	*Paenibacillus polymyxa*	Kumar et al. (2012)
9	Endoglucanase, betaglucosidase	Corn waste	*F. oxysporum*	Panagiotou et al. (2003)
10	Phytase	Orange pulp	*A. niger*	Spier et al. (2010)
11	Endopectinase	Date peel	*A. niger* PC5	Bari et al. (2010)

maltotriose, and glucose. Because of their wide range of actions, amylases are the most studied enzymes across all categories (Noomen et al. 2009). In an effort to take advantage of their physiological and biotechnological applications, this huge diversity of amylases, in contrast to the specificity of their activity, garnered global attention.

Due to their relative ease of large-scale synthesis (cheap downstream cost because they are extracellular in nature) compared to amylases from plants and animals and their usefulness in afterwards applying at industry, amylases of bacteria, fungus, and viruses are being explored more and more (Ashis et al. 2009). The major constituent od starch are amylase, a highly branched D-glucose chain called amylopectin amylopectin that is composed of an unbranched linear chain of D-glucose residues connected by 1–4 links. Exo-amylases and endo-amylases are two categories for amylases based on how they hydrolyze substances. The types of amylases are shown below in Fig. 1.

Exo-amylase attacks α—1–4 bonds, and other exo-amylases, like glucoamylase, target both α—α-1–4 bonds and α-1–6 bonds to create maltose and glucose, which are simpler sugars (Kar and Ray 2008). The α-1–4 bonds in starch are broken down by endo-amylase, however, amylopectin and other analogous complex polysaccharides α-1–6 linkages are unaffected. The best example of an endo-amylase is alpha amylase. Alpha amylase is in charge of breaking down starch into various oligosaccharide fragments. While glucoamylase can target the non-reducing ends of the starch, alpha-amylase can act on arbitrary sites on the starch (Horvathova et al. 2000). The loquat (Eriobotrya japonica Lindley) kernels, a waste produced from loquat fruit (a prominent South Asian fruit), are low sugar containing waste that *Penicillium expansum* utilized in Solid State Fermentation (SSF) to produce -amylase (Erdal and Taskin 2010). The ideal conditions are starting moisture content of 70%, particle

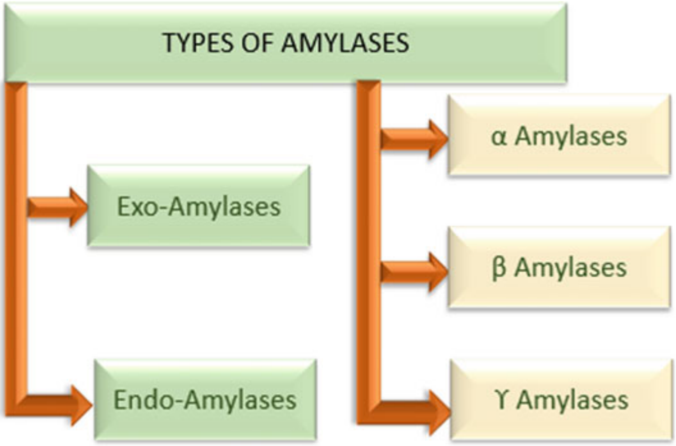

Fig. 1 Different types of amylases (*Source* Saini et al. 2017)

size of 1 mm, pH of 6.0, and incubation temperature of 30 °C. The peptone and starch are consumed as nutritional supplements. Loquat kernel flour had the highest enzyme content at 1012 U/g. In a similar manner, amylase has been effectively synthesized (0.889 U/g) from mango kernel as substrate (5%) at pH 5, temperature 30, and incubation duration of 9 days with *Fusarium solani* as inoculum (Kumar et al. 2013). The banana is mostly utilized for the fermentation of *bacillus subtilis*, which produces amylase. The optimum conditions consist of the following: a 24-h incubation duration, a 50-g substrate concentration, a 35 °C, a pH of 7, and 0.2% peptone, and 0.02% of $MgSO_4.7H_2O$, 0.04% of $CaCl_2$, 0.4% of KH_2PO_4 for optimum amylase production (Unakal et al. 2012). Starch-rich solid wastes from the cassava sago industry have a high potential for use in the production of amylase. The bioprocessing of cassava waste with *Aspergillus niger, Aspergillus terreus,* and *Rhizopus stolonifer*, independently, allowed for the estimation of amylase activity. *Rhizopus stolonifer*, the most productive of the three fungal cultures, had a saccharification activity on 70% starch and could produce 44.5% of reducing sugar in just 8 days of SSF (Pothiraj et al. 2006). Additionally, utilizing orange waste as the only carbon source, a novel strain of *Streptomyces sp.* obtained from a saline marsh in Algeria was used to produce α-amylase (Mounaimen and Mahmoud 2015). In this way, we can conclude the amylases are industrially important on larger scale. It's applications are summarized in Fig. 2 (Saini et al. 2017).

3.2 *Pectinases*

Pectinases, also known as pectinolytic enzymes, are a group of enzymes that play a crucial role in the degradation of pectin, a complex polysaccharide found in the

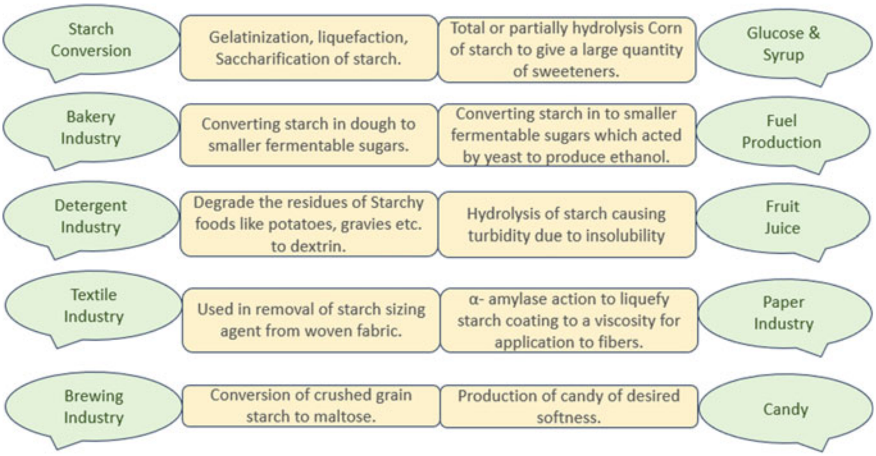

Fig. 2 Industrial applications of amylases

cell walls of plants. These enzymes are naturally produced by various microorganisms, including bacteria, fungi, and yeasts. Pectinases are also found in certain plants and fruits, where they aid in the ripening and softening processes. De-polymerizing enzymes, such as galacturonase and pectin lyase, are in charge of rupturing α-1–4 links in the main pectin chain, and demethoxylating enzymes are in charge of esterifying pectin to pectic acid by eliminating methoxy residues (Mrudula and Anitharaj 2011). Depending on the source of production, pectic enzymes can have an alkaline or acidic character. While eukaryotic bacteria create acidic pectinases, but prokaryotic organisms mostly produce alkaline pectinases (Hoondal et al. 2022; Jayani et al. 2005). Structurally, pectin is structurally divided into three primary sections: the hairy, branching, and smooth (linear) regions. Pectinases make up about one-third of the dry weight of plant tissues. They have been prominently observed in primary cell walls and middle lamella of plants (Valenta 2005). Pectinase is used to degrade plant matter and is particularly useful for accelerating the extraction of fruit juice (Swain and Ray 2010). A strain of *Bacillus sp.* was discovered to produce 49.58 U/ml of polygalactorunase from karat waste at 50 °C and pH 9 after pectinolytic bacteria were isolated from karat (Patil et al. 2012). The two pectinolytic fungi i.e., *Aspergillus niger* and *Penicillium chrysogenum* have the capability of producing pectinases by utilizing different fruit and vegetable wastes as the sole carbon source. From their comparitive study, it was shown that *P. chrysogenum* produced more pectinase from pineapple peels, 220.3 IU/mg protein (Okafor et al. 2010).

Using solid state fermentation technology, *A. niger* produces pectinases from six natural substrates (rice bran, wheat bran, sugarcane bagasse, orange peel, lemon peel, and banana peel) for the production of pectinases by using six natural substrates (Mrudula and Anitharaj 2011). From this particular study, the orange peel is a good source among the examined substrates for the *A. niger* produced pectinase (1224 U/g DMS). Xylose, rhamnose, galacturonic acid, and sugar beet pectin were used to grow

A. niger, and examination of the related transcriptomes showed that 46 distinct genes encoding pectinolytic enzymes were expressed in the fungal organism (Martens-Uzunova and Schaap 2009). Orange peel hydrolysis using a hybrid fungus strain was demonstrated by a study of Solis et al. (2009). The hybrid fungus strain was produced by protoplast fusing mutant *Aspergillus flavipes* and *Aspergillus niveus*. The hybrid strain produced more pectin lyase than either of its parent strains, *A. niveus or A. flavipes* by 450% and 1300%, respectively. The data for some of the microbial pectinases with their optimal parameters are represented in some of the research studies. For instance, the enzyme, polygalacturonase shows its maximum activity at 10.5 pH and 75 °C by the use of *Bacillus species NT-33* (Bacteria). The enzyme, endopolygalacturonase shows its maximum activity at 5.5 pH and 45 °C by the use of *Saccharomyces cerevisiae* (Yeast). Also, the enzyme, pectin lyase shows its maximum activity at 5 pH and 35 °C by the use of *Penicillium paxillin* (Fungi).

In recent years, the use of pectinases in the extraction, clarity, and stabilization of food has increased dramatically (Suneetha and Prathyusha 2011). The acidic pectinases contribute significantly to the production of fruit and vegetable juices due to the unique function of *Aspergillus* spp. in the food industries. Pectin lyases, esterases, and polygalacturonases are the main components in enzyme preparations. The action of pectin esterases is followed by the degradation of de-esterified pectin by polygalacturonases, whereas pectate lyases operate on the ester group of pectin. There are some other enzymes like cellulases, arabinases, or xylanases that can work with pectinases to enhance the pressing fruit efficiency for their extraction of juice (Sarioglu et al. 2001; Souza et al. 2003; Ribeiro et al. 2010). Additionally, pectinases along with cellulases increases juice yield up to 100% (Alkorta et al. 1998). Pectinases are found to be present in many fruits and vegetables in appropriate amount such as in fresh tissues of apple, the pectic substance (%) are found to be 0.5–1.6. In fresh tissues of banana, the pectic substance are found to be 0.7–1.2. Also, in dry matter of orange and potatoes, the pectic substance are found to be 12.4–28.0% and 1.8–3.3% respectively (Kubra et al. 2018). Additionally, pectinases easily remove the fruit peels by softening process (Kashyap et al. 2001).

By using natural substrates such as malt sprout, wheat bran, rice bran, pomegranate, lemon, banana, and orange, *Aspergillus fumigatus* was able to produce the highest pectinase activity, which was found to be around 589.0 0.36 U/ml in wheat bran (Phutela et al. 2005). The presence of 1.25 g/25 ml on *Solanum tuberosum (Solanum melanogena, Eichhornia crassipes*, and citrus peel) produced the highest polygalacturonase productivity of 437.5 U/ml when compared to other agricultural and industrial wastes by the action of *Bacillus firmus* at its optimal conditions like temperature of 37 °C for 92 h (Bayoumi et al. 2008). According to the research study, the substrate should be selected by biosynthesis of enzymes on the basis of affordability of the agro-industrial waste, easy storage, and they should be resistant to different severe effects brought on by exposure to other environmental factors, such as temperature and weather variations from season after season and from day to night. It is well known that the citrus fruit family contains a sizable amount of pectin. This family includes citrus fruits such as oranges, kinnow, khatta lime, lemon

(Galgal), Malta, Mausami, sweet orange, etc. Some more examples of agro-waste used for pectinase production are shown in Table 3.

3.3 Cellulases

Cellulase is a class of enzyme that causes the cellulolysis i.e., hydrolysis of cellulose. Cellulase is a complex of three different enzymes: endoglucanase (E.C. 3.2.1.4), exoglucanase (E.C. 3.2.1.91), and β-glucosidase (E.C. 3.2.1.21). In cellulose hydrolysis, endoglucanase (EG) and exoglucanase (CBG) work synergistically to transform cellulose into small cellooligosaccharides and then β-glucosidase (BG) hydrolyzes the cellooligosaccharides into simple sugars (glucose). These three enzymes are involved in the hydrolysis of cellulose by synergetic action for accomplished and effective hydrolysis of cellulose (Patel et al. 2019). According to the researchers, the most studied cellulolytic fungus, *Trichoderma resei,* produces seven β-glucosidases, eight endo-β-1, 4-glucanase components and two cellobiohydrolase components (Sakka et al. 2000). Endoglucanase interacts with the interior sites of oligosaccharides present in cellooligosaccharides, carboxymethyl cellulose, and amorphous cellulose. Cellobiose or glucose are the main byproducts of exoglucanase's hydrolysis of crystalline cellulose's non-reducing ends. β-glucosidase acts on non-reducing ends of cellobiose and cellodextrin (Ohmiya et al. 1997). Cellulase is one of the most significant groups of enzymes used in the processing of lignocellulosic materials for the manufacture of feed, fuel, and chemical feedstocks, along with other related enzymes including hemi-cellulases and pectinases.

Cellulases are mostly produced by microorganisms, commonly bacteria and fungi (Bahkali 1996a, b; Suresh Chandra Kurup et al. 2005; Suresh Chandra Kurup and Nagendra Prabhu 2001). Aerobes and anaerobes, mesophiles and thermophiles, and complex and non-complex organisms are some of the groups into which they can be categorized (Kuhad et al. 2016; Haldar et al. 2016). In contrast to bacteria, filamentous fungi are more flexible and may development on a variety of substrates, such as hexose and pentose monomers as well as the polysaccharides xylan, arabinan, and glucan. They make it simpler to use lignocellulosic biomass for hydrolysis by breaking down lignin, the most resilient component of plant cell walls. They can break lignin, the most resistant component of plant cell walls, making it easier to use lignocellulosic biomass for hydrolysis. They can also be used to valorize fruit wastes, such as banana, orange, apple, pineapple, and citrus, in order to produce cellulase enzymes. On a commercial level, the main suppliers of cellulolytic enzymes are filamentous fungus. *Trichoderma species (Trichoderma reesei, Trichoderma viride, and Trichoderma longibrachiatum*) fungi are recognized to be potent cellulosic material degraders because they release a full cellulase system (Bischof et al. 2016). The research on cellulase has been continuing since 1950 with the goal of enhancing the cellulase enzyme system for effective cellulose hydrolysis on an industrial scale. This research includes cellulase production with its maximum yield (Colonia et al. 2019; Roth et al. 2020).

Table 3 Agro-industrial waste to produce pectinase by using microorganisms

S.No	Agro-industrial residues	Microorganisms	Types of enzymes	Fermentation states	Sources
1	Wheat bran residues	*A. giganteus,* *A. sojae*	Polygalacturonase	Solid state fermentation	Demir and Tari (2014), Heerd et al. (2014), Anand et al. (2017), Ortiz et al. (2017)
2	Rice rice bran wastes	*A. fumigatus*	Polygalacturonase	Solid state fermentation	Wong et al. (2017), Tai et al. (2014)
3	Papaya wastes	*A. tubingensis*	Pectin methylesterase	Solid state fermentation	Maran and Prakash (2015), Patidar et al. (2016)
4	Mango wastes	*A. foetidus,* *Enterobacter spp.*	Pectin methylesterase	Solid state and submerged fermentation	Cheok et al. (2018)
5	Sugarcane waste	*A. niger*	Pectinase	Solid state fermentation	Patidar et al. (2016)
6	Sunflower wastes	*A. niger*	Pectinase	Solid state and submerged fermentation	Patidar et al. (2016)
7	Banana waste	*A. terreus*	Pectinase		Sethi et al. (2016), Barman et al. (2015)
8	Algal biomass waste	*B. licheniformis*	Pectinase	Submerged fermentation	Pervez et al. (2017)

(continued)

Table 3 (continued)

S.No	Agro-industrial residues	Microorganisms	Types of enzymes	Fermentation states	Sources
9	Grape pomace	*A. awamor*	Polygalacturonase	Solid state fermentation	Patidar et al. (2016)
10	Strawberry peels	*Lentinus edodes*	Polygalacturonase	Solid state fermentation	Patidar et al. (2016)

Fruit wastes are an excellent source of reducing sugars, cellulose, and hemicellulose. As an illustration, consider banana peels, banana stalks, banana pseudo stems, grape pomace, pineapple peels, apple pomace, and citrus wastes. These wastes are created in great quantities every year all throughout the world, and they are constantly being the topic of research (John et al. 2017). Because these wastes include sugars, microbes can make enzyme more effectively with fewer steps. Additionally, the presence of cellulose and sugar in this waste causes the production of cellulase feasible over an extended period of time. Therefore, the availability of cellulose when combined with reducing sugars indicates an improvement in its large-scale synthesis (Srivastava et al. 2021a, b). Cellulase enzyme can be extremely important for the technique of synthesizing biofuels from biomass because it has been produced from a range of fruit wastes under the right conditions.

Cellulase comes as an essential enzyme on industrial level due to its vast range of functions in biofuels synthesis (Srivastava et al. 2015). Due to the manufacture of ethanol, butanol, hydrogen, or any other fuel from cellulosic biomass to commercially viable transportation fuel, it started moving up to number one position from third position in the industrial enzyme market (Wobiwo et al. 2016). Cellulase enzymes can be used to create biofuels from cellulosic biomass, including apple pomace, grape pomace, pineapple pomace, banana peels, citrus peel, rice straw, wheat straw, maize cob, sugarcane bagasse, forest byproducts, grassy and woody materials, and fruit waste (Rodrıguez et al. 2010; Zacharof et al. 2017). The Cellulosic biomass must first undergo pretreatment (mechanical, chemical, and biological) before being enzymatically hydrolyzed into sugars by cellulase enzymes. These sugars are then fermented to produce biofuels, and the process is completed by separating and purifying the biofuels (Park et al. 2016). Cellulase cocktail, which combines the actions of exo-glucanase, endo-glucanase, and β-glucosidase enzymes to hydrolyze cellulosic biomass, converting it into oligosaccharides and monomer reducing sugars in the process. Then, through a fermentation process, these sugars are transformed into biofuels (Srivastava et al. 2021a, b). The applications of cellulase enzyme are also represented in Fig. 3. Cellulosic biomass has a complicated structure that makes it difficult to produce biofuels economically and presents a challenge to competing with the fossil fuels (Kuhad et al. 2016). Hemicellulose, lignin, pectin, minerals, and other components found in natural sources of cellulosic biomass make the hydrolysis

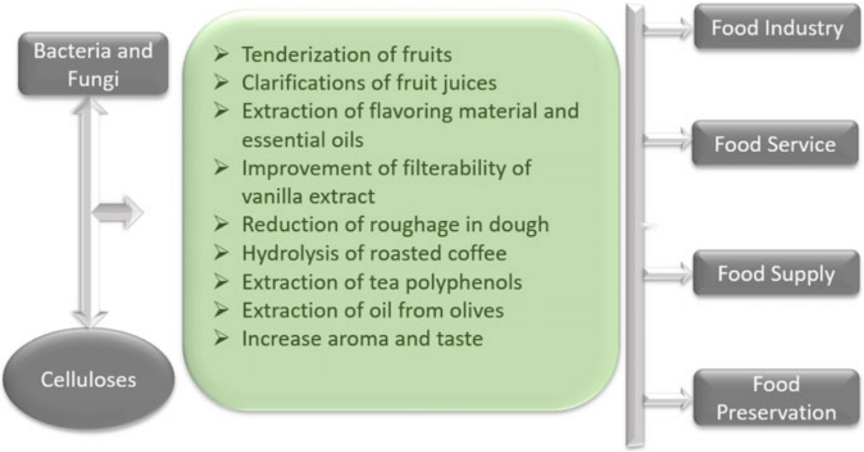

Fig. 3 Cellulases application in food industry (Ejaz et al. 2021)

process more difficult. Pretreatment of the substrate is necessary to make more cellulose in biomass available for the cellulase enzyme's action and to boost the yield of fermentable sugars. Thus, one of the main elements that raises the price of producing biofuels is pretreatment (Kuhad et al. 2016). Moreover, types of pretreatments and its severity depend on the composition of the substrate. The next step is hydrolyzing the substrate, a critical step that converts the substrate into fermentable sugars using the cellulase enzyme and supporting enzymes like hemicellulases. In this process, the enzymes utilized can either be synthesize in laboratory or purchased from the market (Singhania et al. 2015; Park et al. 2016).

3.4 Lipases

Lipases are the class of enzyme that can hydrolyze (break down) triglycerides to produce monoacylglycerols (MAGs), diacylglycerols (DAGs), and glycerol as well as free fatty acids. Additionally, they are capable of producing new product in organic media by esterification, transesterification, and aminolysis mechanisms (Sandoval 2018). For instance, lipase can be extracted from lemon peel, citrus seeds, coffee husk, gold processing waste, and soy leftovers (Kumar and Kanwar 2012). Various substrates, such as natural oils, synthetic triglycerides, and esters of fatty acids, can be acted upon by lipases. On the basis of structure, a highly conserved catalytic triad found in lipases consists of histidine as the base, aspartate/glutamate as the acidic residue, and serine as the nucleophile. Lipases have an electrophilic area known as an oxyanion cavity in their active conformation that is surrounded by a set of hydrophobic residues that are grouped around the catalytic serine. Lipases can also be classified on the basis of presence of di-sulfide bridges that give them stability and are critical for their catalytic activity (Sandoval 2018). A structural component of certain lipases called the "lid," that covers the active site, opens at hydrophobic/hydrophilic interphases. In ancient classification, esterases were denoted as lipolytic enzymes lacking a lid. However, because some lipases, such as *Candida antarctica lipase B (CALB)*, lack the lid, therefore, an alternative classification has been proposed (Ali et al. 2012).

Lipases are produced by animals, plants and microorganisms (Szymczak et al. 2021; Lee and Park 2019; Rivera et al. 2012; Gao et al. 2017; Villeneuve 2003). Recently, the microbial lipases are gaining much more awareness with the efficient utilization of enzyme technology. In fact, they contribute to approximately 90% of global lipase market (Guerrand 2017). There is a vast range of applications in food and other industries. However, due to the origination, diversification and instable nature of the structure and properties would impact on research and application of lipase. It helps to increase in oil yield and appearance of the end product for the processing of the vegetable oil. As per the research study, solid fruit and vegetable residues heated to more than 45 °C under thermophilic conditions can have a lipolytic activity of up to 12,000 UA/g of dry matter (Santis-Navarro et al. 2011). Milk fats broke down by lipase enzyme and provide characteristic flavors to cheeses. By the hydrolization of the milk fat that gives fatty acids which leads to the better flavor (Jooyandeh et al. 2009).

The maximum lipase activity is produced by *Lasiodiplodia theobromae* growing on coconut cake (698 U/g dry substrate) (Venkatesagowda et al. 2014). Since fungal lipases are more efficient than bacterial lipases, batch fermentation and simple extraction techniques are more readily available and less expensive. However, thermostability is possible if lipase is isolated from bacteria. Figure 4 describes some food processing applications of microbial lipases in different industries with its action on product of application. Today, researchers in the food and pharmaceutical industries are primarily interested in alkalophillic and thermostable lipases since they can survive higher temperatures (45–50 °C) and pH (8.0) (Chakraborty and Raj, 2008). A potential expression system was created for *bacillus stearothermophilus L1* in an Escherichia coli system to produce thermostable lipase. The market of microbial lipase is estimated to be USD 425.0 Million in 2018 and projected market to reach USD 590.2 Million by 2023, growing at a CAGR of 6.8% from 2018 (Chandra et al. 2020). Triacylglycerol acylhydrolase, a member of the hydrolase family, is found in lipases and exhibits its activity on carboxylic ester linkages. They are a type of serine hydrolase that does not require a cofactor. Hydrolyzing triglycerides with lipases yields diglycerides, monoglycerides, fatty acids, and glycerol (Chandra et al. 2020). There are multiple reaction takes place by lipases like esterification, transesterification, interesterification, acidolysis, alcoholysis, and aminolysis conversion.

The lipases consist molecular weight ranges from 19 to 60 kDa and seems to be monomeric protein. Commercial lipases are mostly employed to process other fat-containing meals and generate flavors in dairy products (Aravindan et al. 2007). Through their action on the milk fats to form free fatty acids following hydrolysis, they can enhance the distinctive flavor of cheese (Jooyendeh et al. 2009).

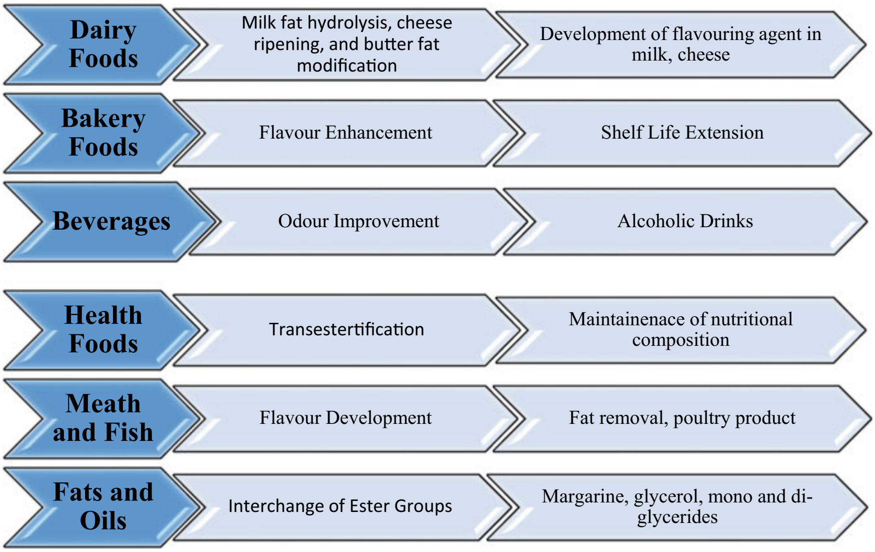

Fig. 4 Lipase in the different industries with its function on different product of application (Sharma et al. 2001)

Table 4—Lipase applications in the food industry.

Different sources can be utilized for different types of cheese for, e.g., Romano cheese using kid/lamb pre-gastric lipase, Camembert cheese using lipase from *Penicillium camemberti* and cheddar cheese using *Aspergillus niger* or *A. oryzae* (Aravindan et al. 2007). The aroma can be modified using lipase in alcoholic beverages. They can be used to change the quality of cocoa butter that has a melting point of 37 °C due to the presence of palmitic and stearic acids (Sharma et al. 2001; Jaeger and Reetz 1998). The microbial lipases, such as those derived from *Candida rugosa*, have a variety of uses that cannot be satisfied by chemical synthesis. This lipase finds application in the production of ice cream, single-cell protein, carbohydrate esters and amino acid derivatives (Aravindan et al. 2007). Additionally, lipase can also be used in the processing of different waste streams that are released from food industries (Raveendran et al. 2018).

3.5 Proteases

Proteases is a group of enzymes responsible for breaking or hydrolyze proteins into smaller peptides or amino acids by catalyzing the hydrolysis of peptide bonds. This process is known as proteolysis and is essential for maintaining proper cellular functions, regulating various physiological processes, and controlling protein turnover. This group of enzymes plays a fundamental role in various biological processes. The proteases demonstrate their activity on the peptide bond that joins nearby amino acid residues in a protein molecule and cleave them to produce shorter peptides and amino acids (Razzaq et al. 2019). The bacterial and archaeal prokaryotic domains as well as the eukaryotic kingdoms of plants, animals, fungus, and protists all contain these water-soluble enzymes, which are widely distributed in nature. In fact, it is known that a number of viruses also encode their own proteases (Bernardo et al. 2018). According to the Enzyme Commission classification, proteolytic enzymes are classified as belonging to the class 3 (hydrolases), subclass 4, and are given the unique number EC 3.4.x.x (Contesini et al. 2017). These enzymes are categorized based on factors including the location of action, the kind of substrate, the active pH range, and the mechanism of action that uses a certain amino acid that is present in the active site (Guleria et al. 2016a, b). Based on function, proteases can be categorized as endopeptidase and exopeptidase. In order to create shorter peptides, the former has a tendency to hydrolyze non-terminal peptide bonds, whereas acts on the peptide bonds that are present at the termini of the substrate. Exopeptidases are further divided into aminopeptidases and carboxypeptidases depending on whether they preferentially act on the N-terminal or C-terminal of a given exopeptide, respectively (Naveed et al. 2021). Dipeptides, tripeptides, or amino acids with proportionately shorter peptides are released by the exopeptidases. The major classes of protease are serine proteases, cysteine proteases, threonine proteases, glutamic proteases, asparagine proteases, aspartic proteases, mixed proteases, etc. based on specific amino acid residue(s) at the active site and mode of action (Contesini et al. 2017). Based on pH range, proteases can be classified as Alkaline, Acidic, and Neutral, which is represented in Table 4.

The researcher's investigation are discussed below that showed the bioconversions of fruits and vegetable wastes into protease. It is known that numerous bacteria and fungi make protease. Proteases are enzymes that are mostly produced by bacteria with a narrow pH range (pH 5–6). *Bacillus species* was evaluated for protease production after being isolated from damaged fruits and vegetables. According to the researcher,

Table 4 Different types of Proteases with their sources (Solanki et al. 2021)

S.No	Types	pH range	Use of proteases	Classification	Sources
1	Basic	9–11	Leather and detergent industries	Serine proteases, Carlsberg and Novo subtilisins	Produced primarily by bacterial species such *Bacullus* species and *Cryptococcus aureus*
2	Acidic	3.8–5.6	As a digestive aid, soy sauce, protein hydrolysate, and a source of flavour	Aspartic proteases, pepsin (A1), retropepsin (A2)	Mostly produced by fungal species such as *A.niger, A.oryzae, A.fumigatus*
3	Neutral	5–8	Food industry, Brewing industry	Neutrase, thermolysin	Genus *Bacillus*

Bacillus sp. is present in 20% of the supermarket samples and 60% of local market samples. SSF has investigated the generation of protease from the solid waste (outer covering) of the African locust bean (Parkia biglobossua) shell using *A. niger* and *B. subtilis. B. subtilis* outperformed *A. niger* in terms of proteolytic activity (0.83 mg/ml/s at ideal conditions, pH-9) (0.74 mg/ml/s, pH-6) (Oyeleke et al. 2011). Some of the novel microbial proteases and their potential applications is demonstrated in Table 5. A two-part DegS-DegU regulatory mechanism regulates the secretion of B. subtilis protease. According to several reports, the proB gene works in synergetic mode with multiple copies of the degR gene increase the yield of extracellular protease, and the proB gene's impact is reliant on the degS gene e (Ogura et al. 1994). Using wheat semolina as its primary substrate to produce protease, SSF uses *Aspergillus sp.* The other two nutrients employed in the fermentation were fructose and chickpea meal (Radha et al. 2012). By substituting fruit and vegetable waste for the best carbon source, such as pomegranate, mango, karat, and potato peels, the cost of production was reduced. Therefore, the highest protease activity was found in the fermentation medium containing potato peel, or 717.53 U/g.

Microbial proteases have numerous applications in different industries is represented in Table 5. Proteases are employed in the food industry to increase the palatability and shelf life of all readily available sources of protein. In meat tenderization, alkaline proteases of microbial origin are of immense importance (Sumantha et al. 2006). The hydrolysis of proteins into amino acids caused the formation of antioxidants that inhibit autoxidation of linoleic acid and the scavenging effects for α,α-diphenyl-β-picrylhydrazyl free radicals (Wu et al. 2003). The bioactive peptide that is created when different dietary proteins are hydrolyzed is crucial for cells as antioxidants (Thiansilakul et al. 2007; Nalinanon et al. 2011; Kittiphattanabawon et al. 2012).

4 Future Scope

Enzymes are biological catalysts that can be used as an effective, secure, and sustainable alternative for traditional food processing in the food industry. The demand for enzymes has grown steadily, i.e., the global enzymes market size was valued at USD 12.27 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 6.5% from 2023 to 2030, according to a research report published by Grand View Research (Enzyme market size 2023). Due to their biodegradable nature and ability to substitute harsh chemicals, enzymes have assisted in the development of cleaner, greener technology. Future trends may involve the development of more efficient systems that maximize product yield and performance while utilizing significantly lower amounts of chemicals, water, and energy. The development of new enzymes through modern biotechnology will result in enzyme products with improved effects at various physiological conditions, such as low/high pH and temperatures, which could allow for the operation of various industrial processes at low temperatures, as well as reduced environmental harm, increased efficiency,

Table 5 Selected microbial proteases and their potential applications

S.No	Type of protease	Microorganism	Source	Potential application	References
1	Tolerance of halophilic organic solvents	*A. faecalis*	Debris waste	Waste from deproteinizing shells	Maruthiah et al. (2016)
2	Tolerance of alkaline solvents	*Bacillus. subtilis*	Soil from paper mill	Dehairing of skins, detergent addition	Hussain et al. (2017)
3	Tolerance of Thermo stable-solvent	*Bacillus. Halo. sp. CJ4*	Hypersaline water	Synthesis of peptides and detergent formation	Daoud et al. (2017)
4	Tolerance of acidic solvent	*Aspergillus foetidus*	Soil	Food sector	Souza et al. (2017)
5	Tolerance of alkaline solvents	*Bacillus. subtilis AKAL7 and AKAL11*	Chicken faeces, chicken guano, chicken poop	Animal hair removal, gelatin removal from X-ray film	Hakim et al. (2018)
6	Tolerance of alkaline solvents	*Bacillus halotolerans strain CT2*	Potato waste	Soap, cleaner additive	Dorra et al. (2018)
7	Tolerance of alkaline solvents	*B. cereus FT 1*	Mixture of soil	Detergent, soap, cleaner additive	Asha and Palaniswamy (2018)
8	Fibrin degrading proteases	*Bacillus tequilensis*	Soil waste	Dissolution of blood clots	Xin et al. (2018)
9	Serine alkaline protease	*Bacillus safensis strain RH12*	Oil fields	Detergent, soap, cleaner additive	Rahem et al. (2021)
10	Serine alkaline protease	*Salipaludibacillus agaradhaerens strain AK-R*	Highly Alkaline water	Detergent, soap	Ibrahim et al. (2019)
11	Rennin-rich enzyme	*L. paracasei 2.12*	Caprine milk	Milk coagulation process	Putranto et al. (2017)
12	Thermostable pH-neutral protease	*S. species Al-Dhabi-82*	Soil	Degradation of keratin	Al-Dhabi et al. (2020)

(continued)

Table 5 (continued)

S.No	Type of protease	Microorganism	Source	Potential application	References
13	Tolerance of alkaline protease	*Bacillus atrophaeus NIJ*	Contaminated soil rich in hydrocarbons	Detergent, soap, cleaner additive	Rahem et al. (2021)
14	Tolerance of alkaline thermostable protease	*Bacillus stearothermophilus*	Olive wastes	Detergent, soap, cleaner additive	Karray et al. (2021)

lower costs, and reduced energy consumption. Enzyme immobilization is an area of potential research where the recent advances in the design of immobilization support have enabled more precise control of enzyme immobilization.

5 Conclusion

Fruits and Vegetable wastes have the ability to be processed into a variety of value-added products using particular microbes. The bioprocessing of fruits and vegetable wastes to achieve zero waste economics in a sustainable way is further encouraged by issues with greenhouse gas emissions and waste management. The successful bioconversion of fruit and vegetable waste into high-end quality products such as enzymes like pectinases, proteases, and lipases had been made possible because of recent developments in microbial biotechnology. Genetic engineering has been specifically applied to the overproduction of various useful biotechnological products in terms of quality and quantity by incorporating the desired genes into the microbe's genome. Recombinant DNA technologies and protoplast fusion are used to achieve this. The majority of study outputs are limited to small laboratory size and need to be converted into larger scale, even if tests connected to the generation of best quality biological products from fruits and vegetable wastes have been shown to be effective. In order to translate laboratory-scale research to an industrial scale, the cross functional research incorporating chemical engineering, computer engineering, mechanical engineering, biotechnology, and microbiology is required. Studies should address the costing, economics, and cost per unit of the production process and the final product. The genomes of novel extremophiles could be mined for data to improve the chances of finding new genes and using them in the biorefinery process. Data pertaining to the genomes of significant microorganisms have previously been reported. Therefore, it is advisable to make use of the current understanding of fruit and vegetable wastes (FVWs) bioprocessing and to get around any obstacles to scaling up the process in order to generate better biological products like enzymes.

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Utilization of Fruit By-Products to Produce Value-Added Products: Conventional Utilization and Emerging Opportunities

Karnam Sangwan, Renu Garhwal, Yash Pal Sharma, Anuradha Bhardwaj, and Harish Kumar

Abstract Fruit by-products are a rich resource that can be used to make nutraceuticals, biofuels, and other healthy products. Fruit by-products are made up of a variety of organic substances, such as lipids, proteins, carbohydrates, and vital nutrients like potassium, nitrogen, and phosphorus. The procedures employed for valorization and the end products are greatly influenced by these elements. A green technique to lower greenhouse gas emissions, landfill waste, and leachate production while simultaneously fostering economic growth is the valorization of fruit by-products. To effectively limit the production of fruit waste, the relevant policies must be put into place. The goal of this chapter is to show how fruit waste may be used as a useful resource to develop novel transformation opportunities and produce goods with increased value.

Keywords Fruit by-products · Nutraceuticals · Biofuels · Green technique · Landfill waste

1 Introduction

The rapid pace of industrialization, urbanisation, and inadequate waste management practises has led to the significant buildup of a concerning quantity of food waste. According to (Shafiee-Jood and Cai 2016), approximately 33% of the food intended

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for human consumption is lost throughout various stages, including harvest, production, handling, and storage. The annual global production of solid waste from municipal is estimated to be approximately 2 billion tonnes. Among this amount, over 50% of municipal waste is comprised of food waste in developing nations (Negri et al. 2020). Typical organic food waste consists of fruits, vegetables, prepared foods, and meat which have also been studied in relation to their potential for bioconversion into valuable products. Food waste can be defined, as stated by the Food and Agriculture Organisation (FAO), as the unnecessary disposal, loss, or deterioration of any edible substances throughout the entire food supply chain. This includes the organic waste that is produced from different sources, such as food processing plants and households. The dietary guidelines recommend the consumption of a diet that is abundant in fruits and vegetables in order to promote a state of good health and well-being. Currently, a significant portion of fruits, approximately one third, is being discarded during preparation and processing due to the removal of peels, seeds, and pulps. This practise not only results in wastage but also diminishes the overall nutritional value that these fruits can offer. Presently, there is a growing inclination among consumers to prioritise the maintenance of a nutritious diet and a healthy lifestyle. In their study, (Schieber et al. 2001) conducted a comprehensive analysis of by-products, with a specific emphasis on the significant functional compounds including carotenoids, polyphenols, tocopherols, and other relevant constituents. This chapter emphasises the abundance of untapped natural sources of micronutrients and their potential to be efficiently utilised as a beneficial ingredient. The disposal of fruit byproducts typically occurs in landfills, leading to the emission of significant amounts of greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4). The objective of this chapter is to examine the potential of both traditional and emerging applications in the management of fruit waste across multiple sectors, in light of the exponential growth in waste generation and its environmental consequences. This chapter provides a concise overview of the existing traditional and emerging technologies utilised for the valorization of fruit byproducts to create products with increased value. The emphasis has been placed on various conventional methods of utilisation, such as animal feeding, landfilling, anaerobic digestion, vermicomposting, and thermal treatments. Additionally, emerging opportunities in the fields of bioactive compounds, nutraceuticals, enzymes, nutraceuticals, biofuels, films and packaging, flavouring agents, have also been highlighted due to their considerable potential for a sustainable future. The objective of this chapter is to demonstrate the potential of fruit waste as a valuable source for creating innovative transformation opportunities and generating products with added value.

2 Characterization and Composition of Fruit Waste

Fruit waste is commonly produced by various sources such as food production industries, households, restaurants, and other establishments that serve food. Fruit waste can be categorised into two types, namely pre-consumption and post-consumption waste, depending on the source. Waste that occurs before consumption is generated during the processes of production and preparation. Pre-consumption fruit wastes encompass various items such as peelings, apple cores, seeds, pulps. Fruit waste after consumption primarily comprises of remnants of cooked or processed food. The composition of fruit by-products exhibits variations depending on factors such as the origin, geographical location, climatic conditions, seasonal variations, cultural practises, and economic circumstances of the nation (Negri et al. 2020). The study conducted by Xu et al. (2018) observed that the moisture content of fruit by-products ranged from 70 to 80%, while the total solids accounted for 20–30% of the waste. Additionally, it was found that 90% of the total solids were volatile solids. The organic constituents of fruit byproducts generally encompass polyphenols, proteins, polysaccharides such as cellulose, starch, lignin, and hemicelluloses, as well as lipids/oil and also organic acids. Fruits wastes exhibit a relatively low lipid content, whereas kitchen waste demonstrates a higher lipid content. The researchers (Wang et al. 2015; Yong et al. 2015) made an observation that the aggregate lipid content of fruits and vegetables accounted for 11.8% overall waste of kitchen, while the remaining 21.6% was attributed to other sources. Despite the fact that biomass with a high lipid content yields substantial energy, the presence of long-chain fatty acids, which are detrimental to methane production, can lead to system malfunction. The absence of globally recognised standards for categorising fruit waste has presented a significant obstacle to conducting research on the conversion of waste into valuable products. The assessment of food waste composition and properties, such as moisture level, nutrient content, pH, particle size, and volatile solids, significantly impact the composting process and the effectiveness of converting fruit waste into energy. According to (Nayak and Bhushan 2019), food wastes that contain a significant amount of oil require an extended composting period. Conversely, a high lipid content is advantageous for the production of biodiesel. Additionally, it was observed that the water content in food waste has a suppressive impact.

3 Fruit Waste Valorisation

Conventional waste management approaches for addressing food waste encompass various methods such as animal feeding, landfilling, anaerobic digestion, vermicomposting, and thermal treatments. Growing interest has been seen in recent years in exploring innovative alternative methods to mitigate the environmental impact caused by disposal strategies such as incineration and landfill. Fruit by-products are renewable resource primarily consisting of organic materials. These materials have the potential to be transformed into various value-added products, including chemicals, bioactive compounds, enzymes, biofuels, and pharmaceuticals. Currently, there is a notable level of interest in the substitution of petrochemical-derived materials with renewable materials sourced from fruit by-products generated during fruit processing (Vandermeersch et al. 2014). Fruit byproducts are compelling and valuable renewable resource that can be transformed into a diverse range of value-added products. The practise of transforming fruit waste into valuable products, known as waste valorization. It is a compelling strategy that enables the production of more beneficial and valuable goods. The practise of assigning value to components of fruit waste has been in existence for a considerable period, primarily linked to waste management procedures. However, it is currently garnering increased attention due to its potential to greatly influence the development of sustainable and economically viable approaches for generating high-value products. The significance of waste valorization is particularly notable in the present era due to the substantial global demand for enzymes, biofuels, solvents, pharmaceuticals, and surfactants. The increased demand for solutions to address fruit waste has led numerous countries to formulate strategies aimed at establishing large-scale facilities for the conversion of various food waste streams into diverse value-added products. There are four main ways for valorizing food wastes that have been used. In the subject of using food waste, there are four primary research areas: (1) the conversion of food waste into biofuels, (2) the extraction of value-added components from food waste, (3) the utilisation of microbial activity to convert food waste into biomaterials, and (4) the development of efficient adsorbents derived from food waste for wastewater treatment purposes (Fig. 1).

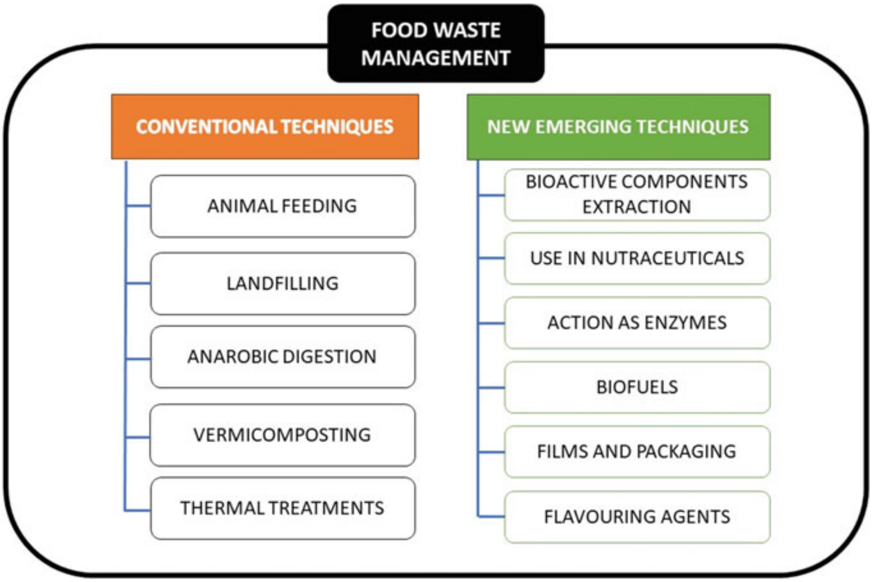

Fig. 1 Conventional and new emerging techniques for food waste management

4 Conventional Utilization of Fruit By-Products

4.1 Animal Feeding

One method that has been explored for the effective disposal of waste is the utilisation of waste materials in animal feeding. The practise of valuing and utilising fruit, as well as their byproducts, in animal feed has long been regarded as a traditional practise. It is imperative to thoroughly evaluate this particular option due to the fact that not all animals possess the ability to consume every type of fruit residue. Furthermore, it is important to consider the potential hazards associated with residues intended for animal consumption, as they may contain toxic substances that can transmit diseases or disrupt the nutritional balance of the animals' diet. In addition, the costs related to transportation and conservation render this alternative often impractical. The implementation of thermal treatments to ensure the safety of fruit waste also results in an increase in associated expenses. However, (Salemdeeb et al. 2017) have demonstrated in a controlled environment that animal feeding is more beneficial when compared to alternative methods such as anaerobic digestion or landfilling. The benefits primarily arise from the partial replacement of conventional feed, which is known to have substantial environmental and health consequences.

4.2 Landfilling

Despite its environmental impact, the most common and straightforward method for disposing of fruit residues is through this approach. In the case of fruit waste, its high biodegradability is primarily attributed to its elevated nutrient content (Ravindran and Jaiswal 2016). The release of methane from landfills is a consequence of the anaerobic microbial decomposition of deposited organic materials, is considered to be the third most significant anthropogenic contributor to atmospheric methane levels. Within landfill sites, the primary macronutrients found in organic matter undergo hydrolysis, resulting in the formation of soluble substances. These soluble substances then undergo further transformation, ultimately leading to the production of biogas through the process of methanogenesis. Nevertheless, it should be noted that lignin and lignocellulose exhibit recalcitrance when subjected to anaerobic conditions. In the absence of an appropriate pretreatment, these components have the potential to impede the bioavailability of cellulose, consequently leading to a decrease in the production of biogas (Kibler et al. 2018).

4.3 Anaerobic Digestion

Biogas is a resultant substance generated through the anaerobic decomposition process of the organic matter that takes place within landfill environments. Anaerobic digestion is a widely recognised technological solution utilised for the purpose of managing sludge and manure produced in wastewater treatment facilities. The potential for its application in fruit waste valorization is substantial, despite the current low level of implementation (Braguglia et al. 2018). The biological processes associated with the anaerobic digestion of organic matter present in freshwater are fundamentally similar to those occurring in a landfill. The primary distinction lies in the fact that anaerobic digestion occurs within purposefully engineered bioreactors, known as digesters, which facilitate the regulation of key operational parameters. The control of temperature is of particular significance due to the involvement of anaerobic bacteria that exhibit mesophilic or thermophilic characteristics, displaying activity within the temperature ranges of 30–40 °C or 50–60 °C, respectively (Kibler et al. 2018). Additional significant factors include the composition of organic acids, pH levels, alkalinity, carbon-to-nitrogen ratio, and the existence of metallic elements. Due to the regulation of fermentation conditions, digesters enable the acquisition of significantly greater quantities of methane compared to landfills. The primary constituents of biogas are CO_2 (30–40 vol%) and CH_4 (55–65 vol%), accompanied by smaller amounts of H_2, H_2S, and other gases.

4.4 Vermicomposting

This technology facilitates the management of organic matter found in waste, making it highly suitable for fruit waste. However, there are several requirements that must be met in order to effectively manage waste: the sorting of waste to separate the organic component, the provision of energy for aeration and mixing, the addition of water, and the meticulous controlled operating conditions. In contrast to the processes occurring in landfills, composting entails the aerobic enzymatic transformation of organic matter, resulting in the generation of carbon dioxide (CO_2), ammonia (NH_3), nitrogen gas (N_2), and a solid, resistant material commonly known as compost, which contains humic substances. Compost serves as a soil amendment that enhances water retention, thereby reducing the necessity for irrigation. However, it is crucial to ensure the absence of heavy metals, pathogens, and micropollutants when utilising compost for this purpose (Kibler et al. 2018). The critical variables that influence the composting process include carbon-to-nitrogen (C/N) ratio, pH, moisture content, particle size, porosity, and aeration rate, which refers to the degree of compaction of the organic matter. In certain unsuitable circumstances, the release of odorous substances can have a notable effect on the environment, while simultaneously resulting in the production of compost of inferior quality. In recent times, there has been a development in the practise of vermicomposting fruit wastes for the purpose of producing bio-fertilizers (Rorat and Vandenbulcke 2019). This process involves the stabilisation of organic matter from waste through the combined activities of microorganisms and earthworms. Vermicompost, which is the final product obtained, exhibits superior properties compared to conventional compost in terms of nutrient availability in soil.

4.5 Thermal Treatments

Incineration, also known as combustion, is a practise that can be considered advantageous due to its ability to significantly reduce the volume of fruit waste that is ultimately disposed of. This reduction in waste volume helps to extend the lifespan of landfills. It is imperative to ensure that the design and operation of the incineration plant are conducted with utmost care to mitigate the potential for significant atmospheric air pollution concerns. However, it is worth noting that contemporary incineration plants incorporate appropriate air pollution control technologies, thereby yielding remarkably minimal emissions of harmful substances. Nevertheless, the implementation of this technology necessitates substantial investments and operating costs due to the significant energy requirements involved. Primary energy sources such as natural gas can be utilised to maintain adequately elevated operating temperatures. The heat generated from combustion can be partially reclaimed and utilised within the incineration process, such as for preheating air, or it can be directed towards power generation based on specific requirements and objectives. The process of combustion results in the production of a solid residue known as ash. This ash is primarily composed of the inorganic components found in the solid fuels that are utilised. Typically, this ash is disposed of in landfills, although there have been efforts to explore alternative applications for ash, such as its use as a building material (Silva et al. 2019).

Gasification and pyrolysis are two thermal treatment methods that involve the conversion of organic matter into a range of products. In both treatment methods, the resulting gaseous stream consists of carbon monoxide and hydrogen, along with other components. The present stream has the potential to undergo further processing, resulting in the production of synthesis gas, commonly known as syngas. Syngas is a combination of carbon monoxide and hydrogen, with varying ratios between the two components. Syngas possesses the potential to function as a valuable raw material for chemical synthesis or can be employed directly as a source of fuel for the generation of power and/or heat (Kibler et al. 2018). Pyrolysis involves the thermal decomposition of wastes in an atmosphere devoid of oxygen and other reactants. This process yields three fractions, namely solid, liquid, and gas, with their proportions determined by various operating conditions, primarily the process temperature, residence time, and heating rate of the vapours (García et al. 2015). The technologies mentioned are currently in the early stages of development with regards to fruit waste management. The increased moisture content present in these substrates makes gasification a more attractive alternative in theory. Nevertheless, the substantial amount of energy needed to raise the temperature of water and convert it into vapour, or to reach supercritical conditions, poses a significant disadvantage in thermal waste treatment methods due to its adverse impact on thermal efficiency. Despite the advancements made in recent years in conventional methods for managing food waste, only a small portion of the generated residues can be effectively utilised or valorized. Within the realm of waste management, incineration and landfilling are commonly regarded as the least favourable alternatives. On the other hand, it should be noted that animal feeding, anaerobic digestion, and composting, while they do involve some form of valorization of the residues, result in the production of lower-value products (Capson-Tojo et al. 2016). As a result, these strategies may not be particularly appealing for the purpose of valorizing food waste. Hence, it is imperative to implement effective fruit waste management strategies that are based on valorization.

5 New Emerging Techniques in Fruit By-Products Utilization

5.1 Bioactive Components

Presently, there exists an increasing consumer inclination towards health-enhancing products that encompass bioactive compounds. As a result, various industries are increasingly focused on developing new bio-products with added value to meet the demands of current market. It is widely acknowledged that plant-derived foods have a positive impact on human health. This positive influence has been attributed to the presence of secondary metabolites that are not nutrients, which exhibit a diverse range of biological activities. It can be argued that fruits can be considered as the most basic type of functional foods due to their significant concentration of bioactive compounds (Górnaś and Rudzińska 2016). Nevertheless, the successful utilisation of these resources relies on the advancement of technologies that can achieve substantial extraction yields while minimising adverse effects on the environment.

The functional composition of fruit waste has garnered significant attention. In recent decades, it has been observed that approximately 60% of medicinal drugs have been developed through structural modifications of compounds obtained from natural sources. The extraction of bioactive compounds from fruits, vegetables, and whole grains (FVW) yields a diverse range of molecules that exhibit significant structural and functional variations. These include fatty acids, phenolic compounds, dietary fibre, terpenes, phytostrogens, saponins, and other compounds. These substances have the potential to be incorporated into cosmetic products or utilised as additives within food products. Furthermore, over the past few years, a considerable number of bioactive components found in food have been successfully marketed as nutraceuticals or dietary supplements. Phenolic compounds derived from fruits, have been extensively investigated as bioactive substances. According to (Haminiuk et al. 2012), these substances are commonly linked to a diverse array of physiological characteristics, including anti-inflammatory, antioxidant, anticarcinogenic, and cardioprotective effects. In the context of winery operations, the by-products generated, such as grape pomace, skins, stems, and lees, contain a significant amount of phytochemicals, with phenolic compounds being the most abundant. Notably, phenolic acids, including caffeic, caftaric, and gallic acids, as well as flavonoids such as epicatechin, catechin, anthocyanidins, and quercetin derivatives are prominent. Additionally, condensed tannins in the form of procyanidins and stilbenes, particularly trans-resveratrol, are also present in notable quantities.

The apple pomace obtained from the jam, apple juice, vinegar, and cider processing industry contains significant amounts of phenolic acids such as gallic acid and chlorogenic acid, as well as flavonoids including procyanidins, quercetin and its derivatives, and catechin (Perussello et al. 2017). Additionally, previous studies have identified the presence of phloretin and phlorizin in apple pomace. It is noteworthy to mention hydroxytyrosol, a phenolic alcohol known for its strong antioxidant properties is one of the primary polyphenols found in olive residues, which are derived from the most widely consumed edible oil globally. Indeed, it is feasible to acquire a quantity ranging from 4 to 5 kg of this bioactive substance with a purity level of 99.6% per metric tonne of olive wet cake. This outcome has the notable effect of substantially diminishing the accumulation of waste during the process of olive oil production. Considering the fact that this particular antioxidant is typically derived through synthetic means and sold at elevated costs, the extraction of hydroxytyrosol from olive residues emerges as a highly significant alternative. In addition to apple, grape, and olive, there exists a diverse range of fruits that possess by-products that can serve as valuable sources of polyphenols. These include rosehip, citrus, pomegranate, mango, banana (Jiménez et al. 2017; Kowalska et al. 2017; Kumar et al. 2017). Terpenoids represent the most extensive category of secondary metabolites found in plants. Among the constituents of this group, carotenoids are particularly noteworthy. The pigments in question belong to the tetraterpenoid group and occur naturally. These pigments are accountable for the diverse range of red, yellow, and orange hues observed in numerous fruits. There has been significant scholarly attention directed towards these bioactive compounds owing to their provitamin A properties, their potential in cancer prevention, and their role in age-related macular degeneration. Furthermore, carotenoids are extensively utilised as food colourants, possess significant antioxidant properties, and can also serve as precursors for aroma or flavour development. These compounds have garnered significant attention within various industries, including food, pharmaceutical, chemical, cosmetics, nutraceutical, and personal care sectors.

Fruit waste can also serve as a valuable source of dietary fibre, which is a significant value-added product for various sectors including food, healthcare, and polymer processing industries. The term “dietary fibre” encompasses a diverse combination of indigestible polysaccharides, lignin, and waxes present in plant-derived food sources. The insoluble fibre fraction is comprised of cellulose, hemicellulose, and lignin, whereas the soluble fibre fraction encompasses pectins, arabinoxylans, β-glucans, and fructans. These two fractions exhibit distinct physiological effects and offer varying nutritional advantages. According to (Tosh and Yada 2010), the consumption of insoluble fibre has been found to enhance laxation and facilitate the proliferation of intestinal microflora, including probiotic species. Conversely, soluble fibre has been shown to contribute to the reduction of blood cholesterol levels and the regulation of blood glucose levels. Pectin has traditionally been utilized within the agricultural and food industry as a substance that imparts gel-like properties and enhances viscosity. Additionally, it serves as a stabilizing agent for fruit juices. Nevertheless, in recent times, pectin has been employed in novel contexts, including its utilisation as a substitute for fat (Zhang et al. 2018), a vehicle for delivering bioactive compounds via encapsulation (Seeranguráyar et al. 2018), and a carrier molecule for antioxidant and/or antimicrobial substances in edible packaging (Espitia et al. 2014).

Furthermore, there have been advancements in the development of applications that are not related to food. The bioactivities and health-promoting benefits of pectin have been utilised by the medical and pharmaceutical industries in various applications including drug delivery, wound healing, and tissue engineering. The primary sources utilised for the extraction and manufacturing of commercial pectin are citrus peel, apple pomace, and sugar beetroot pulp. Nevertheless, there has been a surge of interest in exploring alternative sources of pectin with diverse functional properties derived from fruit waste. Notably, pomegranate, banana, papaya, and mango peels have been investigated as potential sources of pectin (Do Nascimento Oliveira et al. 2018; Khamsucharit et al. 2018).

A range of extraction techniques can be utilized to retrieve the wide range of bioactive compounds found in fruit waste. The extraction methods that are most commonly utilised are those that rely on conventional solvent extraction. Solvent extraction is an economically viable procedure; however, it necessitates the use of organic solvents, which can be both toxic and highly contaminating in certain instances. Polar solvents such as water mixtures and ethanol are commonly employed in the food industry due to their cost-effectiveness and wide availability for the extraction process of phenolic compounds. However, when it comes to extracting hydrophobic compounds with low solubility in water, like carotenoids, the use of organic solvents becomes essential. Consequently, meticulous stages of solvent elimination and recovery are imperative. Green solvents are purported to be viable substitutes because of their minimal toxicity, significant biodegradability, and sustainable nature. Ethyl lactate, a potentially advantageous environmentally friendly solvent, exhibits complete biodegradability and can be found naturally in various food sources. According to Strati and Oreopoulou (2011), this substance exhibits miscibility with both hydrophobic solvents and water, enabling it to effectively extract compounds with diverse polarities. Several recent studies have provided evidence for the efficacy of ethyl lactate as a solvent for extracting curcuminoids (D'Archivio et al. 2018), alkaloids (Bermejo et al. 2013), and particularly carotenoids (Kua et al. 2018). The substance in question has been classified as Generally Recognised as Safe (GRAS) and has received approval from both the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) for use as a food additive and pharmaceutical. Although solvent extraction is widely utilized, it is accompanied by various limitations. Some of the challenges associated with this process include extended extraction durations, the need for high-quality and occasionally costly solvents, limited selectivity, insufficient recovery efficiency, and the requirement to evaporate substantial quantities of solvents for the purpose of recovery and reuse. As a result, there is a growing inclination towards the utilisation of novel extraction techniques or the integration of traditional and emerging technologies.

5.1.1 Microwave-Assisted Extraction (MAE)

Among the various emerging technologies, the process known as microwave-assisted extraction (MAE) has gained significant popularity for its extensive utilisation in the extraction of diverse compounds from a wide range of natural products and solid matrices. The primary benefits of this method include a greater extraction rate and efficiency, resulting in a reduced need for solvent volumes (Delazar et al. 2012). The considerable interest in the feasibility of MAE on a large industrial scale has been prompted by these various factors.

5.1.2 Ultrasound-Assisted Extraction

According to Barba et al. (2016), ultrasound-assisted extraction is widely acknowledged as a method that offers enhanced environmental sustainability and cost-effectiveness when compared to traditional extraction methods. The process induces an accelerated diffusion of solvents into the cellular materials, resulting in enhanced mass transfer and the disruption of cell walls. Consequently, this process enables the liberation of bioactive compounds. The process of ultrasound extraction necessitates reduced quantities of solvents, resulting in a commensurate decrease in energy consumption. Both the techniques microwave-assisted extraction as well as ultrasound-assisted extraction can be employed in conjunction with traditional extraction systems to enhance the yield of separation.

5.1.3 Supercritical Fluid Extraction

Supercritical fluid extraction is a cutting-edge and ecologically sound technique employed for the retrieval of natural compounds from botanical matrices. The technique is characterised by its rapidity and efficiency, although its scalability presents greater challenges compared to other methods. Emerging technologies, including pulsed electric field extraction, pressurized liquid extraction, and enzyme-assisted extraction, are being recognized as feasible alternatives to conventional methods.

6 Nutraceuticals

Given the rising prevalence of diet-related health issues, the incorporation of dietary supplements has become imperative. Nutraceuticals refer to bioactive compounds obtained from food sources or their constituents, which possess the potential to promote human health through disease treatment or prevention. According to (Manju Wadhwa et al. 2015), fruit by products are categorised as a compound that consists of dietary fibres, antioxidants, polyphenols, and fatty acids. The utilisation of bioactive compounds derived from discarded fruit waste serves as a valuable resource for the development and production of nutraceuticals. Researchers worldwide are increasingly drawn to the investigation of the utilisation and intake enhancements associated with dietary fibres present in a diverse range of fruits. The bulking mediators identified by (Garcia-Amezquita et al. 2018) are accountable for the augmentation of faecal hydration, intestinal mobility, and sugar absorption. The main components of this include carbohydrates, lignin, hemicellulose, pectin, and cellulose. In addition to its utilisation in plant-based food products, this ingredient has also found application in the baking industry, as well as in the manufacturing of snacks and pasta. When considering plants or plant-based foods, it is necessary to conduct a thorough examination of dietary fibre concentrations due to the wide range of species and cells involved. One of the conventional and frequently employed techniques is the utilisation of crude fibres (CF). The residues consist of varying proportions of cellulose (50–90%), lignin (10–30%), and hemicellulose (10–20%), depending on the specific food component. Nevertheless, the primary obstacle of the crude fibre method is variability of feed due to its chemical composition.

Two methods were used to analyse dietary fibre in the study. The first method, known as Neutral Dietary Fibre (NDF), involved dissolving insoluble dietary fibre in the hot detergent solution under neutral conditions. The second method, Acid Dietary Fibre (ADF), involved dissolving the residual ash and isolating cellulose and lignin, and also the least digestible fibrous fractions, using a hot detergent solution under acidic conditions. The fruit waste materials contain a significant amount of phenolic content, which can be recognised as a valuable resource for the development of preservatives, additives, or supplements after encapsulation. In a study conducted by (Sir Elkhatim et al. 2018), the researchers examined the polyphenol levels in various components of citrus waste, including seeds, pulp, and peels. The findings of the study indicated that peels exhibited the highest phenolic content in comparison to both seeds and pulp. Agro industries should prioritise investment in technological advancements, particularly through international collaborations. These collaborations can facilitate the conversion of by-products and waste into bioactive compounds, thereby optimising nutrient recovery. Furthermore, it is imperative to allocate more attention to the identification of appropriate solvents for extraction, particularly by delving into the realm of environmentally friendly solvents and ionic liquids.

7 Enzymes

Enzymes are a class of proteins that function as highly efficient and specific catalysts for specific chemical reactions, operating under gentle environmental conditions. Biomolecules have significant applications in various crucial economic sectors, including food, pharmaceuticals, cosmetics, textiles, fuels, and chemicals. Commercial enzymes are typically costly, primarily because of the elevated expenses associated with manufacturing and acquiring raw materials. The utilisation of fruit waste for cultivating microorganisms presents a significant opportunity for reducing costs by producing enzymes. Furthermore, a wide range of enzymes can be derived from these substrates. Several pertinent examples include the following: The enzymes mentioned in the text include cellulolytic enzymes, laccases, hemicellulases, and xylanases derived from lignocellulosic biomass. Additionally, amylases can be obtained from banana, mango grains. Pectinolytic enzymes can be sourced from pineapple bunches, lemon and orange peels, and grapes. Tannases can be found in grapefruit peels and cherries. Proteases are present in pomegranate bunches, and mango. Lipases can be extracted from lemon peel. Invertase is found in orange and banana peels, as well as pomegranate and coconut bunches.

The primary bioprocesses utilised for the production of enzymes can be categorised into two distinct groups: Solid-State Fermentation (SSF) and Submerged Fermentation (SmF) (Kapoor et al. 2016). The process of SmF involves the growth of microorganisms in a medium that contains an abundance of freely available water. The typical operating modes employed in this context are generally categorised as semi-continuous or batch-type. Soluble substrates undergo dissolution in the liquid phase, while insoluble substrates are either suspended or submerged. This particular arrangement facilitates effective regulation of the reaction parameters, albeit with a drawback of low productivity. Additionally, there is a potential concern regarding the significant influence of inhibitory compounds, and the energy demands associated with this configuration are comparatively elevated. In contrast, solid-state fermentation (SSF) involves the cultivation of microorganisms on moist and solid substrates without the presence of free liquid phase. According to Viniegra-González et al. (2003), this particular configuration is better suited for the cultivation of yeast and fungi as opposed to bacterial growth.

Fruit wastes that possess a high solids content demonstrate a favourable suitability for solid-state fermentation (SSF) due to their characteristic as substrates that offer microorganisms an environment akin to their native habitat. The aforementioned study conducted by Kapoor et al. (2016) demonstrates that this approach exhibits a preference for attaining an increased product yield and cell density in comparison to the configuration of Submerged Fermentation (SmF). Regardless, it is imperative to thoroughly examine each case in terms of the specific benefits and limitations associated with both SmF and SSF (Hansen et al. 2015). Currently, there is limited utilisation of the SSF technology in the commercial sphere. The primary constraints of solid-state fermentation (SSF) are primarily attributed to the challenges related to scaling up the process and controlling it effectively.

8 Biofuels

Biofuels, which are derived from biomass sources and have a low carbon footprint, are widely acknowledged as a crucial component of a future sustainable energy system. It is important to note that these biofuels should not compete with the food sector. The field of biofuels production is currently undergoing continuous evolution. The utilisation of biogas as a biofuel presents various potential avenues for valorization. It has the potential to be utilised as a source of heat and fuel for cooking, as well as for on-site electricity generation in gas engines and turbines, and in co-generation systems (Budzianowski 2016). However, it is important to note that the methane concentration in the upgraded biogas should generally exceed 95%, and in some cases, reach levels as high as 98%. As a result, the process of upgrading entails the elimination of gaseous byproducts found in the untreated biogas, primarily carbon dioxide, as well as other minor contaminants like hydrogen sulphide or siloxanes. Biogas compositions commonly exhibit CO_2 concentrations ranging from 35 to 45 volume percent. Consequently, a variety of biogas upgrading technologies can be employed in order to eliminate carbon dioxide (CO_2) and other contaminants from the biogas. The two most commonly utilised methods are water or amine scrubbing and pressure swing adsorption (PSA), which are absorption processes. However, membrane separation technologies have been attracting growing attention in recent years. In addition, the generation of syngas, which primarily consists of hydrogen (H2) and carbon monoxide (CO), through the reforming of biogas has garnered significant interest among numerous researchers. This approach is appealing due to its ability to effectively utilise raw biogas as a valuable intermediary gaseous product, thereby offering enhanced flexibility. It can be utilised as a biofuel, either directly or through the process of upgrading to bio-hydrogen.

The dark fermentation (DF) method has been extensively studied in the field of bio-hydrogen production (Das and Veziroglu 2008). Dark fermentation (DF) occurs as a result of the activity of anaerobic bacteria, which can be categorised as either strictly anaerobic (such as *Clostridium*) or facultative (such as *Enterobacter aerogenes* and *Escherichia coli*). The facultative bacteria, however, yield lower amounts of hydrogen. These factors include the type of microorganism and the metabolic pathways it follows, the substrates used as feedstock and inoculum, the characteristics of the bioreactor, and the process conditions like temperature, pH, gas-phase composition, presence of inhibitors, and the nutrient availability, among other variables. The substrates of choice are monosaccharides derived from the hydrolysis of polysaccharides found in fruit waste. In their study, (Yasin et al. 2013) conducted a comprehensive examination of hydrogen production from fruit waste. Their findings revealed significant disparities in the reported hydrogen yields, which were attributed to variations in the substrate utilised and the specific conditions employed during fermentation. The biogas production potentials of 55 mL H2/g-VS and 171 mL H2/g-VS were achieved from olive pomace and pumpkin waste, respectively, under batch conditions.

Limited information is currently accessible regarding the utilisation of fruit waste as substrates for ethanol production via fermentation. Apple pomace has been recognised as a highly promising raw material. The substrate has the potential to undergo solid-state fermentation, either with or without prior pretreatments. The enzymatic pretreatment method has been observed to yield a maximum of 190 g of ethanol per kg of apple pomace. One significant limitation is the temporal variability in the availability of this particular substrate. The study conducted by Hegde et al. (2018) documented ethanol yields derived from various substrates. These included 47 g per kg of tomato serum, 18–50 g per kg of grape pomace obtained through supercritical extraction of tomato pomace. Biobutanol possesses several advantages compared to bioethanol, including a higher energy density, reduced corrosive properties, and lower volatility. Furthermore, it exhibits non-hygroscopic behaviour, thereby enhancing its stability. Currently, there is a significant amount of research being conducted on the production of biobutanol from lignocellulosic biomass. In contrast, there is a limited amount of research available that examines fruit waste as a primary resource. When supplementing apple pomace with minerals and nitrogen yields a concentration of 22 g/L of butanol (Hegde et al. 2018).

9 Films and Packaging

Plastics have played a crucial role in a wide range of applications for many years, encompassing everything from household electrical appliances to food packaging. Petroleum-derived sources exhibit characteristics such as lightweightness, affordability, and superior durability in comparison to glass materials. Nevertheless, the non-biodegradable nature of this substance has had a significant impact on the entire ecosystem. The negative consequences associated with these effects have prompted a global transition towards the utilisation of environmentally sustainable materials or bio composites, which consist of a combination of food waste. The utilisation of diverse fruit and vegetable-derived materials in the development of bio-packaging films has garnered the attention of numerous researchers aiming to create environmentally friendly alternatives to conventional plastics. Several experiments were conducted utilising starch and cellulose as the predominant material. Cellulose is a naturally occurring polymer derived from abundant resources. An example of a potential application in the field of edible packaging is the utilisation of bioplastic composed of chitosan and cellulose nanocrystals, which is derived from mango waste. This bioplastic, when combined with polyvinyl alcohol, has demonstrated promising properties as an active film (Dey et al. 2021). The production of bioplastics from fruit waste can be regarded as a sustainable process owing to its inherent biodegradability and carbon–neutral characteristics. Bioplastics possess significant environmental advantages, which serve as a catalyst for their prospective growth in the global market. While certain bioplastics may experience negative effects from moisture and sensitivity, it is suggested that future research should focus on operational enhancements.

10 Flavouring Agents

Aroma compounds, referred to as active flavor compounds in academic literature, consist of volatile and non-volatile constituents that exhibit physio-chemical properties. The presence of flavours is of paramount importance in determining the level of acceptance of food. The diverse array of natural aromas found in flowers and plants possesses a multitude of uses within industries such as fragrance, perfumery, cosmetics, food, and surfactants, where they are employed as additives. However, a relatively unexplored area of research pertains to the utilisation of fruit waste as potential flavouring agents following appropriate processing methods. The fruit waste materials, or their constituent components, possess bioactive compounds and flavonoids that contribute to the nutritional properties of food. While it is essential to engage in waste pre-processing for the purpose of re-utilization, the utilisation of such agents, potentially involving microorganisms, presents a promising alternative for production when compared to the use of artificial flavours. The utilisation of fruit waste holds significant potential in enhancing the flavour profiles of various food products. For instance, pineapple cannery waste, which serves as a source of ferulic acid, is regarded as the precursor for aroma compounds like vanillin and vanillic acid. Research has been conducted on the extraction process utilising two specific fungal strains, namely *Pycnoporus cinnabarinus* MUCL 39,533 and *Aspergillus niger* I-1472. In a study carried out by Mantzouridou et al. (2015), the cultivation of yeast VitilevureMT (*S. cerevisiae*) has been observed to be feasible through the process of solid-state fermentation utilizing orange peel waste. This process leads to the synthesis of various flavouring compounds, including isoamyl acetate, phenyl ethyl acetate, ethyl octanoate, ethyl decanoate, ethyl hexanoate, and ethyl do decanoate. The resultant substances of this procedure encompass bioactive constituents, including phenolic compounds, pectin, carotenoids, and L-ascorbic acid.

The study conducted by Lalou et al. (2013) yielded encouraging findings in the extraction of flavouring compounds from orange peel hydrolysate. The immobilisation of *Saccharomyces cerevisiae* led to the synthesis of chemical compounds, specifically α-terpineol and limonene. The utilisation of fungi for the extraction of flavour compounds from waste materials was also examined in the investigation. As an example, the utilisation of fungus (*T. chioneus*) in the biotransformation of apple pomace resulted in the identification of 14 distinct flavours, primarily including 3-phenylpropanal, acetic acid, benzyl alcohol, benzaldehyde, and 3-phenyl-1-propanol (Bosse et al. 2013). Furthermore, the inclusion of cinnamic acid resulted in a nearly tenfold augmentation in the production of 3-phenyl-1-propanol and 3-phenylpropanal. Therefore, the utilisation of microorganisms or enzymes for extraction purposes yields outcomes that effectively align with the objective of waste valorization. While both solid-state fermentation and enzyme-assisted extraction have shown potential for the isolation of diverse compounds, it is crucial to thoroughly investigate and address challenges such as sensitivity and volatility to physical conditions. One potential approach entails meticulous optimisation of the process conditions during fermentation in order to mitigate the loss of volatile aromatic compounds within the reactor. According to Hadj Saadoun et al. (2021), the incorporation of hybrid technologies has the potential to enhance overall efficiency.

10.1 Conclusion

Fruit by-products are valuable resource that can be utilised for the production of biofuels, nutraceuticals, and other beneficial substances. Fruit by-products are comprised of various organic components, including lipids, proteins, carbohydrates, as well as essential nutrients such as nitrogen, phosphorus, and potassium. These constituents play a significant role in determining the techniques used for valorization and the resulting products. The valorization of fruit byproducts is an environmentally conscious strategy aimed at reducing the production of greenhouse gases, landfills, and leachate, while simultaneously promoting economic growth. The implementation of appropriate policies is also necessary in order to effectively reduce the generation of fruit waste. In addition to the well-recognized challenges related to supply chain, technological advancements, and substantial investments, the successful establishment of a sustainable framework for managing fruit and vegetable waste necessitates addressing critical factors such as technical feasibility, social acceptance, and economic viability. This endeavour also entails academic-industrial collaborations on a global level, encompassing various aspects including pre-treatment, valorization, logistics, and continuous monitoring. It is imperative to adopt a more coordinated strategy in waste management that is in line with the objectives of sustainable development. This approach is crucial for the production of environmentally friendly value-added products derived from waste materials.

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Waste Valorization in Food Industries: A Review of Sustainable Approaches

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

Abstract The global food industry generates substantial volumes of solid and liquid waste throughout its production, processing, and consumption cycles. Remarkably, around one-third of the world's produced food is wasted annually, amounting to an alarming 1.3 billion tons of discarded resources. Stringent environmental regulations have intensified waste management challenges, prompting a transition towards more sustainable practices. In response to this pressing issue, there is growing emphasis on extracting valuable nutrients from food industry waste to create value-added products. Formerly seen as a liability, this waste is now recognized for its untapped potential in a circular economy framework. The conversion of waste-derived nutrients into innovative products not only reduces environmental impacts but also aligns with principles of resource efficiency. This comprehensive review presents a holistic overview of diverse strategies for mitigating and managing food industry waste. Covering reduction at the source, advanced treatment methods, and waste valorization techniques, the review illuminates how stakeholders are adapting to the evolving waste management landscape. It underscores the potential of converting waste into valuable resources, thereby establishing a more sustainable trajectory for the food industry. In essence, this review synthesizes current advancements and challenges in food industry waste management. It highlights the urgency of collaborative efforts among industry, policymakers, and researchers to devise and implement innovative strategies. These strategies aim to not only alleviate waste burdens but also unlock its inherent value, contributing to a more sustainable and resource-efficient future.

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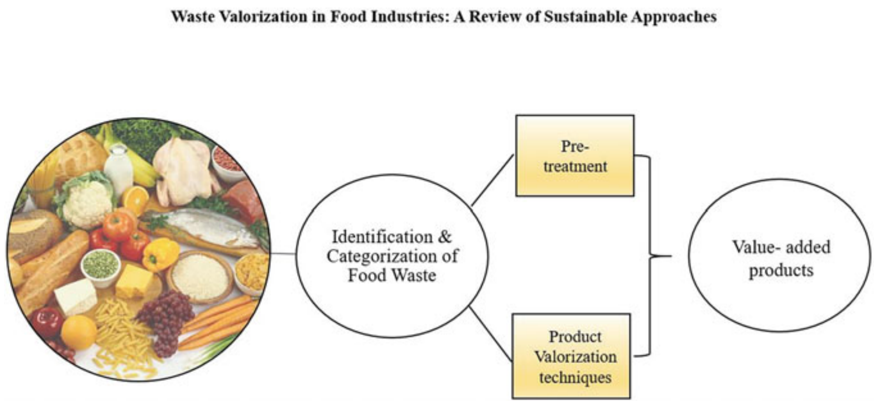


Keywords Food wastage · Food supply chain · Food waste management · Food waste regulations · Biomass · Value added products

1 Introduction

"Waste" refers to substances that are discarded at the end of their intended lifespan. Effective "waste management" involves a series of crucial steps, including segregation, collection, transportation, and reprocessing, recycling, and proper disposal. For waste management to be considered sustainable, it must adhere to environmentally, socially, and economically responsible practices that prioritize sound methods.

It is important to distinguish between "food waste" and "food loss." Although these terms are often used interchangeably, they have distinct meanings. "Food loss" occurs during the production, post-harvesting, and processing stages within the food supply chain (FSC). In contrast, "food waste" takes place at the final stages of the FSC, namely at the retail and consumption stages.

Various definitions exist to elucidate the concept of food waste:

- According to the Food and Agriculture Organization (FAO) in 1981, food loss refers to any edible substance within the Food Supply Chain (FSC) that is intentionally or unintentionally discarded, lost, degraded, or consumed by pests, instead of being used for human consumption.
- Stuart (2009) provides a similar definition, encompassing edible material that is intentionally fed to animals or is a result of food processing, thereby deviating from its original course as human food.

Food waste presents a substantial challenge with far-reaching implications. It not only squanders valuable resources but also exacerbates environmental concerns. Inefficiencies in the food supply chain, inadequate storage, and consumer behaviours all contribute to the issue. Addressing food waste necessitates collaborative efforts across sectors to implement sustainable practices, raise awareness, and reshape consumption patterns.

By adopting measures to curtail food waste at both the production and consumption ends, society can unlock significant benefits. Not only does this contribute to more responsible resource usage, but it also supports food security, reduces greenhouse gas emissions, and lessens the burden on landfills. In conclusion, understanding the nuances between food loss and food waste is crucial for formulating effective waste management strategies. The impact of food waste is profound, affecting not only resource utilization but also environmental sustainability. Embracing sustainable practices throughout the food supply chain and promoting responsible consumption is essential for a more equitable and environmentally conscious future (Parfitt et al. 2010).

2 Sustainable Management of Food Waste

In recent years, the sustainable management of food waste has emerged as a critical and rapidly advancing research domain. This surge is propelled by the growing recognition of the three core pillars of sustainability: environmental, economic, and social dimensions, as illustrated in Fig. 1 (Garcia-Garcia et al. 2017). Effectively managing food loss and waste in a sustainable manner presents a formidable challenge. The complexity arises from the diversity in waste generation patterns, the inherent physical and chemical attributes of the waste, and underlying issues that complicate accurate volume assessments. Factors such as population growth, industrialization, urbanization, and globalization have collectively contributed to the rapid escalation of food waste in Asia. These trends have induced shifts in dietary preferences and increased people's purchasing power, resulting in the accumulation of excess products. Notably, the absence of sufficient emphasis, funding, and awareness towards food waste management in the Asian context has exacerbated the problem.

Consequently, this upsurge in food waste has far-reaching consequences, extending to the utilization of critical natural resources like land, water, and energy. The continuous strain on these resources is projected to persist until at least 2050 (Joshi and Visvanathan 2019), reflecting the pressing need for immediate interventions to ensure sustainable practices. This review paper aims to comprehensively delve into the multifaceted landscape of sustainable food waste management. It will explore the intricate interplay between the environmental, economic, and social facets of sustainability within the context of food waste. The challenges posed by the heterogeneous nature of waste generation patterns, the variability in waste properties, and the complex issues influencing waste quantification will be dissected.

Moreover, the review will delve into the contributing factors specific to Asia, where the burgeoning population, rapid industrial growth, urbanization, and changing consumption patterns have contributed to a marked increase in food waste. The

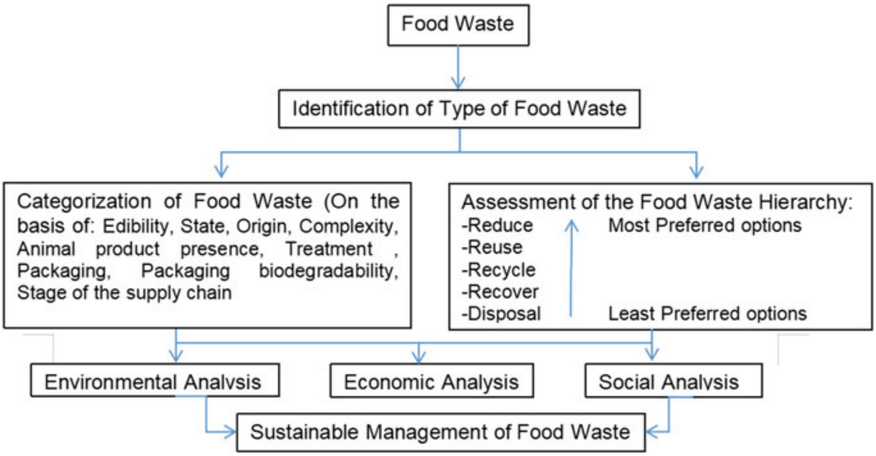


Fig. 1 Sustainable management of food waste

resultant strain on vital natural resources necessitates urgent measures for mitigation and sustainable management. By shedding light on the current state of food waste management practices in Asia, this paper aims to underscore the urgency of addressing this critical issue.

In conclusion, the escalating concern of food waste, particularly in Asia, demands a comprehensive understanding of its complexities and implications. This review will critically evaluate the existing literature, analyze sustainable management approaches, and propose viable strategies for tackling the challenges posed by food waste. Ultimately, it strives to contribute to a more sustainable future by fostering awareness, encouraging policy changes, and promoting responsible consumption patterns.

The imperative for sustainable waste management and the optimization of food waste on a global scale stems from several key factors:

a. **Stringent Environmental Regulations and Growing Concerns**: The proliferation of rigid and non-negotiable environmental regulations underscores the heightened environmental consciousness prevailing globally. This escalation in environmental awareness has led to increasingly stringent guidelines governing waste management practices.
b. **Technology-Driven Sustainable Resource Utilization**: The quest for sustainable usage of natural resources has been propelled by technological advancements. Innovative technologies have paved the way for more efficient and eco-friendly resource utilization, bolstering the imperative for sustainable waste management
c. **Escalating Costs of Waste Disposal**: The escalating costs associated with waste disposal have accentuated the need for adopting sustainable waste management practices. As disposal expenses rise, industries are compelled to explore

alternative strategies to minimize waste generation and optimize resource utilization.

The food industry, in particular, is a significant contributor to environmentally friendly waste, often discarding considerable amounts of residual materials with elevated biochemical oxygen demand (BOD) and chemical oxygen demand (COD) levels. This has prompted global legislative bodies to implement stringent regulations over the past decade (Otles et al. 2015).

The concept of sustainable food management holds the potential to not only optimize resource usage for food entrepreneurs and consumers but also bridge the gap between those with inadequate access to food resources. By effectively managing food waste, resources can be conserved for future generations.

Aligned with the principles of the 3Rs—Reduce, Reuse, and Recycle—sustainable food management endeavors to foster environmental protection and mitigate the repercussions of food wastage. According to the Food and Agriculture Organization (FAO), as of 2011, approximately one-third of global food production is either lost or wasted. A concerted effort to curtail this wastage would yield economic, societal, and environmental benefits, thus resonating with both the economy and communities while mitigating environmental impacts (EPA 2016).

This review paper aims to comprehensively explore the pivotal drivers behind the adoption of sustainable waste management practices, particularly focusing on the global food industry. It will delve into the intricate interplay between stringent environmental regulations, technological innovations, and the escalating costs of waste disposal as catalysts for sustainable practices. Furthermore, the paper will investigate the profound impact of food waste within the context of the food industry, emphasizing the pressing need for sustainable management strategies.

In essence, this review seeks to critically analyze the complex and multifaceted landscape of sustainable waste management, underscored by a comprehensive understanding of global regulations, technological advancements, and economic implications. It endeavors to contribute to the discourse on sustainable food management by shedding light on its multifarious benefits and implications, ultimately advocating for a more responsible and resource-efficient approach to waste management within the food industry and beyond.

3 Categories and Classifications of Food Loss and Waste

According to the Food and Agriculture Organization (FAO) in 2011, the Food Supply Chain (FSC) for both vegetable and animal commodities encompasses five distinct system boundaries, each representing specific stages of production and consumption. These system boundaries are detailed as follows:

3.1 Vegetable Commodities and Products

(a) Agricultural Production: This phase encompasses losses incurred during various agricultural activities such as harvesting, which can result in mechanical treatment-induced losses and spillage. The sorting process after harvesting also contributes to losses.
(b) Post-Harvest Handling and Storage: Losses during this phase are attributed to spillage and degradation that can occur during storage, handling, and transportation of crops between the farm and distribution centers.
(c) Processing: Both industrial and domestic processing stages lead to losses due to spillage and degradation. Processes like baking bread, canning, and juice production contribute to such losses.
(d) Distribution: Losses within the distribution phase occur at different points within the market system, including wholesale markets, supermarkets, and retail outlets.
(e) Consumption: At the level of domestic consumption, food losses can arise, further impacting the overall efficiency of the food supply chain.

3.2 Animal Commodities and Products

(a) Agricultural Production: In the context of animal commodities, agricultural production involves losses due to animal death during breeding. For instance, the loss of bovine, pork, and poultry meat can occur due to animal mortality.
(b) Post-Harvest Handling and Storage: This phase encompasses losses related to the transportation of animals to slaughterhouses and the subsequent condemnation of carcasses. Losses in the realm of fish meat occur during processes like canning and smoking. Similarly, milk losses transpire due to factors such as industrial milk treatment (resulting in spillage) and the processing of milk-derived products like cottage cheese and yogurt.
(c) Distribution: The distribution phase sees an increase in food wastage as products move through wholesale markets, retailers, supermarkets, wet markets, and other distribution points.
(d) Consumption: The consumption stage pertains to food wastage at the domestic level during meal preparation and consumption.

The elucidation of these distinct system boundaries within both vegetable and animal commodities underlines the multifaceted nature of food loss and waste. Each phase presents its own set of challenges and opportunities for mitigation strategies. Understanding these delineated boundaries provides a comprehensive view of where food losses and wastage can occur across the entire spectrum of food production, distribution, and consumption. This knowledge is essential for devising targeted interventions and sustainable management approaches to reduce the overall impact of food loss and waste in both vegetable and animal-based supply chains (Thakur et al. 2021).

4 Characteristics of Waste from Food Processing Industries

4.1 Fruit and Vegetable Processing Waste

The organized fruit and vegetable sector in countries like India, the Philippines, China, and the United States contributes significantly to the global food waste issue, generating a staggering fifty-five million tonnes of food waste annually (Wadhwa and Bakshi 2013). Within this sector, several practices contribute to the production of substantial waste volumes, including the process of vegetable washing, which results in wastewater laden with soil and organic matter. Notably, cannery wastewater exhibits similarities to household kitchen waste (Valta et al. 2017). The generation of waste within this sector stems from various activities, such as fruit and vegetable preparation, sorting, juicing, and bleaching. These processes yield waste streams rich in suspended solids and organic content, encompassing constituents like starch and fruit sugars.

However, the inappropriate disposal of such waste, either in landfills or bodies of water, presents formidable environmental challenges. The accumulation of these waste materials not only strains disposal systems but also poses significant risks to ecosystems, water quality, and the overall balance of the environment (Zahid and Khedkar 2021a).

In light of these challenges, there is a growing emphasis on exploring innovative solutions to harness the untapped potential within fruit and vegetable waste. The adoption of methods to convert this waste into valuable resources is gaining momentum as a means of mitigating the environmental impacts associated with its disposal (Fig. 2).

One promising avenue involves the transformation of fruit and vegetable waste into compost, a nutrient-rich organic material that can enhance soil quality, promote plant growth, and contribute to sustainable agricultural practices. Additionally, the incorporation of such waste into animal feed offers an opportunity to minimize waste generation while potentially providing supplementary nutrition for livestock.

Furthermore, the concept of converting fruit and vegetable waste into renewable energy sources has garnered attention. Technologies such as anaerobic digestion can be employed to generate biogas, a renewable energy resource, through the decomposition of organic waste materials. This not only addresses waste management challenges but also contributes to the diversification of energy sources and reduction of greenhouse gas emissions. Moreover, the innovative utilization of fruit and vegetable waste in the creation of value-added products underscores the concept of

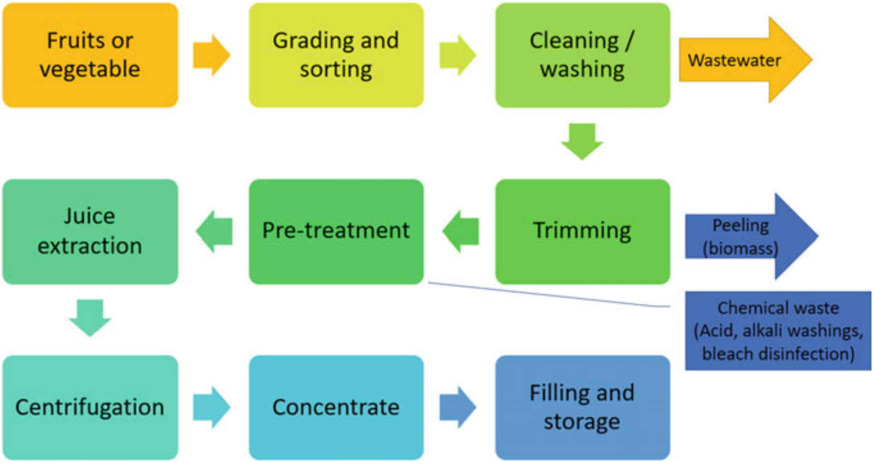


Fig. 2 Fruit and vegetable processing unit and waste discharge

a circular economy. This approach involves transforming waste materials into novel products, such as bio-based packaging materials, natural dyes, and extracts for the cosmetic and pharmaceutical industries (Zahid and Khedkar 2021b).

Hence, the considerable food waste generated by the organized fruit and vegetable sector necessitates urgent and strategic interventions. The exploration of alternatives to traditional waste disposal practices is paramount. By redirecting fruit and vegetable waste towards composting, animal feed, renewable energy production, and the creation of value-added products, the sector can contribute to sustainable resource management, environmental protection, and the reduction of its ecological footprint. These solutions not only address the challenges posed by food waste but also align with the broader global sustainability agenda.

4.2 Dairy Processing Waste

Among the industries that contribute significantly to wastewater generation, the Dairy Industry stands out as a major player. This industry is engaged in the production of various dairy products such as butter, cheese, pulverized skim milk, and ghee, alongside generating by-products like buttermilk, whey, and edible casein. Particularly noteworthy is the production of whey as a waste product, which poses serious contamination challenges. The biochemical oxygen demand (BOD) of whey is typically in the range of 35–40 g/L, indicating a lactose content of approximately 4.5–5% (Mansoorian et al. 2016). Whey, being a common waste by-product in the dairy sector, carries significant environmental implications due to its composition and characteristics.

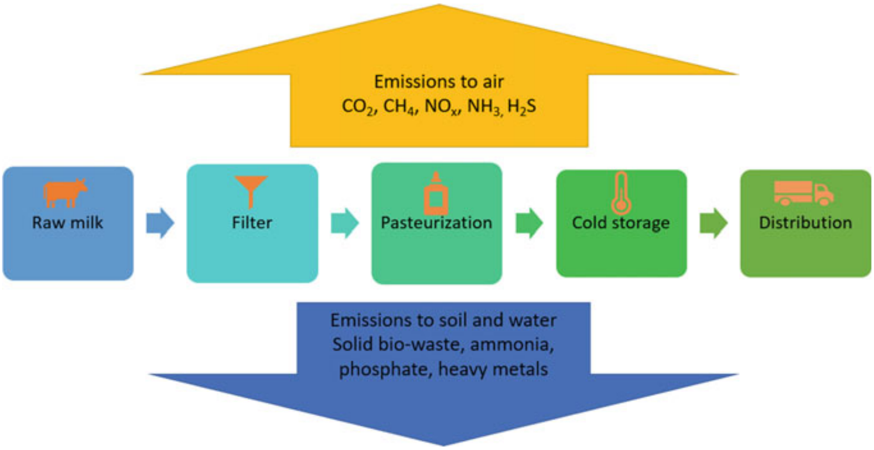


Fig. 3 Milk processing unit and waste discharge

The primary contributor to dairy industry wastewater is whey, which is generated during various cheese manufacturing processes. It is estimated that for every 1000 kg of cheese produced, around 150–200 kg of whey is generated as a by-product (Mistry 2003). The disposal of this whey waste presents a considerable challenge due to its environmental impact and potential for causing pollution. Throughout different phases of dairy production, such as milk processing, equipment cleaning, and packaging, substantial amounts of potable water are used. The resulting wastewater from these processes contains a notable concentration of organic liquid constituents, including whey, lactose, fat, and minerals. Although milk waste typically maintains a neutral or slightly alkaline pH, the fermentation of milk sugars can swiftly lead to highly acidic conditions (Hansen and Cheong 2019). The precipitation of casein, a protein component in milk, occurs particularly at lower pH levels (Fig. 3).

To address the environmental concerns associated with dairy industry wastewater, there is a growing focus on the development and implementation of effective treatment strategies. These strategies aim to mitigate the negative impact of dairy waste on water bodies and ecosystems, ensuring compliance with environmental regulations and safeguarding human and environmental health. Technologies such as biological treatment processes, anaerobic digestion, and advanced filtration systems are being explored to manage and treat dairy industry wastewater effectively.

To summarize, the Dairy Industry's significant contribution to wastewater generation, particularly through the production of whey waste, underscores the importance of sustainable waste management practices. As the industry grapples with the challenges posed by these waste by-products, the adoption of efficient treatment methods becomes paramount. By addressing the environmental repercussions of dairy waste, the industry can align itself with broader sustainability goals and contribute to a healthier and more ecologically balanced future.

4.3 Meat, Fish, and Poultry Waste

Meat Industry and Its Environmental Impact

The meat industry has a substantial environmental footprint due to the production of not only meat itself but also the extensive range of by-products that arise from slaughterhouses. These by-products include skins and fur, which find applications in various industries like leather, athletic equipment, cosmetics, edible gelatin, and glue. A notable example is the manufacturing of gelatin, where animal bones are utilized. Furthermore, valuable compounds such as Vitamin D3 are extracted from sources rich in cholesterol, such as the brain, nervous system, and spinal cord, while Vitamin B12 is sourced from the liver of pigs and cattle. Even insulin, crucial for regulating blood glucose levels in diabetic patients, is procured from the animals' pancreas.

One of the key processes in slaughterhouses is disemboweling, which contributes to the generation of a distinct scent known as "mist." The odor output is linked to the biodegradability of the raw materials used in the manufacturing processes. To mitigate unpleasant odors, rendering is employed, a process that separates and stabilizes protein and fat components, thereby reducing odor development. Rapid processing further aids in minimizing undesirable smells and ensuring product consistency (Fig. 4) (Okoro et al. 2017).

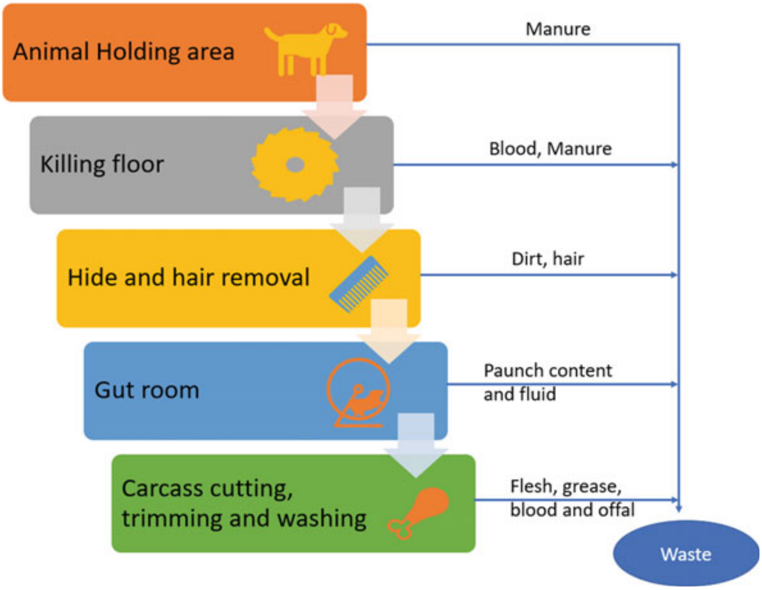


Fig. 4 Meat processing unit and waste discharge

Utilization of Fish Waste

The utilization of fish waste is another avenue through which the fishing industry's environmental impact can be addressed. Fish waste contains essential components like protein, minerals, and fat, making it a valuable resource. Additionally, the waste yields chemicals, chitosan, fish protein hydrolysate (FPH), and fish oil. These constituents find applications in various industries, contributing to the reduction of waste and the generation of useful products (da Rocha et al. 2018).

Poultry By-Products and Sustainability

The poultry sector generates a significant amount of by-products, notably feathers, which require proper treatment to avoid environmental emissions. These feathers can be repurposed in a variety of ways, including being used as feed, in oxidation and heat separation processes, cooling systems, and even as composites for biodegradation and fabric manufacturing. The potential for utilizing poultry feathers extends to biofuel development post hydrolyzation, adding to their value in sustainable practices (Seidavi et al. 2019).

Common Traits of Meat, Poultry, and Fish Waste

The waste generated by the meat, poultry, and fish industries shares several common characteristics. These include decomposed organic matter, specific proteins, oils, organic nitrogen, fat, and a notable presence of pathogens. These characteristics highlight the importance of proper waste management practices to mitigate their potential negative environmental impact. Furthermore, wastewater from slaughterhouses and meat packing facilities also includes urine and feces, which need to be carefully managed to prevent contamination and pollution (Carpentier 2009).

In conclusion, addressing the environmental impact of the meat, poultry, and fish industries requires a holistic approach that considers not only the primary products but also the by-products and waste streams. Efficient and sustainable utilization of these by-products can contribute to reducing waste, minimizing emissions, and creating valuable resources for various industries (Jayathilakan et al. 2012).

Brewery and Distillery Waste

Waste water procured from Brewery is distinctive which includes alcohol, sugars and proteins. As a supplemental raw material, dduring the brewing cycle, malts, rice and maize starch are fed into the breeding tank and it is saccharized followed by filtration of the malt liquid blended with hops. The filtrated malt liquid is then boiled in caldron and cooled down to 7–10 °C to blend with yeast for fermentation for 7–10 days in advance as the final product. Waste-water of Brewery, is abundant in various nutrients, which significantly conflict with natural environment if it is liberated without the appropriate treatment. The brewery and distilleries wastewater has plentiful of solid matter which includees nitrogen and fermented substance inclusive of their matter. The fermentation waste, specifically by products i.e., spent yeast are strong and very high which is dissolved or colloidal fractions of the suspended solid content, almost

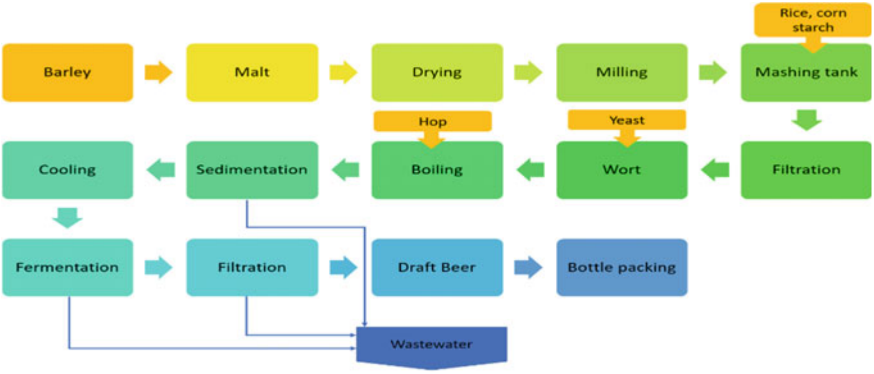


Fig. 5 Beer brewery processes and Waste-water discharge

having BOD of 2000–15,000 mg/L, total nitrogen of 800–900 mg/L and phosphate of 20–140 mg/L (Gunes et al. 2019, 2020) (Fig. 5).

5 Waste Management Strategies

Waste management strategies are centered on minimizing waste, recovering valuable resources, and treating waste before its ultimate disposal. The substantial amount of solid waste generated in the agro-food sector presents not only potential environmental concerns but also economic challenges for organizations in terms of waste treatment. Consequently, the advantages of proper food waste management extend beyond environmental benefits and encompass cost savings and resource efficiency. To effectively reduce costs, the food industry must prioritize the prevention of food waste. Embracing the use of by-products and food waste as raw materials represents a promising and recommended approach. Moreover, emerging technologies for food waste recovery involve additional processing methods, such as separation, concentration, and biological or chemical conversion (Joshi and Visvanathan 2019).

6 Waste Prevention

The priority should always be given to avoidance of food wastage, as wastage at all times be valued at money and the majority of the companies are inattentive of the true costs of wastage. While the concept of prevention of waste is broadly acknowledged, the exercise has fall behind. Table 1 illustrates the major causes of loss of food in distinct levels of the food chain and its avoidance.

Table 1 The major causes of loss of food in distinct levels of the food chain and its avoidance

Stage of FSC	Reason of food loss and wastage	Ways of prevention
Agriculture	Exceeded production in comparison to consumer's demand	Strengthening communication and collaboration between farmers and consumers
	Untimely harvesting	Facilitating the organization of small farmers and diversifying and expanding their production and marketing capabilities
Post harvest	Faulty storage system and inappropriate infrastructure	Financing infrastructure and transportation
Distribution	Stringent "appearance quality standards" set by supermarkets for fresh products	Supermarkets conduct consumer surveys to ensure that customers do not purchase food products with incorrect weight, size, or appearance
		Selling agricultural products nearby consumers and not having to pass the strict quality regulations made up by supermarkets
	Unsafe food is inedible to consumers	Development of knowledge among the operators with
	Disposal of food waste costs much more as compared to usage of the food waste in industrialized countries	Development of the markets for products that are sub-standard and are still safe for consumption with good nutritional value and taste
	Displaying large quantities and supply of various products/brands	Marketing cooperatives and market facilities in improved state
Consumption	In industrialized countries wasteful consumer behaviour is observed in case of abundance	People's attitude can be altered on awareness

Source Eunomia (2014)

7 Solid Waste Treatment

Considering the prohibition of landfilling food wastes, the recommended course of action involves utilizing solid waste by extracting valuable components, nutrients, or energy. Composting currently enjoys widespread adoption in Europe as a bio-waste treatment approach. However, it is anticipated that energy utilization from bio-waste will gain greater preference in the future. Nevertheless, for maximizing value recovery from food wastes, the priority should be given to recovery methods. Figure 6 below illustrates the technologies for product recovery (Fig. 6).

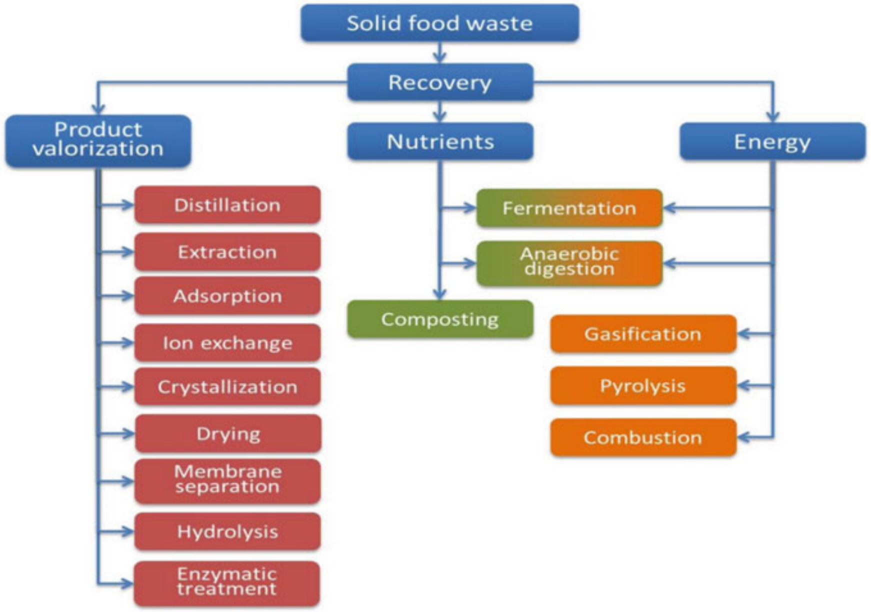


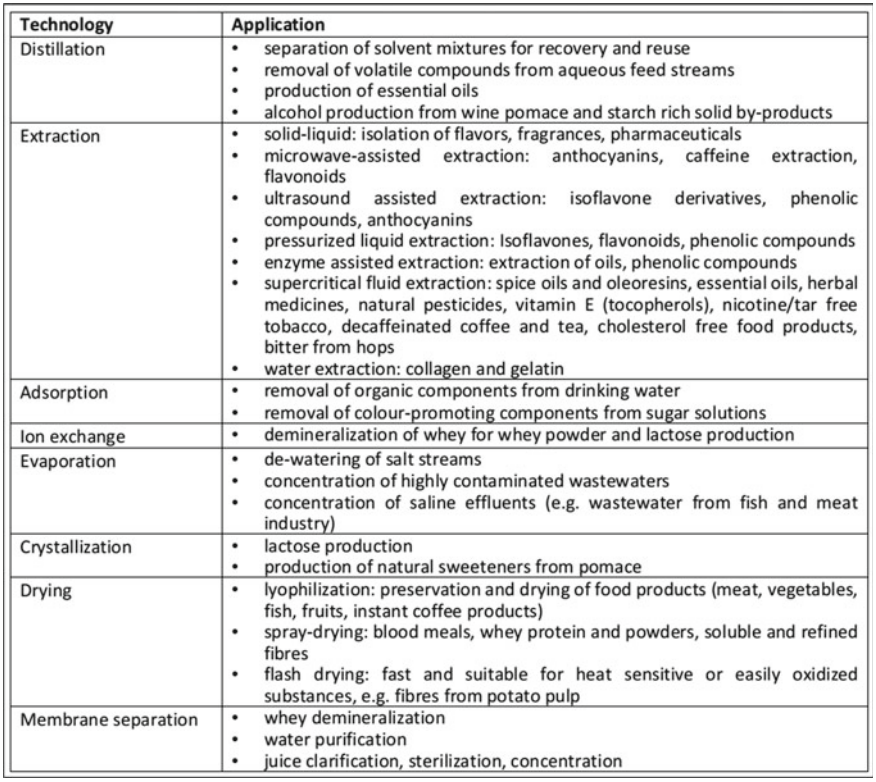
Fig. 6 Solid food waste product valorization technologies

8 Waste and By—Product Valorization

Valorization means generating value or recovering from the wastage. The Agro-food wastes minimization and recycling network (AWARENET) defines valorization as: *"Increase of technical and/or economic value of by-products and wastes that are generated in different agro-food industries"*. The technologies involved in Valorization are mechanical, diffusional separation technologies, chemical and biochemical modifications technologies.

8.1 Mechanical Separation Methods

The mechanical separations techniques involves the extraction or pressing in a solid–liquid phase mechanically. Therefore, in various different oil seeds presence of Fat and oil are separated by pressing mechanically, additionally it can be used for extraction of fruit juice.



Technology	Application
Distillation	• separation of solvent mixtures for recovery and reuse • removal of volatile compounds from aqueous feed streams • production of essential oils • alcohol production from wine pomace and starch rich solid by-products
Extraction	• solid-liquid: isolation of flavors, fragrances, pharmaceuticals • microwave-assisted extraction: anthocyanins, caffeine extraction, flavonoids • ultrasound assisted extraction: isoflavone derivatives, phenolic compounds, anthocyanins • pressurized liquid extraction: Isoflavones, flavonoids, phenolic compounds • enzyme assisted extraction: extraction of oils, phenolic compounds • supercritical fluid extraction: spice oils and oleoresins, essential oils, herbal medicines, natural pesticides, vitamin E (tocopherols), nicotine/tar free tobacco, decaffeinated coffee and tea, cholesterol free food products, bitter from hops • water extraction: collagen and gelatin
Adsorption	• removal of organic components from drinking water • removal of colour-promoting components from sugar solutions
Ion exchange	• demineralization of whey for whey powder and lactose production
Evaporation	• de-watering of salt streams • concentration of highly contaminated wastewaters • concentration of saline effluents (e.g. wastewater from fish and meat industry)
Crystallization	• lactose production • production of natural sweeteners from pomace
Drying	• lyophilization: preservation and drying of food products (meat, vegetables, fish, fruits, instant coffee products) • spray-drying: blood meals, whey protein and powders, soluble and refined fibres • flash drying: fast and suitable for heat sensitive or easily oxidized substances, e.g. fibres from potato pulp
Membrane separation	• whey demineralization • water purification • juice clarification, sterilization, concentration

Fig. 7 Diffusional separation methods

8.2 *Diffusional Separation Methods*

Diffusional separation methods encompass a range of techniques such as distillation, various types of extraction, adsorption, ion exchange, crystallization, drying, evaporation, and membrane separation. These methods find extensive application in diverse areas of the food industry, facilitating the valorization of by-products (Fig. 7) (Thakur et al. 2021).

8.3 *Chemical Separation Methods*

Chemical modifications in the food industry entail the breakdown of chemical compounds through a process known as hydrolysis, which is primarily affected by water. Hydrolysis is considered the most prevalent chemical separation method. In certain cases, when ordinary water proves ineffective, strong acids, bases, or steam are employed. For example, starch can be converted into sugars using a strong acid catalyst, while animal fats or vegetable oils can be transformed into glycerol and fatty acids through steam utilization. Furthermore, specific enzymes can be applied to facilitate the conversion of proteins, fats, oils, or carbohydrates.

8.4 Biochemical Methods

Biochemical modification encompasses various techniques, including pasteurization, biogas production, enzymatic treatment, and fermentation. In the dairy industry, pasteurization commonly utilizes High Temperature Short Time (HTST) and Low Temperature Long Time (LTLT) methods for the valorization of by-products. The outcomes of fermentation processes are diverse and heavily reliant on the specific microorganisms involved. For instance, yeast and fungi can produce ethanol from glucose during fermentation. On the other hand, enzymatic treatment involves the use of enzymes to break down proteins, lipids, and carbohydrates present in food waste (Pap et al. 2014).

9 Extraction of Bioactive Components From Plant Material

To recover the valuable compounds from plants, several types extraction processes can be used. Apart from the conventional extraction methods, like Soxhlet extraction or conventional solid/liquid extraction, more environment friendly and efficient non-conventional extraction techniques have been developed over the last 50 years such as ultrasound for bioactive compounds extraction from herbs and grape peel, pulsed electric fieldd, enzyme assisted extraction of edible oil, extrusions for oilseeds, microwave assisted extraction and pressurized solvent extraction, ohmic heating for extraction of oils, supercritical fluid extraction and superheated water technique (Pap et al. 2012; Thakur and Belwal 2022; Thakur et al. 2023).

9.1 Waste-to-Energy Technologies

Over the past decade, tertiary biomass has gained significant attention as a primary source for bioenergy generation, leading to increased efforts in harnessing the energy content of organic waste and effluents. The agro-food sector's biomass-based waste materials can be converted into energy through various process routes, including thermochemical, biochemical, mechanical, chemical, or electrochemical methods.

Thermochemical and biochemical conversion technologies are particularly well-suited to a wide range of waste biomass, whereas other methods have limitations related to the feedstock. Thermochemical conversion processes, such as combustion, pyrolysis, and gasification, occur at high temperatures and take place in environments with varying oxygen concentrations. They are better suited for relatively dry woody and herbaceous biomass.

On the other hand, biochemical conversion involves the use of microorganisms to transform biomass into biofuels. Technologies like anaerobic digestion and alcohol fermentation are part of biochemical processes and can handle biomass with high moisture content. These wet processing techniques are more cost-effective and efficient than thermochemical conversion processes when dealing with high moisture materials (McKendry 2002).

9.2 Fermentation

Conversion of sugar containing biomass to alcohol in anaerobic conditions (sometimes in aerobic conditions) is known as Fermentation, e.g. production of ethanol by the biological process of microorganisms (usually yeast, bacteria and fungi which is less frequently used). The type of fermentation processes can be batch, fed-batch or continuous. This process is generally appropriate for crops and plants with excessive sugar or starch content (e.g. grapes, corn, potatoes, etc.) (Fulekar 2010).

9.3 Anaerobic Digestion

A biochemical process involving production of biogas from organic matter in the presence of microorganisms and absence of oxygen is known as Anaerobic digestion (AD). Biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2). Usage of consumer's food waste and wastewaters from food industry can also produce Biogas. Anaerobic digestion occurs in a bioreactor, which can be classified as a wet or a dry reactor (European Biomass Industry Association EUBIA 2012).

9.4 Pyrolysis

When an organic matter is heated at high temperature in the absence of oxygen that process is known as Pyrolysis, which produces gases, oils and char that are further utilized for various purposes. Pyrolysis increases the yield of such products (Basu 2010).

9.5 Gasification

This process conventionally comprises of drying of biomass, pyrolysis, reduction steps and oxidation which in turn converts biomass into product gas or syngas which is a gas mixture. The raw materials used are agricultural wastes and crop residues. It generally depends on several factors like feed stock's particle size range, content of moisture, mode of gas–solid contact, pressure, rate of heat, temperature and time of.

9.6 Combustion

The most common oldest method to convert biomass to energy is Combustion where oxygen reacts with carbon in the fuel and produces CO_2, H_2O and heat. Ash produced from the process is used as fertilizer (Pap et al. 2014).

10 Standards and Regulations

There are various policies aiming at food waste challenges which cover approaches functioning as, but not restricted to, scaling down of food waste at source, restraining of overproduction, effective divisions of food supplies, and accurate portion sizing. These policies are implemented via national plans as well as market-based instruments, trading schemes, voluntary participation, and public-level information and awareness campaigns, and are generally focused at dynamic consumer behaviour, and redistribution of food for human utilization. Various European countries have managed to reduce food waste by well-mannered means using method of enforcing stringent policies, escalating public awareness and involvement, and using contemporary technological solutions accessible now-a-days. For instance, countries like Denmark, France, Norway and Sweden have instructed all redundant food from restaurants, hotels and departmental stores should be redistributed for human consumption rather than discarding it of as trash. Few countries have also unfolded the mobile applications which notifies customers of food products that are closer to their expiration dates or which can be procured at a lesser price. These practices have progressively come ahead in selected (developed) Asian countries as well.

11 Food Waste Management Legislation in Asian Countries

Different countries have acquired various novel strategies to aim at the problem of management of food waste. These strategies target the fostering of the interventions across distinct phases by laying down policies to avoid wastage of food, encourage segregation of food waste and further proper disposal of the same (Thakur et al. 2020; Table 2). Following are the policies followed by the Asian countries:

12 Future Scope

Recent advancements in utilizing potential microbial strains in food waste and enhancing the indigenous microbial population have shown promising results. Understanding the process of contaminant destruction, whether from native or introduced fungal mycelium, is crucial for further development. Efforts are focused on strategically refining the entire process to establish a comprehensive and sustainable system. Implementing this technology on a large scale will require further streamlining of methodologies. By harnessing microorganisms for remediation, commercial enterprises can offer cost-effective and safe products to their customers. Exploring the underexploited potential of bacterial cultures and fungus mycelium can significantly enhance sustainable food waste management.

Food processing wastes are being produced at an alarming rate, necessitating effective waste management. Biofuel production from these wastes proves to be a feasible option, reducing reliance on conventional fuels and mitigating greenhouse gas emissions. Anaerobic digestion, alcoholic fermentation, and thermochemical conversion methods are promising approaches for biofuel production from food processing wastes. To promote efficient utilization of food processing wastes, there is a need to conduct further research and disseminate knowledge to the general public. Collaborative efforts between governments and industries can propel research from laboratories to commercial scale.

The emergence of the Digital Knowledge Ecosystem offers a powerful tool to achieve sustainable food waste management. Food waste occurs at various stages of the supply chain and contributes to global issues of hunger and malnutrition. Digital technologies have the potential to reshape relationships between customers, workers, and employers, and they are increasingly being used to combat food waste. Digital applications have proven to be effective in reducing food waste and redistributing surplus food to those in need. These technologies play a crucial role in addressing the social, environmental, and economic challenges caused by food wastage. This chapter highlights recent technological advancements that are revolutionizing sustainable food waste management processes (Thakur and Modi 2020).

13 Conclusion

The food industry generates a significant amount of food waste, much of which is discarded despite still being usable or fit for consumption. In poorer countries, food wastage is more commonly observed at the early and middle stages of the Food Supply Chain (FSC), with relatively less waste occurring at the consumer

Table 2 Food waste management legislation in Asian countries

Sr. No	Country	Food wwaste management legislation
	Food waste legislation in Japan	In 2001, Japan's Food Waste Recycling Law got sanctioned, and was revised in the year 2007 and a second time in 2015, to reuse the food waste produced by food corresponding industries and organizations i.e., food producers, dealers, distributors, eateries. In this law, each division of business and industry were provided with recycling targets as 95, 70, 55 and 50% for food manufacturers, wholesalers, retailers, and restaurants respectively by the month of March 2020. Moreover, massive food waste generators who produce food waste more than 100 tonnes annually are required to present the food waste- associated data each year, including the details of the total amount of food waste produced and the amount of waste recycled. The Japanese government has additionally initiated a certification system for businesses, known as 'Recycling loops', where the certified businesses are discharged from law on loading/unloading of food waste
	Food waste legislation in Hong Kong	Hong Kong has adopted strategies like segregation of food waste, making community aware about the segregated food waste and its treatment before final disposal to reduce the total wastage of food from 3600 t/d in 2014–2160 t/d in 2022. Therefore, Hong Kong has introduced drives like 'Food Wise Hong Kong Campaign' which promulgate prudent practices in the commercial and industrial sectors in association with government departments, schools and NGOs to steer clear of and reduce wastage of food in the beginning. To encourage schools for reducing the wastage of food and usage of disposable lunch boxes, 'Green Lunch Charter' has been launched which is being co-ordinated between the public, academic institutions and Education Bureau of Hong Kong
	Food waste legislation in Malaysia and Singapore	The Act of Solid Waste and Public Cleansing Management was imposed in Malaysia in the year 2011, where illegal dumping of wastes is penalized and therefore it is mandatory for an individual to separate the solid waste in the beginning. Moreover, another policy have been implemented I.e., the 2 + 1 collection where the number '2' states the gathering of remaining waste like food waste two times in a week, and '1' means the collection of reusable and voluminous waste once in a week; whereas in Singapore, the National Environmental Agency (NEA) and Agri-Food and Veterinary Authority (AVA) are functioning to turn down the quantity of food waste by organizing various educational programs to restrict the itch of buying of unnecessary food products whereas also imparting knowledge on food planning, storage, with the instructions or recipes to utilize the unused or leftover food to prepare new foodstuffs

(continued)

Table 2 (continued)

Sr. No	Country	Food wwaste management legislation
	Food waste legislation in India	In 2000, the Municipal Solid Wastes (Management and Handling) Rule, was implemented in India and eventually was altered in the year 2013 and afterwards in 2015, which highlights the assortment of food waste into three different categories namely., bio-degradable, non-biodegradable and hazardous which are collected in colour coded bags before handing it over to collectors. Moreover, monetary help is given to the companies which sets up the collection camps at farms and food retail channels. Additionally, to link the agricultural and food industries together and to maximize value and minimize the food waste, Mega Food Parks were installed
	Food Waste legislation in Thailand	Various policies have been introduced by Thailand for food waste management. Such as in the year 2015, the government of Thailand united with FAO to uprear the sensitivity towards food loss and food waste by organizing a national campaign recognized as "The National Save Food". The food waste reduction targets have also been established as 5%, 30% and 50% by 2016, 2021 and 2026 respectively by using the National 3Rs Strategy and the 3Rs Act
	Food waste legislation in China	China generates approximately 80–100 million tonnes of food waste annually, and this quantity has been increasing over time. As a response to this concerning trend, China has implemented national campaigns, including the 'Plan of Action for Implementation of Resource Saving and Loss Reduction in the Grain Production Sector' and the '13th Five-Year Plan (2016–2020)'. These campaigns include specific measures and guidelines aimed at reducing grain loss and enhancing the efficiency of foodstuff trading, retailing, wholesale, and storage, encompassing crops and meat Moreover, China has enacted policies targeting food waste management, such as the 'Food Security Law' introduced in 2009. This law regulates the safety aspects related to food waste management. Additionally, the 'Grain Law' includes provisions to promote grain conservation and address the issue of food wastage. These policy measures are part of the country's concerted efforts to tackle the pressing challenges of food waste and enhance food security
	Food waste legislation in South Korea	In the field of management of food wastage and recycling efforts, South Korea has shown exceptional progress. The country has improved its performance from 2% recycling of food waste in 1995 to 95% at present day. This is achieved by regulating various policies implied by the Government on general public like prohibiting of land filling from wastage of food since 2005 as well as government also introduced compulsory use of biodegradable bags for recyclable food waste in the year 2013. The biogas and bio-oil are produced by using the moisture content of food waste present in these bags however, the dry matter is utilized to generate compost (18)

level. As environmental concerns grow, strict regulations demand a reduction in the environmental impact of the food industry.

This chapter focuses on technologies aimed at preventing and minimizing food waste, as well as methods for recovering valuable by-products, nutrients, and energy from food industry waste. Various techniques such as hydrolysis, distillation, extraction, adsorption, ion exchange, evaporation, crystallization, drying, membrane separation, and enzymatic treatment are widely used across different sectors of the food industry to recover valuable resources from waste. Moreover, food industry waste holds promise as a sustainable option for biofuel production. As such, research efforts should be intensified to enhance the efficiency of food waste recovery technologies. Emphasizing these methods not only contributes to waste reduction but also aligns with the growing global focus on sustainability and resource efficiency within the food industry. By adopting and advancing these recovery technologies, we can move closer to a more sustainable and environmentally responsible food system.

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Sustainable Techniques for Food Safety and Food Diversity

Seaweed- A Sustainable Food Source in the Food Industry

Usha Sharma, Sadhana Jadaun, Ringshangphi Khapudaang, and Saleem Siddiqui

Abstract The global demand for seaweed consumption gaining immense popularity due to the presence of valuable components such as protein, essential minerals, bioactive compounds, antioxidants, vitamins, fatty acids, and polysaccharides. These components possess a wide range of applications in the food and nutraceutical industries. Furthermore, the presence of bioactive compounds employed a key role in preventing cancer, obesity, thyroid, malnutrition, metabolic disorders, hyperglycemia, and heart disease. Seaweed unique polysaccharides such as ulvan, fucoidan, agar, alginate, agarose, and carrageenan, etc., have become a widely used functional ingredient in the food sector due to its impressive functionalities in improving shelf-life and textural properties of food products. These polysaccharides act as antioxidant, gelling, thickening, emulsifying, and solidifying agents. The seaweed could be a functional ingredient in developing '*noble food'* products, like *Palmaria palmate* (4% protein hydrolysate) used to enrich bread in order to enhance amino acid profile. *Gracilaria domingensis* has been used as a texture modifier in fermented milk. Alginate oligosaccharides obtained from *Laminaria* hyperborean act as preservatives in yogurt, while *Ascophyllum nodosum* and *Fucus vesiculosus* have been used as functional ingredients in milk to improve milk quality and in extending the shelf life. Gluten-free fresh pasta has been developed with *Laminaria ochroleuca*. The classification of seaweed, their nutritional benefits, utilization for developing value-added food products, challenges and scope of integration into food industry have been discussed in this chapter.

Keywords Anti-inflammatory · Food products · Gluten-free · Nutritional quality · Seaweed · Shelf-life

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1 Introduction

In the evolution of nutritional development, the demand for sustainable products for human consumption promotes the economy, social equity, long-term stability, health, and well-being. These days the critical question is, how to meet the growing need for healthy food for a growing population in the coming decades without exhausting renewable resources or surpassing planetary limits, beyond which the future of humanity may be jeopardized (Lindgren et al. 2018). According to the United Nations World Population Division (2019), the global population has increased by two billion people in the past 25 years and is estimated to reach 8.5 billion by 2030 and 9.8 billion by 2050 (Pawlak and Kołodziejczak 2020).

Therefore, sustainable approaches have been accompanied to attain the requirements of ***"good food and good health"***. The "sustainable development goals (SDGs)" are intended to not only overcome poverty and hunger by 2030 but also to guarantee that everyone has constant physical, social, and economic access to enough, safe, and nourishing food that meets their dietary needs and food preferences for an active and healthy life (UN 2015). This focuses on every area of malnutrition and the food system. According to the Food and Agricultural Organisation (FAO 2021) and the United Nations (UN 2021), around 828 million people globally suffer from hunger, while approximately 2 billion suffer from micronutrient deficiencies. With the growing popularity of plant-based foods, seaweed-containing products could inspire healthy and sustainable eating habits (Vasvada 2019). Seaweeds are important primary producers in oceanic aquatic food webs. However, flavor, taste, and the appearance of food are essential determinants in affecting food preferences, choices, and eating behaviors (Hartvig et al. 2014). In this regard, seaweeds are particularly well-known for their umami flavor, which can also boost the strength of other tastes and flavors (Zhang et al. 2019). Moreover, they are rich in vitamins (especially A, B, C, and E), proteins, essential fatty acids, minerals, important trace elements, and carbohydrates such as agar, carrageenan, and alginate, which make them nutritionally, functionally, and biologically valuable (Kim and Wijesekara 2010). In nutshell, seaweed has a large potential of being the raw material in food, pharmaceutical, and cosmetics industries.

The seaweeds are also a source of biologically active phytochemicals including pigments like chlorophyll and carotenoids such as β-carotenes and xanthophylls including (violaxanthin, fucoxanthin antheraxanthin, neoxanthin, zeaxanthin, lutein) (Aryee et al. 2018). Furthermore, these pigments are bioactive and possess antioxidant, immune-modulatory, antidiabetic, anti-inflammatory, antiangiogenic, etc. activity which imparts desired biological features with potential advantages in a variety of disorders such as hyperlipidemia, thrombosis, tumors, and obesity (Kim et al. 2011) (Fig. 1). In addition, they possess sensorial properties (as food colorants) in different food products, including feed products, functional food, and ingredients. Due to their extensive properties, whole seaweed and extracts products are commercially available in the supplement market under the category of value-added food products which claim good health (Thakur and Modi 2022).

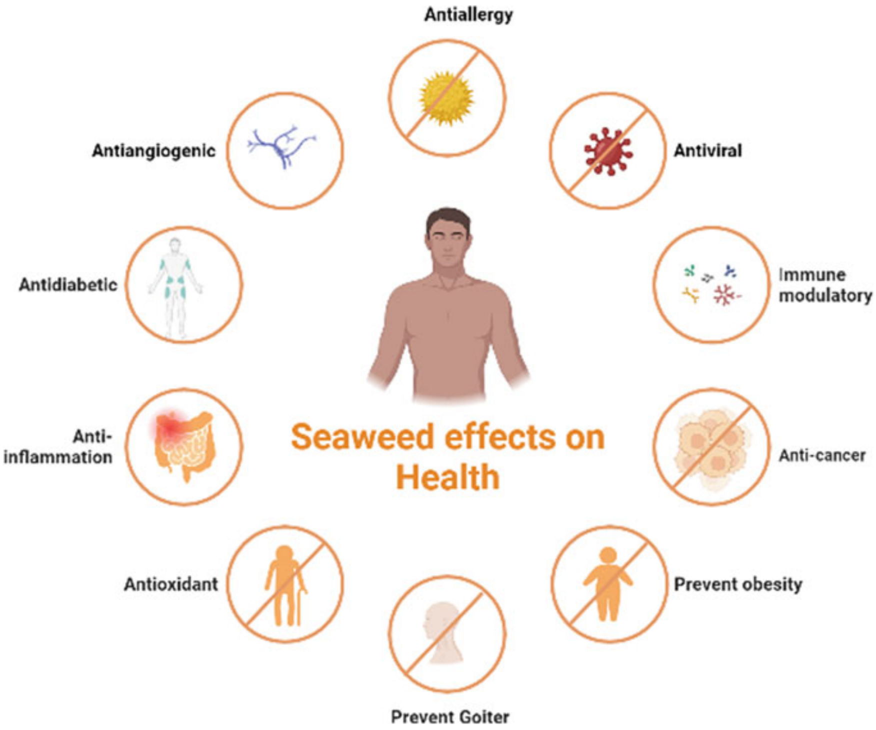

Fig. 1 Nutritional and therapeutic effects of seaweed

The economic worth of seaweeds has significantly risen and is expected to result in a billion-dollar global market (Farghali et al. 2023). The market for seaweed was valued at U.S. $15.01 billion in 2021; and by 2028, it is projected to grow to U.S.$ 24.92 billion. Seaweeds in food applications accounted for a significant market share from 2017 to 2021, and since then their usage for human consumption has increased globally (Farghali et al. 2023; Pandey et al. 2020). Moreover, there are significant safety concerns regarding potential adverse outcomes connected with seaweed eating, because of high quantities of iodine and heavy metals (including arsenic species) in various types of seaweeds (Wendin and Undeland 2020). This chapter outlines the importance of seaweeds followed by the nutritional properties of seaweed, and the classification of seaweeds under the category of brown seaweed, red seaweed, and green seaweed. Seaweed's health benefits and associated challenges in the food industry.

2 Classification of Seaweeds

In many Asian countries, seaweed has been utilized as a food source from the beginning of time, while in other parts of the world, it is widely employed as a source of biochemicals for use in pharmaceutical, cosmetic, and food products. According to Ramu Ganesan et al. (2020), seaweed is widely produced in India around the coasts of Gujarat, Tamil Nadu, Lakshadweep, and the Andaman and Nicobar Islands. A variety of aquatic plants are classified mostly on the basis of morphological characteristics, chemical substance organization, and photosynthetic pigment. Traditionally, algae are classified based on color: red algae (phylum: Rhodophyta, around 7000 species), brown algae (phylum: Ochrophyta, around 2030 species), and green algae (classes: Phaeophyceae and Chlorophyte, around 600 species). The majority of these algae are located in bodies of seawater, which is why they are known as seaweed (El-Beltagi et al. 2022; Kumar et al. 2021).

2.1 Brown Algae (Pheophyte)

Brown seaweed is the second-largest widespread type of seaweed that is utilized as an edible source in Asia, particularly in China and Japan. Members of this category which are found majorly in coastal areas of China are *Laminaria* spp, *Sargassum pallidum*, *Undaria pinnatifida,* and *Ecklonia cava subsp. kurome* (Xie et al. 2021). They have an immense range of shapes and sizes from undifferentiated to more complex ones with a well-distinct thallus with cauloid, rhizoid, and phylloid. They are rich in high protein content (5–15%) and amino acids such as glutamic acid and aspartic acid. They also possess anti-allergic and anti-inflammatory properties, making them suitable for pharmaceuticals (Barbosa et al. 2019). Pigments such as chlorophyll a and c, b-carotene, xanthophylls specially fucoxanthin responsible for the brown color of these algae (El-Beltagi et al. 2022). Brown algae produce alginates and mucilage in an abundant amounts which makes them important for keeping algal hydration. They are rich in carbon and iodine hydrates, so they have also been used extensively in the past to treat endemic goiter. Moreover, Brown algae possess a wide range of nutritional, diuretic, and therapeutic properties, due to the presence of iodine, alginates, and mucilaginous substance. These substances make them useful for the formulation of food, herbal and pharmaceutical products that support low-calorie diets by increasing satiety and lowering fat and sugar absorption. In the food industry, alginic acid is used as a thickening and stabilizer for making puddings, glazes, cream cheeses, and meringues. It is especially useful when making ice cream because it prevents the formation of ice crystals even at low temperatures. The ability of alginic acid's salts to chelate, or remove from the body through feces, toxins such as lead, and heavy metals is another benefit of the compound. Moreover, they also exhibit high solubility, emulsifying, and foaming properties which could be used in the food industry to formulate the food products such as bread, cakes, soups, sausages, and salad dressing (Garcia-Vaquero et al. 2016).

2.2 Red Algae (Rhodophyta)

The red color of these algae is due to the presence of water-soluble pigments known as phycoerythrins and phycocyanins. *Chondrus crispus*, *Gigartina mamitiosa*, *Kappaphycus alvarezii, Eucheuma denticulatum*, *Caloglossa* spp., *Codium* spp., *Dermonema* spp. and *Hypnea* spp., *Gelidium cartilagineum,* are the most common red seaweed. Red seaweeds are highly rich in amino acid but lack methionine, cysteine, and lysine (Wong and Cheung 2000), and other major chemical composition such as protein content (10–40%) (Barral-MartÃnez et al. 2020), cellulose, polysaccharides such as agarans and carrageenans which are known as galactans, lipid content (1–5%) specially $\omega - 3$ and $\omega - 6$ polyunsaturated fatty acids, including -linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), as well as proteins such phycobiliproteins, mycolectins (Kumar et al. 2021; Ferrara et al. 2020). Pina et al. (2014) and Pooja et al. (2020) observed that phycobiliproteins have anti-inflammatory, hepatoprotective, anti-anemic, and antioxidant activities. The pigments isolated from this seaweed are widely used as food colorants in the food industry. Polysaccharides such as alginates, agar, and carrageenan exhibit excellent gelling properties, which are widely used in the food industry to improve the appearance of cheese and yogurts, texture of puddings and jams, preserve canned meat and fish, and help in clarifying fruit juice and wines.

2.3 Green Algae (Chlorophyta)

Green seaweed or chlorophyte are mostly aquatic species but some of them are terrestrial, these green seaweeds are commonly found in fresh and marine habitats. Chlorophyll-a and chlorophyll-b are responsible for the green color of these seaweeds (El-Beltagi et al. 2022). The most common genera of green seaweed are *Ulva*, *Cladophora*, *Enteromorpha*, and *Chaetomorpha.* They can reproduce quickly, grow swiftly in shallow waterways and tide pools, and do not require land for cultivation like terrestrial plants do (Puthiya Veettil et al. 2023). These seaweeds contain valuable components such as protein 11%, ash 53%, and carbohydrates 36% (Lakshmi et al. 2020). It also contains a sulfate polysaccharide called Ulvan which has been used as a stabilizer, emulsifier, and thickener in many food products (Kumar et al. 2021). Ansari and Ghanem (2017) reported that the protein content varies over time, where in July and October the protein content was higher than in the other months. Moreover, due to the presence of different antioxidant compounds such as polyphenols, carotenoids, terpenes, and chlorophylls showed an immense effect against several pathogenic bacterial strains such as *Serralia marcescens, Micrococcus luteus, Bacillus subtilis, Bacillus cereus, Staphylococcus aureus, Klebsiella pnetumoniae,* with minimum inhibitory concentration values between 400 and 350 μg/ml. Olasehinde et al. (2019) observed that seaweed's potential to treat Alzheimer's disease, insomnia, headache, diabetes, carcinogenesis aging, and osteoporosis due to the presence of bioactive compounds. Arumugam et al. (2018), working on wastewater treatment with the technology of metal biosorption, reported that seaweed such as *Ulva lactuca* has the ability to adsorb heavy metals such as Fe, Pb, Cd, Ni, and Zn with the help of a natural anion exchange mechanism.

3 Nutritional Value and Health Benefits

Seaweed possesses a high nutritional value and is considered a superfood as they are highly rich in vitamins (A, B_1, B_2, B_9, B_{12}, C, E, D, and K), dietary fiber, vital minerals (iron, iodine, calcium, zinc, phosphorous, manganese, magnesium, selenium, copper, and fluoride), protein (combination of different amino acids), lipids (polyunsaturated fatty acids (PUFAs), waxes, acylglycerols, saturated fatty acids) and polyphenols which exhibit an anti-inflammatory, antioxidant, anticancer, antiviral, antidiabetic, anticoagulant, antitumor, and antimicrobial activities (El-Beltagi et al. 2022; Lomartire et al. 2021). Furthermore, seaweeds are regarded to comprise unique polysaccharides, which can be particular to a given algal group. According to Øverland et al. (2019), brown seaweed contain 380–650 g/kg d.m, green seaweeds150–650 g/kg d.m. and red seaweed 360–660 g/kg d.m. of polysaccharides. Brown seaweeds contain polysaccharides such as fucoidan, alginate, and laminarin, red seaweeds contain agar and carrageenan, and green seaweeds contain ulvan (Michalak et al. 2022). Sulfated polysaccharides such as ulvan, fucoidan, and carrageenan possess anticoagulant, antiviral, anti-inflammatory, anti-hyperlipidemic, immunomodulatory, and anticancer properties (Fig. 2). According to Senthilkumar et al. (2013), seaweed also inhibit cancer cell proliferation by inducing apoptosis and cell cycle arrest and inhibition of angiogenesis and metastasis. Meenakshi et al. (2014) showed that rats' body weight (BW) and serum protein levels increased and the hepatic indicators were downregulated when fucoidan was added to their diet, acting as a hepatoprotective agent. According to a different study by Tae Young et al. (2016), fucoidan nanocomposites had been employed to enhance bone healing in rabbits. According to Han et al. (2015), fucoidan is an effective therapeutic agent for treating ischemic illnesses in mice and a possible anticancer agent for treating colon cancer.

The mineral content in seaweed is up to 36% of the dry mass. Therefore, eating seaweed can help in consuming the recommended daily intake (RDA) of minerals, including iodine. But there are some consequences of consumption of seaweed in excessive amounts such as thyroid dysfunction, heavy metal contamination, Allergic reactions, and blood-thinning (Murai et al. 2021). Therefore, it is necessary to consume seaweed in proper amounts to take benefits. Nowadays, sodium chloride (table salt) is mostly used to preserve food and improve its flavour. However, it is

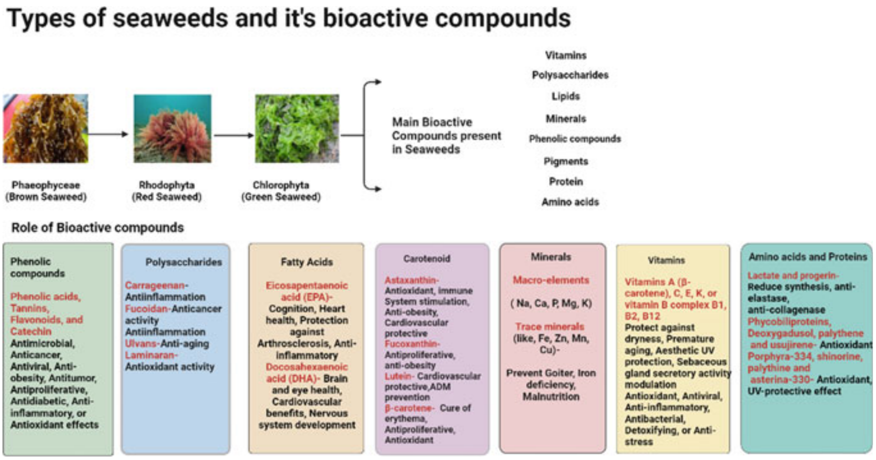

Fig. 2 A summary of seaweed bioactive compounds and their role in the field of health and nutrition. *Source* El-Beltagi et al. (2022)

known that consuming too much sodium contributes to hypertension and cardiovascular disease, among other health problems (Cherry et al. 2019). Seaweed salt can aid in reducing sodium consumption and its related diseases (Cappuccio 2013).

Researchers have investigated the bioactive molecules present in Rodophyta, Pheophyata, and Chlorophyata, the three distinct groups of seaweeds. The findings are summarized in Table 1, which offers valuable perception into the diverse array of bioactive compounds found in these seaweeds such as polysaccharides (Fucoidan, Ulvan, Carrageenan), other polysaccharides (alginate, laminarin, agar), polyphenols, pigment (Fucoxanthin), protein and fatty acids. Additionally, these molecules possess a variety of biological activities as antiradical, antioxidant, anti-inflammation, antiinflammatory, antihypertensive, antiobesity, osteogenic, cardioprotective agents, etc., and numerous applications in the food industry (Lomartire et al. 2021; Torres et al. 2019).

4 Seaweed Values Added Food Products

There is tremendous potential for supplementing food items with edible seaweeds to give consumers additional health benefits. However, there have only been a few researches on improving the nutritional characteristics of food and developing functional foods by seaweed supplementation. Seaweeds have been added to meat products, fish products, bakery products, cereal-based products, and dairy products. Utilization of seaweed in the food industry not only for improving functional properties but also for their ability to protect the products during storage.

Table 1 Types of seaweeds, bioactive compounds, health benefits and its application

Types of seaweed	Examples of algae	Types of bioactive compounds extracted	Types of compound	Application in the food industry	Health benefits	References
Phaeophyta (Brown algae)	Laminaria cloustonii	Laminaran, Fucoxanthin	Polysaccharides of glucose, Pigment	Stabilizer and thickening agent (Desserts, Drink, Ice cream, Jelly, Syrups, Flavor sauces, Bakery products, Milk shakes, and Fruit juice)	Prevent goiter, Heal wounds, Anti-inflammatory, Cure edema, Antioxidant, Anticancer, Anti-inflammatory, Antibacterial, Anticoagulant, Antioxidant, Antidiabetic, Anti-HIV, Antiallergic, Antiapoptosis activities, and Immunomodulatory effects	Lomartire et al. (2021), Saeed et al. (2021), Kumar et al. (2021), Torres et al. (2019), El-Beltagi et al. (2022)
	Fucus evanescens	Fucoidan	Sulfated polysaccharide			
	Sargassum fulvellum, Eisenia arborea	Phlorotannins	Polyphenolic compound			
	Ascophyllum nodosum	Algins,	Polysaccharide			
	Macrocystis spp	Algins	Polysaccharide			
Rhodophyta (Red algae)	Kappaphycus genera	k-Carrageenans	Sulfated polysaccharides	Water binding capacity, Thickening agent (Dairy products and bakery), As food additive in Jellies, Fruit candies, and Canned food	Prevent Diarrhoea, Dysentery, Gastric ulcers, Cold	Lomartire et al. (2021), Kumar et al. (2021), Torres et al. (2019), El-Beltagi et al. (2022)
	Gelidium and Gracilaria	Agar	Sulfated polysaccharides			
	Gigartina or Chondrus spp	Carreageenan	Sulfated polysaccharides			

(continued)

Table 1 (continued)

Types of seaweed	Examples of algae	Types of bioactive compounds extracted	Types of compound	Application in the food industry	Health benefits	References
Chlorophyta (Green algae)	Ulva lactuca, U.reticulta, U. rigida, U. fasciata	Ulvan, fucoxanthin	Sulfated polysaccharides pigment	The applications in food, Cosmetics, Therapeutics, Biofuel and packaging material and Edible films	Astringent, Antigenotoxic, Chemotherapeutic agent Mitomycine-C, Antioxidant, Anti-inflammatory, Anticancer, Antiobesity, and Antidiabetic activity	Lomartire et al. (2021), Kumar et al. (2021), Torres et al. (2019), El-Beltagi et al. (2022)
	Caulerpa racemose	Flavonoids	Phenolic compounds	Act as preservative	Antioxidant, Scavenging, Anti-proliferative activities of cancer line cells	

4.1 Seaweed-Based Meat Products

Among the different species of seaweed, brown seaweed such as *Focus vesiculosus*, is commonly used in fish and oils. Diaz-Rubio et al. (2011) studies have shown that *F. vesiculosus* positively impacts lipid oxidation in minced horse maclerel. Additionally, this macroalgae can enhance the water-holding capacity of Granola bars when employed at levels of 1–2%, resulting in a reduction in drip losses after thawing. *Sargassum wightii*, another brown seaweed, has been proposed as a useful component in ready-to-eat dry foods like tuna jerky in the proportion of 0, 3, and 5% and observed fiber, macrominerals, and trace elements in the final product, which also enhanced its antioxidant and microbiological quality. However, employing increasing amounts of *Sargassum wightii* (3–5%) led to brownish color, sponginess, and grassy flavour, even though customer approval remained identical to trials without seaweed. Jannat-Alipour et al. (2019), developed restructured fish surimi-based products by adding *Ulva intestinalis* and sulphated polysaccharide (SP) at concentrations of 0.27 and 0.05%. This addition resulted in noticeable alterations in cooking loss and textural properties.

4.2 Seaweed-Based Bakery Products

The bread industry is being pushed to re-formulate its products. While maintaining the product's typical sensory attributes, this reformulation strives to satisfy consumer's nutritional needs. To improve their nutritional profile, many firms have already begun to enrich their products with nutrients like protein or folic acid. In this situation, adding seaweeds to bakery products may boost their nutritional content as well as their appearance by serving as carriers of advantageous bioactive elements. The red seaweed *Palmaria palmate* (4% protein hydrolysate), boasts protein values ranging from 9 to 25% and lysine levels of 5.9 g/100 g of total amino acids, and there are no significant changes in textural and sensory scores (Peñalver et al. 2020; Fitzgerald et al. 2014).

Similarly, the green seaweed *Caulerpa racemose* has been added to semi-sweet biscuits in varying amounts (1.0, 5.0, and 10%) to replace refined flour, making them a healthier alternative to traditional cookies due to their lower fat and sugar content. By boosting the biscuit's fiber (0.30–1.83%), protein (7.69–9.01%), and phenolic content as well as their antioxidant capabilities and ability to absorb both water and oil, the addition of seaweed increased their nutritional value. The sensory evaluation of the biscuits, however, dropped with increased *Caulerpa racemosa* administration. When applied to breadsticks, *Himanthalia elongata* seaweed at concentrations between 5 and 15% produced useful products with higher dietary fiber and phytochemical content (Kumar et al. 2018). Similarly, Jenifer and Kanjana (2019) investigated the impact of *Ulva lactuca* (30%) fortified biscuits on the consumption of malnourished children and notice a significant improvement in the children's anthropometric profile. Oh et al. (2020) enriched cookies by adding freeze-dried powder derived from *Codium fragile* (Chlorophyta), *Sargassum fusiforme*, *Ulva linza,* and *Sargassum fulvellum* at a concentration of 5% to enhance the dietary fiber content of cookies. Turuk and Banerjee (2023) fortified cookies, cake, and bread by incorporating 2 g of *Ulva lactuca* and *Gracilaria corticata.* The result showed that the seaweed-enriched products had better nutritional profiles and longer shelf life as compared to conventional products.

4.3 Seaweed-Based Dairy Products

The addition of seaweeds to dairy products including cheese, yoghurt, cottage cheese, cream, and milk desserts has a great deal of potential to increase their nutritional content and shelf life. Several studies have looked into adding seaweeds and their extracts to milk. O'Sullivan et al. (2016) noticed that both shelf life and quality of milk had improved by adding *Ascophyllum nodosum* and *Fucus vesiculosus* seaweed extracts. *Gracilaria domingensis* has successfully been used as a textural modifier in fermented milk (Prabhasankar et al. 2009). On the other hand, *Laminaria*, a type of brown algae, was added to yoghurt, milk sweets, and smoked cheese. Alginate oligosaccharides from *Laminaria* hyperborean were added as an additive to yoghurt at a concentration of 2% (w/v). These oligosaccharides were found to have antibacterial qualities that effectively inhibited several yeasts (Okhotnikov et al. 2020). However, similar to many natural substances, a somewhat high concentration was needed to provide this preservation effect, which might have an impact on the yogurt's flavour and consistency. Similarly, Del Olmo et al. (2019) observed a substantial enhancement in the physicochemical properties of hard cheese when added to seaweeds i.e. *Laminaria ochroleuca*, *Ulva lactuca, Porphyra umbilicalis, Himanathalia elongate* and *Undaria pinnatifida* species and observed the changes in nutritional properties is due to the types of species supplemented. Zhang et al. (2018) found a notable improvement in mice intestinal microbiota due to the ingestion of seaweed polysaccharides supplementation such as *Porphyra haitanensis* and *Ulva prolifera.* Additionally, a notable improvement was observed in the lipolysis of hard cheese when supplemented with *Ulva lactuca*, showing a six-fold increase in free fatty acids compared to the control. Moreover, the cheese enriched with seaweeds exhibited up to 40% increase in flavoring compounds than the control and also indicate that the addition of *Ulva lactuca* seaweed enhanced the overall flavor profile of the cheese.

4.4 Seaweed-Based Extruded or Gluten-Free Products

Undaria pinnatifida (Phaeophyceae), often known as Wakame, has been added to pasta in order to enhance its nutritional quality (Peñalver et al. 2020; Prabhasankar et al. 2009). Fradinho et al. (2019) enriched gluten-free pasta with *Laminaria ochroleuca*, and found that the addition of seaweed to the gluten-free pasta resulted in similar mechanical and textural characteristics as the control pasta. Additionally, the seaweed-based pasta had improved nutritional properties, with increased mineral and fiber content.

4.5 Seaweed-Based Confectionery Products

Jayasinghe et al. (2016), infused Jelly with seaweed of *Gracilaria verricosa*, *Ulva lactuca*, and *Sargussum wightti* and found over 30 days at room temperature it retained its color, and experienced only 30% loss, comparable to artificial colors. The inclusion of seaweed colors not only enhanced stability but also contributed to higher nutritional content in the final products. Similarly, Mamat et al. (2018), studied the effect of adding *Kappaphycus alvarezii* (2–10%) in muffins and observed an effect such as the increase in hardness from 484.84 control to 1569.38 N 10% seaweed, while a decrease in springiness 0.75–0.55 cm, height 53.33, to 48.33 mm and specific volume 2.15 to o 1.80 cm^3/g of muffins these all depend upon addition of seaweed (%). Huang and Yang (2019) utilized *Eucheuma* sp. Powder with a concentration of 5–20%, which contains 13.1% ash and 69.3% fiber, and found the incorporation of seaweed increased three times of dietary fbre content and 32.6% of mineral profile in sponge cake as compared to the control cake.

5 Challenges and Opportunities for the Integration of Seaweed into the Food Industry

Hunger and food insecurity is the major challenge in several countries due to the changes in ecosystems. Therefore, the demand for seaweed-fortified food supports significant promotion of the consumption of healthy food. There are many challenges of using seaweed in the food industry including consumers' scant grasp of seaweed, reluctance or hesitation in using seaweed as a culinary ingredient because it is still largely new to many people. In order to overcome this challenge, it will be crucial to inform consumers about seaweed's health and environmental benefits. Another challenge is the diversity of seaweed's composition and quality presents (approx 70 species of seaweed have been approved around the world by national food safety authorities) (Bizzaro et al. 2022). As stated by Barkia et al. (2019), factors such as taste, texture, risk of heavy metals contamination, and relatively high prices for top-quality algal products are depend on the type of species, the conditions of the production, and the method used to harvest. Maintaining consistent quality and standardizing production processes will be crucial to meeting customer needs and establishing seaweed as a reliable ingredient. Creating food products with seaweed in them can thus be challenging. Seaweed may have unique flavours, textures, and capabilities that call for careful product development and formulation in order to deliver a proper taste and texture profile. Finding the ideal mix between seaweed's health advantages and consumer acceptance will be essential.

Despite these obstacles, incorporating seaweed into the food industry has many advantages. A healthy and sustainable substitute for conventional components is seaweed. Essential minerals, vitamins, antioxidants, and bioactive compounds are abundant in algae, and they can improve the nutritional value of food products. Seaweed also possesses useful qualities that can be used in a variety of food applications, including the ability to gel, emulsify, and create films. Additionally, seaweed supports rising consumer desire for plant-based, sustainable foods. For, this it's important to support value-addition, new or expanded production of seaweed in order to expand income growth by providing appropriate policies, infrastructure, and good investments.

6 Conclusion

In conclusion, the research conducted on seaweeds highlights their immense potential as a sustainable source for the food industry in the future due to the presence of high nutritional and therapeutic properties. The findings discussed in this chapter, along with the rising market value, address the challenges faced by the food industry in terms of sustainability and resource availability. However, it is important to acknowledge that further research is needed to address large-scale seaweed cultivation, processing, and product development challenges. Additionally, efforts should be made to promote consumer acceptance and awareness regarding seaweed-based food product's nutritional and environmental benefits. The various legislations and food laws in different countries with respect to use of the seaweed in food products also need to be taken into consideration.

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Medicinal Plants: Sustainable Scope to Nutraceuticals

Vandana Singh, Akansha, Zoobia Islam, and Bushra Shaida

Abstract Medicinal plants exhibit a broad range of potential for nutraceuticals, presenting a diverse assortment of bioactive compounds that confer notable health advantages beyond fundamental nourishment. These chemical compounds, which encompass polyphenols, flavonoids, alkaloids, terpenoids, and essential oils, demonstrate a wide range of biological activities, including antioxidant, anti-inflammatory, antimicrobial, and anticancer effects. The potential applications of nutraceuticals derived from medicinal plants exhibit promising prospects, encompassing disease prevention and management as well as the promotion of overall well-being. Additionally, the accessibility and affordability of these natural sources, coupled with their potential synergistic effects, render them appealing alternatives to traditional pharmaceuticals. However, it is imperative to address challenges pertaining to standardization, quality control, and regulatory frameworks in order to fully harness the potential of medicinal plants as valuable sources of nutraceuticals. The primary objective of this chapter is to investigate the extent of nutraceuticals obtained from medicinal plants and their importance in enhancing human welfare, while also acknowledging the obstacles and future prospects in the field of nutraceutical research.

Keywords Medicinal plants · Nutraceutical · Bioactive compounds · Phytochemicals · Health benefits · Herbal nutraceuticals

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1 Introduction

Medicinal plants, scientifically referred to as herbal medicines or botanical drugs, encompass plant organisms or specific plant components that possess bioactive compounds exhibiting therapeutic attributes. The aforementioned bioactive compounds, namely alkaloids, flavonoids, terpenoids, and phenolic compounds, possess the capacity to elicit physiological and pharmacological responses within the human organism. Medicinal plants possess the potential to be utilized either in their unaltered state or subjected to processing techniques to yield diverse formulations such as extracts, powders, tinctures, or essential oils, all of which serve medicinal objectives (Farzaneh et al. 2015). Medicinal plants have been employed for numerous centuries as a primary reservoir of traditional remedies and therapeutic methodologies. Throughout diverse cultural and societal contexts, indigenous populations have historically utilized the medicinal attributes of botanical organisms to address physical and mental afflictions, as well as to promote general health and vitality. The abundant biodiversity present on earth presents a valuable collection of plant species harbouring bioactive compounds that exhibit promising medicinal properties (Velu et al. 2018).

In the past few decades, there has been a notable increase in scientific attention towards the study of medicinal plants and their potential as nutraceuticals. This heightened emphasis arises from the escalating cognizance of the constraints and adverse reactions associated with synthetic pharmaceuticals, coupled with the expanding acknowledgment of the significance of proactive healthcare. Medicinal plants present a highly encouraging pathway for the advancement of naturally-derived, non-toxic, and environmentally-friendly therapeutic substances (Ruchi 2017). The extent of nutraceuticals derived from medicinal plants is expansive and includes a diverse array of bioactive compounds, including polyphenols, flavonoids, alkaloids, terpenoids, and essential oils (Fig. 1). These compounds have exhibited diverse biological activities, encompassing antioxidant, anti-inflammatory, antimicrobial, anticancer, and immune-modulatory effects. They have the potential to mitigate and regulate chronic ailments such as cardiovascular disorders, diabetes, neurodegenerative conditions, and cancer. Furthermore, these entities exhibit characteristics that augment cognitive performance, enhance gastrointestinal well-being, and fortify immune response (Velu et al. 2018).

Nutraceuticals from medicinal plants have numerous advantages. First and foremost, these compounds are derived from natural sources, which may render them comparatively safer and more easily tolerated than their synthetic counterparts. Moreover, the extensive presence of botanical species in various geographical areas enhances their accessibility and affordability in comparison to conventional pharmaceuticals. Moreover, the combined impacts of various bioactive compounds found in medicinal plants may offer amplified therapeutic advantages (Srivastava et al. 2015).

Numerous medicinal plants have been acknowledged for their potential as nutraceuticals. Some examples of scientifically recognized substances are turmeric (*Curcuma longa*), which contains curcumin with strong anti-inflammatory and

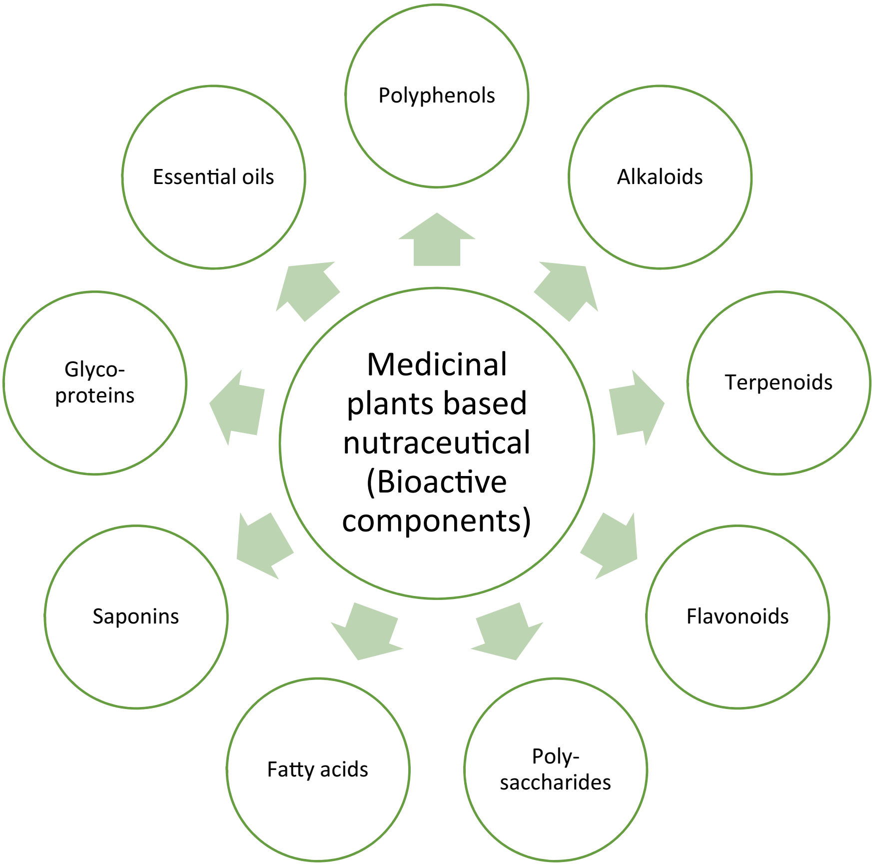

Fig. 1 Medicinal plants possesses bioactive components which may act as nutraceutical

antioxidant characteristics; garlic (*Allium sativum*), known for its ability to combat microbes and promote cardiovascular health; and green tea (*Camellia sinensis*), which is abundant in polyphenols that have been shown to have anticancer and neuroprotective properties. These plants have undergone thorough scientific investigation, and their nutraceutical constituents are currently accessible in diverse formats, including supplements, extracts, and functional foods. Ajanaku et al. (2022) Despite the enormous promise that medicinal plants have as sources of nutraceuticals, there are still a number of difficulties. The implementation of standardized extraction methodologies, rigorous quality control measures, and meticulous dose optimization are imperative in order to guarantee the uniformity and dependability of products. Furthermore, it is imperative to establish regulatory frameworks that guarantee the safety, effectiveness, and accurate labelling of nutraceutical products derived from medicinal plants.

The word Nutraceuticals refer to bioactive compounds obtained from natural origins, such as medicinal plants, which offer health advantages that extend beyond fundamental nutrition. The neologism “nutraceutical” is a portmanteau of the terms “nutrition” and “pharmaceutical,” which aptly captures their shared function in bolstering well-being and mitigating ailments. These compounds have the potential to be extracted from various food sources, such as concentrated extracts, and can also be incorporated into dietary supplements, functional foods, or beverages. The objective of this chapter is to present a comprehensive examination of medicinal plants and their nutraceutical potential. This chapter is mainly emphasised on the extensive array of bioactive compounds present in medicinal plants, elucidates their mechanisms of action, and examines their potential implications in the fields of healthcare and nutrition. Additionally, it also highlights the necessity of interdisciplinary collaborations in order to optimize the complete potential of medicinal plants for the advancement of human health and well-being (Benković 2019; Thaur and Belwal 2022).

2 Components of Medicinal Plants as Nutraceuticals

The pant components which work as Nutraceuticals can be delineated into distinct categories and few are:

2.1 Polyphenols

Polyphenols encompass a wide array of chemical compounds that are abundantly present in various fruits, vegetables, grains, and herbs. They demonstrate antioxidant and anti-inflammatory characteristics and contribute to a range of health advantages, such as promoting cardiovascular health, enhancing cognitive function, and aiding in cancer prevention. Polyphenols exert their effects through the process of free radical scavenging, which involves the removal of unstable molecules that can cause damage to cells. Additionally, they contribute to the reduction of oxidative stress, a condition characterized by an imbalance between the production of reactive oxygen species and the body’s ability to neutralize them. Furthermore, polyphenols play a role in regulating signalling pathways that are implicated in inflammation and the growth of cells (Pandey et al. 2011). Polyphenols, such as resveratrol found in grapes and berries, quercetin present in onions and apples, and catechins abundant in green tea, are notable examples.

2.2 Alkaloids

They are class of organic compounds that contain nitrogen and are commonly present in various plant species. These entities demonstrate a wide range of biological activities, encompassing antimicrobial, analgesic, and anti-inflammatory properties. Alkaloids have the capability to engage with cellular receptors and enzymes, thereby exerting an influence on processes such as neurotransmission, cell signalling, and immune responses (Yan et al. 2021). Instances of alkaloids encompass caffeine (found in coffee and tea), morphine (derived from the opium poppy), and vincristine (obtained from the Madagascar periwinkle) (Fu et al. 2002).

2.3 Carotenoids

They are organic compounds that function as pigments, contributing to the visually striking colours observed in various fruits and vegetables. They exhibit antioxidant properties and are renowned for their involvement in ocular health and immune system functionality. Carotenoids possess the ability to effectively eliminate free radicals, safeguard cells against oxidative harm, and uphold the structural soundness of the retina. Carotenoids, such as beta-carotene found in carrots and sweet potatoes, lycopene present in tomatoes, and lutein found in leafy greens and egg yolks, serve as notable examples (Wang et al. 2021).

2.4 Terpenoids

The other name for them as isoprenoids, encompass a vast array of chemical compounds that are abundantly present in various plant species. These compounds include essential oils and plant resins. These entities exhibit antimicrobial, anti-inflammatory, and anticancer characteristics. Terpenoids elicit their effects via diverse mechanisms, including the modulation of cellular signalling pathways, inhibition of enzyme activity, and interaction with cellular membranes. Terpenoids are a class of organic compounds that can be found in various natural sources. Some notable examples of terpenoids include limonene, which is commonly found in citrus fruits, menthol, which is abundant in peppermint, and curcumin, which is present in turmeric (Jahangeer et al. 2021).

2.5 Omega-3 Fatty Acids

Omega-3 fatty acids are a class of necessary polyunsaturated fatty acids that can be found in various sources such as fish, flaxseeds, chia seeds, and walnuts. These entities are renowned for their advantageous impact on cardiovascular health, cognitive function, and reduction of inflammation. The actions of omega-3 fatty acids are exerted through their influence on the function of cell membranes, gene expression, and pathways related to inflammation (Jaca et al. 2020).

3 Relationship Between Nutraceutical and Medicinal Plants

The interconnection and symbiotic nature of the relationship between nutraceuticals and medicinal plants is evident. Nutraceuticals are derived from botanical sources and harness their bioactive compounds to confer health advantages that extend beyond fundamental nutrition (Gossell-Williams et al. 2006). Here are several fundamental elements of their relationship:

- ***Source of Bioactive Compounds***: Medicinal plants are the predominant origin of bioactive compounds, which are utilized in the development of nutraceutical products. The presence of bioactive compounds, including polyphenols, flavonoids, terpenoids, alkaloids, and various others, plays a significant role in the therapeutic attributes exhibited by medicinal plants. Nutraceuticals employ various methods such as extraction, concentration, or isolation to augment the potency and bioavailability of bioactive compounds within the ultimate product.
- ***Therapeutic Potential***: Medicinal plants possess a lengthy historical record of traditional utilization due to their medicinal attributes, and their bioactive compounds have undergone extensive scientific examination to explore their potential health advantages. Nutraceuticals utilize bioactive compounds to effectively leverage the therapeutic capabilities of medicinal plants in a concentrated and standardized manner. This facilitates precise and efficient utilization of the bioactive compounds, promoting diverse aspects of physical and mental wellness.
- ***The preventive and wellness approach***: its encompasses the utilization of both medicinal plants and nutraceuticals in the context of promoting health and preventing diseases. Medicinal plants have been utilized in traditional medicine systems due to their inherent preventive and therapeutic attributes. In a similar vein, nutraceuticals obtained from botanical sources present a proactive methodology towards health by furnishing an array of bioactive constituents that bolster diverse physiological processes, stimulate antioxidant and anti-inflammatory responses, and augment general state of being. The synergistic blend of bioactive compounds found in nutraceuticals derived from medicinal plants facilitates a comprehensive approach to preventive healthcare.

- ***Research and innovation***: this domain are driven by the correlation between nutraceuticals and medicinal plants. Scientists and researchers engage in the exploration of medicinal plants in order to discern and describe bioactive compounds, examine their mechanisms of action, and assess their effectiveness and safety. This information is subsequently utilized in the advancement of nutraceutical products, wherein particular bioactive compounds are chosen, enhanced, and structured to generate products with precise health advantages.
- ***Integration of Traditional and Modern Knowledge***: The incorporation of botanical resources in nutraceutical products facilitates the amalgamation of indigenous wisdom and contemporary scientific investigations. Traditional medicine systems possess a profound comprehension of the therapeutic attributes exhibited by medicinal plants, as well as their synergistic effects when combined and the suitable methods of administration. This knowledge is integrated with scientific progress, encompassing phytochemical analysis, pharmacological investigations, and clinical trials, in order to substantiate and broaden the traditional applications of medicinal plants. Nutraceuticals originating from botanical sources serve as a scientific link connecting traditional and contemporary knowledge, offering empirically supported uses for their biologically active constituents.

4 Scope of Medicinal Plants as Nutraceuticals

The scope of medicinal plants is extensive and encompasses various aspects of human health and well-being as nutraceuticals. Several crucial elements encompass the scope of medicinal plants, including:

- ***Medicinal plants*** have long been a fundamental component of traditional and indigenous medical practices worldwide. Indigenous communities possess a wealth of knowledge regarding the traditional utilization of medicinal plants, which has been transmitted across generations. The exploration and conservation of this traditional knowledge is imperative in order to comprehend the therapeutic capabilities of medicinal plants (Karunamoorthi et al. 2013).
- ***Drug Discovery and Development***: Medicinal plants have been extensively utilized as a valuable reservoir of primary compounds for the advancement of contemporary pharmaceutical drugs. Numerous pharmacologically significant compounds, such as acetylsalicylic acid (commonly known as aspirin) and morphine, can be traced back to their botanical sources. The investigation of plant biodiversity and the extraction of bioactive compounds present potential avenues for the identification and advancement of innovative pharmaceuticals to address a range of illnesses (Prasathkumar et al. 2021).
- ***Medicinal plants*** are of considerable importance in the realm of complementary and alternative medicine (CAM) modalities. A significant number of individuals are inclined towards natural and holistic healthcare methods, resulting in the incorporation of medicinal plants into complementary and alternative medicine (CAM)

practices such as herbal medicine, Ayurveda, traditional Chinese medicine, and naturopathy (Yuan et al. 2016).

- ***The nutraceutical industry*** has experienced a significant increase in attention regarding the utilization of botanical medicines. Nutraceuticals are biologically active compounds obtained from botanical sources that confer health advantages surpassing fundamental nutritional requirements. Medicinal plants are employed in the manufacturing of dietary supplements, functional foods, and fortified beverages, providing consumers with a natural and comprehensive method for enhancing health and well-being (Bommakanti et al. 2023).
- ***Preventive Healthcare and Health Promotion***: Medicinal plants possess the capacity to contribute to preventive healthcare through the provision of naturally occurring compounds that facilitate the enhancement of overall health and well-being. The bioactive constituents found within medicinal plants demonstrate antioxidant, anti-inflammatory, immunomodulatory, and antimicrobial characteristics, thereby bolstering the body's innate defence mechanisms and aiding in the prevention of chronic ailments (Sofowora et al. 2013).
- ***Sustainable agriculture and conservation***: The practice of cultivating and responsibly harvesting medicinal plants can yield favourable outcomes for agricultural methodologies and the preservation of the environment. The incorporation of botanical species with medicinal properties into agroforestry systems, the advocacy for sustainable cultivation techniques, and the conservation of plant biodiversity all contribute to the maintenance of ecological equilibrium and the safeguarding of traditional knowledge (Chen et al. 2016).

5 Mechanisms Involve in Use of Medicinal Plants as Nutraceuticals

Multiple mechanisms contribute to the health-promoting properties and therapeutic effects of medicinal plants when they are used as nutraceuticals. These mechanisms are based on the bioactive chemicals found in medicinal plants and their interactions with the individuals physiology. Following are several fundamental mechanisms implicated in the utilization of medicinal plants as nutraceuticals:

- **Antioxidant activity**: Medicinal plants harbour bioactive constituents, including polyphenols, flavonoids, and carotenoids, that demonstrate antioxidative characteristics. These chemical compounds exhibit scavenging properties towards free radicals and reactive oxygen species (ROS) within the biological system, thereby inhibiting oxidative harm to cellular structures and tissues. They have the ability to contribute electrons or hydrogen atoms in order to stabilize free radicals and prevent cellular damage caused by oxidative stress. Antioxidants also have a role in the regeneration of naturally occurring antioxidants, such as glutathione, and can influence the activity of antioxidant enzymes, including superoxide dismutase (SOD) and catalase (CAT) (Salehi et al. 2020).

- ***Anti-inflammatory activity***: Medicinal plants harbour a diverse array of phytochemical compounds that exhibit anti-inflammatory properties. For example, the presence of polyphenols, terpenoids, and alkaloids in plants has been observed to possess inhibitory effects on pro-inflammatory enzymes, specifically cyclooxygenase-2 (COX-2) and lipoxygenase (LOX). Additionally, these compounds have been found to decrease the production of pro-inflammatory cytokines, such as interleukin-1β (IL-1β) and tumour necrosis factor-alpha (TNF-α). The aforementioned compounds have the ability to modulate the signalling of nuclear factor-kappa B (NF-κB), a crucial pathway implicated in the process of inflammation, by impeding its activation and the subsequent expression of genes responsible for pro-inflammatory mediators (Roy et al. 2022).
- ***Enzyme activity regulation***: Certain bioactive compounds found in medicinal plants have the ability to modulate the activity of enzymes that participate in various metabolic processes. As an illustration, specific compounds possess the ability to hinder enzymes accountable for the degradation of carbohydrates, thereby resulting in enhanced regulation of blood glucose levels. Various compounds have the potential to stimulate enzymes that play a role in detoxification processes, thereby promoting hepatic function and facilitating overall detoxification (Mihailovic et al. 2021).
- ***Cellular signalling***: These pathways can be modulated by medicinal plants, leading to interactions with specific pathways implicated in the development and progression of diseases. An illustration of this would be the observation that curcumin derived from turmeric has demonstrated the ability to regulate various signalling pathways, such as the mitogen-activated protein kinase (MAPK) pathway, phosphoinositide 3-kinase/protein kinase B (PI3K/Akt) pathway, and NF-κB pathway. These signalling pathways are of utmost importance in the regulation of cellular processes such as cell viability, proliferation, programmed cell death, and immune response. Through the modulation of these biological pathways, medicinal plants have the ability to elicit therapeutic effects in a wide range of diseases (Lu et al. 2023).
- ***Regulation of gut microbiota***: It is influenced by the presence of bioactive compounds found in medicinal plants, which have the ability to impact the composition and functionality of the gut microbiota. As an illustration, specific polyphenols and dietary fibers exhibit prebiotic properties by stimulating the proliferation of advantageous bacteria, such as *Bifidobacterium* and *Lactobacilli*. The aforementioned advantageous microorganisms generate short-chain fatty acids (SCFAs) via the process of fermentation, thereby supplying energy to the cells in the colon and regulating immune responses. Medicinal plants may exhibit antimicrobial properties against pathogenic bacteria, including Escherichia coli and Salmonella, thereby contributing to the preservation of a balanced gut microbial ecosystem (Milutinović et al. 2021).
- ***Neuroprotective Effects***: Certain botanical species possess bioactive constituents that exhibit neuroprotective attributes, thereby facilitating the maintenance of cerebral well-being and cognitive performance. These compounds have the potential to augment synaptic plasticity, shield neurons against oxidative stress, and

mitigate inflammation within the brain. The investigation of nutraceuticals derived from these plants is currently underway to assess their potential efficacy in the prevention of neurodegenerative disorders, including Alzheimer's disease and Parkinson's disease (Shoaib et al. 2023).

- ***Cardiovascular health*** can be enhanced by the consumption of specific medicinal plants containing bioactive compounds. For example, bioactive compounds such as polyphenols and omega-3 fatty acids have been shown to possess properties that can potentially contribute to the reduction of blood pressure, the decrease of cholesterol levels, and the enhancement of blood vessel function. These effects are associated with a reduction in the likelihood of developing cardiovascular diseases, such as hypertension and atherosclerosis (Awuchi et al. 2022).
- ***Immune modulation***: The regulation of immune function is achieved through the modulation of immune responses by medicinal plants, which exert their effects by influencing the activity of immune cells and the production of cytokines. For instance, the presence of compounds in Echinacea, including polysaccharides and alkamides, has demonstrated the ability to augment the functionality of natural killer (NK) cells, macrophages, and dendritic cells. Additionally, they have the ability to induce the synthesis of cytokines, such as interferons (IFNs) and interleukins (ILs), which are pivotal in the regulation of the immune system and the protection against infections (Di-Sotto et al. 2020).

Hence, the mechanisms implicated in the utilization of medicinal plants as nutraceuticals exhibit a wide range of diversity and interconnections. The bioactive compounds found within these plants engage in interactions with diverse physiological processes, thereby facilitating the promotion of well-being and the prevention of diseases. These mechanisms play a role in enhancing the efficacy of nutraceuticals obtained from medicinal plants and their ability to promote general wellness and address specific health conditions.

6 Nutraceutical Potential of Medicinal Plants

The use of plant-based medicines for the treatment of various ailments is practiced from ancient times such as Ayurveda, Unani, and Siddha, and has been part of human culture. Plant-based medication are the basis of the modern pharmaceuticals and search for novel and functional extracts from medicinal plants are in central attraction in recent years because of the presence of diverse bioactive compounds such as alkaloids, terpenoids, glycosides, steroids, flavonoids, and phenolic compounds. These bioactive molecules are reported to have several beneficial effects in lowering the risk of diseases caused by reactive oxygen species (ROS) through different mechanisms of action such as scavenging free radicals, quenching ROS, inhibiting oxidative enzymes. The bioactive compounds present in these plants contribute to their nutraceutical properties, which encompass a range of health benefits (Table 1). The mechanisms of action elucidate the specific ways in which these medicinal plants exert their effects on the body. Following are some kye potential of medicinal plants explored as nutraceuticals.

6.1 Antioxidant and Anti-inflammatory Properties

Medicinal plants have been widely acknowledged for their antioxidative and anti-inflammatory characteristics. The observed characteristics can be primarily ascribed to the existence of diverse bioactive compounds, including polyphenols, flavonoids, terpenoids, and alkaloids. These compounds function as antioxidants and regulate inflammatory pathways (Adegbola et al. 2017). Few instances of botanical specimens recognized for their antioxidative and anti-inflammatory attributes are.

- ***Turmeric (Curcuma longa)***: Curcumin, the primary bioactive compound found in turmeric, exhibits robust antioxidative and anti-inflammatory characteristics. It aids in the scavenging of free radicals, mitigates oxidative stress, and hampers the activity of inflammatory enzymes and molecules. Turmeric has been employed in traditional medicine for its potential to mitigate symptoms associated with inflammation, arthritis, and diverse chronic ailments.
- ***Zingiber officinale***, commonly known as ginger, is a plant species that possesses gingerol and its associated compounds. These bioactive constituents have been found to possess potent antioxidant properties, as well as exhibit anti-inflammatory effects. The bioactive compounds have the ability to hinder the synthesis of pro-inflammatory molecules and regulate the signalling pathways implicated in inflammation. Ginger has historically been utilized for its documented anti-inflammatory attributes and is recognized for its potential to alleviate symptoms associated with osteoarthritis and gastrointestinal inflammation.
- ***Camellia sinensis***, commonly known as Green Tea, is a beverage that contains a high concentration of catechins, specifically epigallocatechin gallate (EGCG). These catechins exhibit strong antioxidant properties and have been found to possess anti-inflammatory effects. The inhibitory effects of EGCG on oxidative stress and inflammation are achieved through the blockade of signalling pathways associated with inflammation. The consumption of green tea has been correlated with a decreased likelihood of developing chronic inflammatory conditions, such as cardiovascular diseases and specific types of cancer.
- ***Rosmarinus officinalis***, commonly known as rosemary, is a plant species that possesses the phenolic compound called rosmarinic acid. This compound is renowned for its notable antioxidant and anti-inflammatory characteristics. According to researchers, it has been observed that the substance aids in the scavenging of free radicals, the suppression of inflammatory enzymes, and the inhibition of the release of pro-inflammatory molecules. The application of rosemary extract has demonstrated encouraging results in mitigating inflammation and oxidative stress in diverse experimental models.

Table 1 List of medicinal plants and its nutraceutical potential, with specific bioactive compounds, and mechanisms of action (Pandey et al. 2011)

Medicinal plant	Bioactive compounds	Nutraceutical potential	Mechanisms of action
Aloe vera	Aloin, Polysaccharides	Anti-inflammatory, Wound healing	Inhibition of pro-inflammatory mediators, Promotion of tissue regeneration, Modulation of immune response
Ashwagandha (Withania somnifera)	Withanolides, Alkaloids	Adaptogenic, Stress reduction	Modulation of stress hormones, Antioxidant activity, Anti-inflammatory effects
Bilberry (Vaccinium myrtillus)	Anthocyanins, Flavonoids	Antioxidant, Eye health	Scavenging of free radicals, Protection of retinal cells, Improvement of blood flow
Black cohosh (Actaea racemosa)	Triterpene glycosides	Menopause symptoms relief	Estrogenic activity, Regulation of hormone levels
Chamomile (Matricaria chamomilla)	Apigenin, Chamazulene	Calming, Sleep aid	Modulation of GABA receptors, Anti-anxiety effects, Anti-inflammatory properties
Cinnamon (Cinnamomum verum)	Cinnamaldehyde, Polyphenols	Blood sugar regulation	Insulin sensitization, Inhibition of glucose absorption, Antioxidant activity
Cranberry (Vaccinium macrocarpon)	Proanthocyanidins, Flavonoids	Urinary tract health	Inhibition of bacterial adhesion, Anti-inflammatory effects, Antioxidant properties
Echinacea (Echinacea purpurea)	Alkamides, Polysaccharides	Immune support	Activation of immune cells, Enhancement of cytokine production, Antioxidant effects
Grape seeds (Vitis vinifera)	Proanthocyanidins	Antioxidant, Anticancer, Cardiovascular health	Scavenging free radicals, Inhibiting tumor growth, Improving blood flow, Protecting cardiovascular system

(continued)

Table 1 (continued)

Medicinal plant	Bioactive compounds	Nutraceutical potential	Mechanisms of action
Garlic (Allium sativum)	Allicin, Sulfur compounds	Cardiovascular health, Immune support	Antioxidant activity, Cholesterol reduction, Immune modulation, Antiplatelet effects
Ginger (Zingiber officinale)	Gingerol, Shogaol	Digestive health, Anti-inflammatory	Anti-nausea, Inhibition of inflammatory pathways, Antioxidant properties
Ginkgo biloba	Flavonoids, Terpenoids	Cognitive function, Circulation	Antioxidant activity, Improvement of cerebral blood flow, Neuroprotective effects
Green tea (Camellia sinensis)	Catechins, EGCG	Antioxidant, Weight management	Scavenging of free radicals, Promotion of thermogenesis, Modulation of metabolism
Hawthorn (Crataegus spp.)	Flavonoids, Procyanidins	Cardiovascular health	Vasodilation, Improvement of cardiac function, Antioxidant effects
Licorice (Glycyrrhiza glabra)	Glycyrrhizin, Flavonoids	Digestive health, Anti-inflammatory	Anti-ulcer, Modulation of immune response, Antioxidant properties
Milk thistle (Silybum marianum)	Silymarin, Flavonolignans	Liver health, Detoxification	Antioxidant activity, Promotion of liver cell regeneration, Anti-inflammatory effects
Peppermint (Mentha piperita)	Menthol, Menthone	Digestive health, Soothing	Anti-spasmodic, Alleviation of gastrointestinal discomfort, Anti-inflammatory properties
Saw palmetto (Serenoa repens)	Fatty acids, Phytosterols	Prostate health	Inhibition of enzyme 5-alpha-reductase, Anti-inflammatory effects
St. John's wort (Hypericum perforatum)	Hypericin, Hyperforin	Mood support, Depression	Serotonin modulation, Inhibition of reuptake, Anti-inflammatory properties

(continued)

Table 1 (continued)

Medicinal plant	Bioactive compounds	Nutraceutical potential	Mechanisms of action
Turmeric (Curcuma longa)	Curcumin, Curcuminoids	Anti-inflammatory, Antioxidant	Inhibition of inflammatory pathways, Scavenging of free radicals, Modulation of gene expression
Valerian (Valeriana officinalis)	Valerenic acid, Valepotriates	Sleep aid, Anxiety relief	Modulation of GABA receptors, sedative effects, Anti-Anxiety properties
Wheatgrass (Triticum aestivum)	Chlorophyll, Antioxidants	Detoxification, Digestive health	Supporting detoxification processes, Aiding digestion

- ***Allium sativum***, commonly known as garlic, is a plant species that is rich in sulfur compounds. One notable compound found in garlic is allicin, which exhibits properties of being an antioxidant and anti-inflammatory agent. The aforementioned compounds exhibit free radical scavenging properties, mitigate oxidative stress, and impede the functionality of pro-inflammatory enzymes. The potential anti-inflammatory effects of garlic supplementation have been extensively investigated in the context of cardiovascular diseases and rheumatoid arthritis.
- ***Bauhinia purpurea*** *L*: It has many bioactive compounds like flavonoids, alkaloids, steroids, triterpenoids, fatty alcohol, acid, and aster, glycerol's, and phenols chromone. The antioxidant activity was measured by 2,2-diphenyl-1-picrylhydroxyl solution (DPPH) radical scavenging assay and the in vitro studies showed considerably antioxidant activity, mainly based a scavenging of oxygen radicals. These flavonoids mainly inhibit of low-density lipoproteins oxidation, likely due to their reductive capacity and protein-binding properties. Hence *Bauhinia purpurea* are to be claimed as good antioxidant properties.

6.2 Anti-cancer Properties

The potential anti-cancer properties of medicinal plants have garnered considerable attention. Numerous compounds derived from plants demonstrate diverse mechanisms of action that possess the ability to impede the proliferation and metastasis of cancer cells, trigger apoptosis (programmed cell death), and hinder angiogenesis (the process of forming new blood vessels to tumors) (Macharia et al. 2022). Here are several instances of botanical specimens recognized for their anti-carcinogenic attributes:

- ***Taxus brevifolia***, commonly known as the Pacific Yew Tree, has been recognized for its medicinal properties. Taxol, a compound extracted from the bark of this tree, has been extensively utilized as a chemotherapeutic agent in the treatment of various forms of cancer. Taxol exerts its inhibitory effects on cell division through the process of microtubule stabilization, resulting in the arrest of the cell cycle and induction of apoptosis.

- ***Camptotheca acuminata*** **(Happy Tree)**: *Camptothecin*, derived from the bark and leaves of Camptotheca acuminata, has demonstrated potent anti-neoplastic properties against a diverse range of malignancies. The compound acts as a potent inhibitor of topoisomerase I, an essential enzyme in the processes of DNA replication and repair. This inhibition disrupts the normal functioning of DNA, resulting in DNA damage and subsequent cell death.
- ***Vinca rosea***, commonly known as Madagascar Periwinkle, is a plant species that has been extensively studied for its medicinal properties. One of the notable findings is the presence of Vinca alkaloids, specifically vincristine and vinblastine, which have shown significant potential in the field of cancer treatment. These alkaloids, extracted from the Madagascar Periwinkle, have been utilized in various therapeutic approaches aimed at combating cancerous cells. These compounds disrupt the process of microtubule assembly during cellular division, resulting in the cessation of the cell cycle and programmed cell death, also known as apoptosis.
- ***Curcuma longa***, commonly known as Turmeric, contains curcumin, a bioactive compound that has demonstrated anti-cancer properties in numerous preclinical and clinical investigations. It has the ability to modulate various signalling pathways implicated in the growth, proliferation, and survival of cancer cells. Curcumin demonstrates antioxidant, anti-inflammatory, and anti-angiogenic characteristics, and it has the ability to trigger apoptosis and hinder metastasis.
- ***Viscum album (European Mistletoe)***: Extracts derived from Viscum album, commonly known as European mistletoe, have been employed as adjunctive interventions in the field of cancer therapy. The extract containing mistletoe lectins has demonstrated immunomodulatory properties by enhancing the immune system's anticancer response. Additionally, they have the ability to impede cellular proliferation and trigger programmed cell death.
- ***Camellia sinensis (Green Tea)***: Green tea is known to possess polyphenolic compounds, specifically epigallocatechin gallate (EGCG), that demonstrate anti-cancer properties. Epigallocatechin gallate (EGCG) has the ability to regulate signalling pathways associated with cellular proliferation, inflammatory responses, and the formation of new blood vessels (angiogenesis). Additionally, it exhibits antioxidant properties and has the ability to trigger programmed cell death in cancer cells.

It is imperative to acknowledge that although these botanical specimens exhibit encouraging anti-neoplastic characteristics, additional scientific investigations and clinical trials are requisite to substantiate their efficacy and ascertain their safety in the context of oncological therapy. Furthermore, the utilization of plant-derived anti-cancer compounds in conjunction with traditional cancer therapies is frequently employed to augment their effectiveness and mitigate adverse reactions. The literature reports showed that there is high correlation between antioxidant activity and phenolics content. Antioxidants have been scientifically proven to be the most efficient method for mitigating the detrimental impacts induced by free radicals, as they possess the ability to scavenge or facilitate the decomposition of these radicals. The use of herbal extracts and phytochemicals with antioxidant activity can be extremely beneficial in the treatment of a wide range of disease and disorders. They show antiallergic, anti-inflammatory, antimicrobial and anticancer activity (Greenwell et al. 2015).

6.3 Cardiovascular Health Benefits

The potential cardiovascular health benefits of medicinal plants have been acknowledged as well. These entities possess bioactive compounds that exhibit potential in promoting cardiovascular well-being, regulating blood pressure, diminishing cholesterol levels, and mitigating the risk of cardiovascular ailments (Rastogi et al. 2016). Presented below are several instances of botanical species renowned for their therapeutic properties in relation to cardiovascular health:

- ***Allium sativum***, commonly known as garlic, is a plant species that possesses sulfur compounds, including allicin. Extensive research has demonstrated the diverse cardiovascular effects associated with these sulfur compounds. Allicin exhibits antiplatelet characteristics, indicating its ability to impede platelet aggregation, consequently mitigating the likelihood of thrombus formation. Garlic additionally demonstrates vasodilatory properties, facilitating the relaxation and dilation of blood vessels, thereby potentially contributing to the reduction of blood pressure. Furthermore, garlic exhibits lipid-modulating properties, as it is capable of diminishing overall cholesterol, low-density lipoprotein cholesterol, and triglyceride concentrations, while concurrently elevating high-density lipoprotein cholesterol levels. The synergistic impact of these combined factors contributes to the potential cardiovascular advantages of garlic (Papu et al. 2014).
- **Hawthorn (Crataegus spp.)**: Hawthorn comprises a variety of flavonoids, procyanidins, and other bioactive constituents that possess antioxidative characteristics and have the potential to enhance cardiovascular well-being. Studies have demonstrated that the presence of flavonoids in hawthorn extracts can effectively augment the flow of blood in the coronary arteries, enhance the contractile function of the heart, and diminish resistance in the peripheral blood vessels. These physiological responses contribute to enhancing the overall performance of the cardiac system and mitigating symptoms associated with heart failure. Hawthorn has been found to potentially exhibit antihypertensive properties, which could contribute to the reduction of blood pressure through the relaxation of blood vessels (Rastogi et al. 2016).
- ***Camellia sinensis***, commonly known as Green Tea, is a beverage that contains a significant amount of polyphenolic compounds, specifically catechins. Among

these compounds, the most prevalent and extensively researched is epigallocatechin gallate (EGCG). Epigallocatechin gallate (EGCG) demonstrates notable antioxidant and anti-inflammatory characteristics, thereby potentially safeguarding against oxidative stress-induced damage and mitigating inflammation within blood vessels. The consumption of green tea catechins has been linked to enhancements in lipid profiles, as they possess the ability to reduce levels of total cholesterol and LDL cholesterol. Green tea exhibits vasodilatory properties, which contribute to the improvement of endothelial function and the facilitation of optimal blood circulation (Hodgson et al. 2010).

- **Ginkgo (*Ginkgo biloba*)**: Extracts derived from Ginkgo leaves consist of flavonoids, terpenoids, and various other compounds that contribute to the cardiovascular effects exhibited by this plant. *Ginkgo biloba* demonstrates antioxidant characteristics, which contribute to the mitigation of oxidative stress and the preservation of blood vessel integrity. It additionally enhances blood flow through the process of vasodilation and the augmentation of microcirculation. *Ginkgo biloba* has been extensively researched for its potential therapeutic effects in the management of peripheral arterial disease (PAD), specifically in alleviating symptoms like intermittent claudication. This is believed to be achieved through the enhancement of blood circulation to the extremities. Furthermore, it has been suggested that ginkgo biloba may potentially enhance endothelial function, a critical factor in the maintenance of optimal blood vessel health (Šamec et al. 2022).
- **Turmeric**, scientifically known as *Curcuma longa*, contains curcumin, an active compound that has shown promising cardiovascular advantages. The substance demonstrates anti-inflammatory and antioxidant characteristics, which have the potential to mitigate inflammation and oxidative stress in blood vessels. Studies have demonstrated that curcumin possesses the ability to impede the synthesis of inflammatory molecules implicated in the development of atherosclerosis, thus potentially diminishing the likelihood of plaque formation. It has the potential to enhance endothelial function, a critical factor in maintaining optimal blood vessel dilation and function (Singletary 2020).
- ***Bauhinia purpurea***, (commonly known as bitter melon) extract may mitigate risk factors for congestive heart disease. Researchers investigated the antihyperlipidemic activity of an ethanolic extract derived from the unripe pods and desiccated leaves of B. purpurea in Albino rats. The extract was subjected to a comparative analysis with the standard lipid-lowering pharmaceutical agent known as atorvastatin. The investigators induced hyperlipidemia in the rodents by introducing a high-fat diet comprising of cholesterol, sodium cholate, and coconut oil into their standard nutrition. The extract was orally administered at a dosage of 300 mg/kg/day for a period of 30 days. The researchers noted a slight elevation in body weight subsequent to the administration of the extract. Nevertheless, the researchers also observed a noteworthy increase in the concentration of high-density lipoprotein cholesterol (HDL-C) in the blood serum, as well as a reduction in total cholesterol, low-density lipoprotein (LDL), and triglyceride levels. The atherogenic index, a significant parameter for assessing congestive heart disease, exhibited a decrease

upon administration of this dosage of the extract. The outcomes of this study indicate that the ethanolic extract derived from B. purpurea exhibited antihyperlipidemic properties in the rats that were subjected to experimentation. The extract yielded a lipid profile that exhibited positive characteristics, including elevated levels of HDL-C (which is considered advantageous) and decreased levels of total cholesterol, LDL, and triglycerides (Lakshmi et al. 2011).

6.4 Neuroprotective Properties

The neuroprotective properties of medicinal plants have been extensively investigated, focusing on their potential to safeguard and maintain the integrity and functionality of the nervous system. These plants possess a diverse range of bioactive compounds that demonstrate antioxidant, anti-inflammatory, and neuro-regenerative properties, thereby contributing to their neuroprotective mechanisms. Here are several instances of botanical species recognized for their neuroprotective attributes in the field of medicine:

- ***Ginkgo biloba***, commonly known as Ginkgo, is a plant species that produces leaf extracts rich in flavonoids, terpenoids, and various other compounds. These compounds have been scientifically demonstrated to exhibit neuroprotective properties. Ginkgo biloba demonstrates antioxidative characteristics, which contribute to the mitigation of oxidative stress and the preservation of neuronal cells by preventing damage. Additionally, it exhibits anti-inflammatory properties by suppressing the synthesis of pro-inflammatory molecules that may contribute to neurodegenerative mechanisms. According to researchers, there is evidence suggesting that Ginkgo has the potential to augment cognitive function, enhance memory, and mitigate age-related cognitive decline (Nowak et al. 2021).
- ***Bacopa monnieri***, commonly referred to as Bacopa, is a botanical species recognized for its medicinal properties in Ayurvedic medicine. It has been historically utilized for its potential to enhance cognitive function. The substance comprises various compounds, notably bacosides, which have demonstrated neuroprotective properties. Bacopa demonstrates antioxidant properties, thereby mitigating oxidative stress and safeguarding neuronal cells against potential harm. Additionally, it exerts modulation on neurotransmitter systems and augments the transmission of nerve impulses, potentially contributing to its neuroprotective and cognitive-enhancing characteristics (Abdul-Manap et al. 2019).
- ***Curcumin***, the bioactive constituent found in *Curcuma longa*, has exhibited neuroprotective properties in diverse preclinical and clinical investigations. The substance exhibits antioxidant and anti-inflammatory characteristics, which contribute to the mitigation of oxidative stress and inflammation within the cerebral region. Curcumin additionally demonstrates neuro-regenerative properties through its facilitation of neurogenesis and enhancement of neuronal viability. Extensive research has been conducted to investigate the potential therapeutic

advantages of this substance in the context of neurodegenerative disorders, including Alzheimer's disease and Parkinson's disease (Kulkarni et al. 2010).

- ***Withania somnifera***, commonly known as Ashwagandha, is a botanical species recognized for its adaptogenic properties. It has been extensively utilized in traditional Ayurvedic medicine to promote holistic wellness, encompassing various aspects such as brain health. The substance in question comprises bioactive compounds, specifically withanolides, which have demonstrated neuroprotective properties. Ashwagandha demonstrates notable antioxidant properties, thereby mitigating oxidative stress and providing neuroprotection to brain cells. Additionally, it exhibits anti-inflammatory characteristics and has the ability to regulate neurotransmitter systems, which may enhance cognitive abilities and mitigate neurodegenerative processes (Bhatnagar et al. 2009).
- ***Hericium erinaceus***, commonly referred to as Lion's Mane Mushroom, is a species of fungi that has gained recognition for its purported neuroprotective properties in the field of medicine. The substance comprises hericenones and erinacines, which have demonstrated the ability to induce the synthesis of nerve growth factor (NGF). Nerve Growth Factor (NGF) is an essential factor in the promotion, sustenance, and viability of neuronal cells. The consumption of Lion's Mane has been suggested to potentially have a positive impact on cognitive function, promote the regeneration of nerves, and provide protection against neurodegenerative disorders (Lakhanpal and Rana 2005; Spelman et al. 2017).
- ***Bauhinia purpurea***, are prescribed for various nervous-related disorders, including convulsions, delirium, asthma and anti-inflammatory agents. Current study reveals the first evidence that Bauhinia purpurea (stem bark) has antiamnesic effect on scopolamine induced amnesia in rats (Abdelghany et al. 2022).

6.5 Others

Medicinal plants provide a significant reservoir of nutraceuticals that have been extensively studied for their therapeutic properties in diverse medical conditions. Plants bioactive compounds, owing to its anti-inflammatory and wound-healing characteristics, has exhibited potential in the management of ulcers, cutaneous inflammation, and gastrointestinal disorders. Similarly, some bioactive compound, demonstrates significant anti-inflammatory and antioxidant properties, thus presenting itself as a promising contender for the treatment of ulcerative colitis, wound healing, and various inflammatory disorders such as glandular swelling, stomach tumors, dysentery, piles, lymph node swelling and enlargement, inflammatory swelling, hemorrhage-bleeding, as well as cold and cough symptoms. Medicinal plant based nutraceutical compounds can also help to cure from ulcer, wound, glandular swelling, stomach tumor, diarrhoea, dysentery, amoebic dysentery, ano-rectal, piles, lymph nodes swelling, lymph node enlargement, inflammatory swelling and hemorrhage-bleeding, cold and cough. Few examples of these plants are listed below:

- **Aloe Vera (*Aloe barbadensis*)**: The gel derived from Aloe vera contains a variety of bioactive compounds, such as polysaccharides, lectins, and anthraquinones, which are responsible for its therapeutic properties. Research has demonstrated the presence of anti-inflammatory, antimicrobial, and wound-healing properties. Aloe vera gel has been found to exhibit properties that can potentially induce collagen synthesis, facilitate angiogenesis, and augment the migration and proliferation of dermal cells, thereby potentially facilitating the process of wound healing. Furthermore, it demonstrates anti-ulcerogenic characteristics and has the potential to mitigate gastric inflammation and facilitate the regeneration of gastric ulcers (Hęś et al. 2019).
- ***Turmeric***, scientifically known as *Curcuma longa*, encompasses curcumin, a polyphenolic compound renowned for its robust anti-inflammatory, antioxidant, and antimicrobial attributes. Curcumin possesses the ability to regulate various signalling pathways implicated in the processes of inflammation and wound healing. It has the potential to mitigate inflammation by suppressing the activity of pro-inflammatory molecules and enzymes. Curcumin additionally facilitates wound healing through augmentation of collagen synthesis, angiogenesis, and tissue regeneration. Moreover, extensive research has been conducted to investigate the potential anti-neoplastic properties of the substance in different types of malignancies, such as gastric neoplasms (Jyotirmayee et al. 2022).
- ***Calendula (Calendula officinalis)***: Calendula exhibits characteristics of anti-inflammatory, antimicrobial, and wound-healing properties. The therapeutic effects of this substance can be attributed to the presence of flavonoids, triterpenoids, and polysaccharides. The anti-inflammatory properties of calendula extracts are attributed to their ability to suppress the activity of pro-inflammatory cytokines and enzymes. Additionally, they demonstrate antimicrobial properties against a range of pathogens, thereby aiding in the prevention of wound infections. The wound healing properties of calendula are attributed to its ability to enhance fibroblast proliferation, stimulate collagen synthesis, and promote re-epithelialization. Moreover, scientific studies have demonstrated that it exhibits anticancer properties and has the potential to impede the growth of tumors (Ahmad et al. 2022).
- ***Psidium guajava (Guava)***: The leaves of Guava are rich in bioactive compounds such as tannins, flavonoids, and essential oils. These compounds exhibit antimicrobial, anti-inflammatory, and gastroprotective properties. The antimicrobial properties of guava leaf extracts have been observed to exhibit efficacy against a range of bacteria and parasites commonly linked to diarrhoea and dysentery, such as Escherichia coli and Entamoeba histolytica. The growth and activity of these pathogens can be suppressed, leading to a reduction in diarrhoea. The anti-inflammatory properties of guava leaves have been observed, suggesting their potential for reducing inflammation in the gastrointestinal tract (Díaz-de-Cerio et al. 2017)
- ***Terminalia chebula***, commonly known as Haritaki, is a botanical species that has been extensively utilized in the field of Ayurveda for the treatment of diverse gastrointestinal ailments. The substance in question comprises bioactive

compounds, namely tannins, chebulic acid, and chebulinic acid, which are responsible for its therapeutic attributes. Haritaki demonstrates antimicrobial properties against a diverse array of bacteria and parasites, encompassing those responsible for inducing diarrhea and dysentery. It has the potential to mitigate diarrhea and facilitate the restoration of regular gastrointestinal motility. Haritaki exhibits antioxidant and anti-inflammatory properties, potentially contributing to its gastroprotective characteristics (Bulbul et al. 2022).

- ***Azadirachta indica (Neem)***: Neem, scientifically known as *Azadirachta indica*, is a botanical species that has been historically employed for its notable antimicrobial, anti-inflammatory, and wound-healing attributes. Neem is comprised of bioactive compounds, namely nimbin, nimbidin, and quercetin, which exhibit antimicrobial properties against various microorganisms including bacteria, fungi, and parasites. Additionally, it demonstrates anti-inflammatory properties through the inhibition of pro-inflammatory cytokines and enzymes. The topical application of neem oil or creams derived from neem has been found to have beneficial effects on wound healing, infection prevention, and inflammation reduction (Alzohairy 2016).
- ***Glycyrrhiza glabra***, commonly known as licorice, has been historically employed for its therapeutic properties in treating ulcers. The substance under consideration comprises glycyrrhizic acid, a compound that has demonstrated inhibitory effects on the proliferation of Helicobacter pylori, a bacterium frequently linked to gastric ulcers. Licorice additionally demonstrates anti-inflammatory properties and has the potential to mitigate inflammation within the gastrointestinal tract. Moreover, licorice has been employed for the alleviation of symptoms associated with gastritis and gastric mucosal injury (Sharma et al. 2018).
- ***Centella asiatica (Gotu kola)***: Gotu kola has been historically utilized for its potential wound-healing attributes. The presence of triterpenoids in this substance is hypothesized to augment the process of collagen synthesis and stimulate the proliferation of fibroblasts, the cellular entities accountable for the reparative process of wound healing. Gotu kola exhibits potential anti-inflammatory properties, which contribute to the mitigation of edema and facilitation of wound and ulcer healing (Belwal et al. 2019).
- ***Plantago*** *ovata*, commonly known as Psyllium husk, is a plant material that exhibits a high concentration of soluble fiber. It has been historically utilized for its advantageous impact on gastrointestinal well-being. It exhibits the ability to undergo hydration and transform into a viscoelastic material, thereby aiding in the regulation of gastrointestinal transit. Psyllium husk is frequently employed as a bulk-forming cathartic agent for the management of diarrhoea and to facilitate the establishment of regularity in gastrointestinal motility. It may also potentially offer alleviation from inflammatory bowel conditions, such as ulcerative colitis (Khan et al. in 2021).
- ***Matricaria chamomilla***, commonly referred to as Chamomile, is recognized for its renowned effects on promoting relaxation and providing a soothing sensation. The substance comprises a diverse array of bioactive compounds, such as chamazulene, flavonoids, and terpenoids, which exhibit notable anti-inflammatory

and anti-ulcer properties. Chamomile has been historically employed for the alleviation of gastrointestinal ailments, including stomach ulcers, gastric inflammation, and gastrointestinal spasms. It has been suggested that it could potentially alleviate symptoms of diarrhoea and facilitate the regeneration of gastrointestinal tissues (Gupta et al. 2010).

- ***Terminalia arjuna***, also known as Arjuna, is a botanical specimen widely employed in the field of Ayurvedic medicine due to its recognized therapeutic properties in promoting cardiovascular well-being. The substance in question is comprised of bioactive compounds, specifically flavonoids and tannins, which exhibit properties associated with antioxidation and protection of the cardiovascular system. Studies have demonstrated that Arjuna exhibits anti-inflammatory properties, enhances cardiac function, lowers blood pressure, and improves overall cardiovascular well-being. The utilization of this intervention has shown potential advantages in the management of cardiovascular disorders, including hypertension, heart failure, and coronary artery disease (Jain et al. 2009).
- ***Asparagus racemosus linn* (shatavari)**: It is a botanical species recognized for its diverse pharmacological attributes, encompassing antioxidative, anti-stress, anti-ulcer, and wound healing properties. The antioxidant properties of *Asparagus racemosus* have received considerable scientific interest in recent years due to their potential as natural substitutes for synthetic additives. A scientific investigation was carried out by researchers to examine the presence of antioxidant compounds in the methanolic extract of *Asparagus racemosus* roots and their capacity to eliminate reactive oxygen species (ROS) and free radicals in a controlled environment. Furthermore, the study revealed that the methanolic extract derived from the roots of *Asparagus racemosus* exhibits a substantial abundance of antioxidant compounds. These compounds demonstrated the capacity to efficiently counteract diverse reactive oxygen species (ROS) and free radicals in an in vitro setting. Additionally, a distinct investigation carried out by Researchers assessed the efficacy of the root extract on lung cancer cells. The findings indicate that *Asparagus racemosus* exhibits potential as a viable candidate for the advancement of novel plant-derived therapeutic medications aimed at addressing lung cancer. Hence, *Asparagus racemosus* (shatavari) contains antioxidant capabilities which may be an safe alternative for treatment of pulmonary disorders (Goyal et al. 2003).
- ***Glycyrrhiza glabra***: It is, commonly referred to as liquorice, is a herb species that possesses a multitude of bioactive compounds. The primary constituents responsible for its distinctively sweet taste are triterpene saponins. Furthermore, the plant contains phenolic compounds. The volatile constituents present in liquorice comprise geraniol, pentanol, hexanol, teroinen-4-ol, and α-terpineol. Additionally, it exhibits a high concentration of propionic acid, benzoic acid, furfuraldehyde, 2,3-butanediol, furfuryl formate, maltol, 1-methyl-2-formylpyrrole, and trimethylpyrazine. The utilization of liquorice extracts is prevalent in the food and pharmaceutical sectors, along with their incorporation in the manufacturing of functional foods and food supplements. It is additionally employed as a traditional Chinese medicinal remedy for the management of diverse ailments, encompassing gastrointestinal disorders, cough, bronchitis, arthritis, gastritis, peptic

ulcers, respiratory infections, and tremors. Moreover, liquorice is utilized as a flavour enhancer and natural sweetening agent in diverse food commodities including American-style tobacco, chewing gum, confectioneries, baked goods, frozen desserts, and carbonated beverages. It is also employed in the manufacturing of beer and fire extinguishers, as well as serving as a skin depigmentation agent. Studies have shown that *G. glabra* can reduce microsomal lipid peroxidation and has strong scavenging action against DPPH radicals, suggesting that it has antioxidant potential. The presence of phenolic compounds in liquorice is known to exert a protective effect on biological systems by mitigating oxidative stress and potentially mitigating skin damage (Pastorino et al. 2018).

- ***Premna integrifolia***: It is used in treating fever, colic, diarrhoea, dysentery, urine retention, flatulence, dyspepsia and rheumatism. Premnine, ganikarine and premnazole alkaloids. In a research it has been found that the roots of *P. integrifolia*, whereas the flavanoids luteolin, sterol and triterpene are present in the leaves. It also contains iridoid glycosides and several diterpenoids. The methanol extracts of *P. integrifolia* leaves, was found to have high antiradical capacities and reducing power and has significant potential for use as natural antioxidants. The antioxidant and radical scavenging activities were investigated by using reducing power and 2,2-diphenyl-2- picrylhydrazyl hydrate (DPPH) assays. Moreover, it exhibits analgesic, antinociceptive, antiarthritic, antibacterial, anticancer, antitumor, cytotoxic, tumor-suppressing, and anti-inflammatory characteristics. Additionally, the administration of *P. integrifolia* and atorvastatin exhibited notable efficacy in preventing the elevation of serum cholesterol, triglyceride, and LDL levels when compared to the nicotine control group. The HDL level exhibited a significant increase in both the treated and standard groups when compared to the Nicotine control group. Based on the aforementioned findings, it is evident that *P. integrifolia* exhibits significant efficacy as an anti-hyperlipidemic agent. It can also be employed in a traditional manner for the treatment of diverse ailments such as rheumatism, asthma, dropsy, cough, fever, boils, and scrofulous diseases (Mali 2016).

7 Importance of Medicinal Plants in Nutraceuticals

The role of medicinal plants in nutraceuticals is extensive and multifaceted. There are several primary factors that contribute significantly to the pivotal role of medicinal plants in the advancement and application of nutraceuticals:

Rich Source of Bioactive Compounds: Medicinal plants serve as an extensive and varied repository of bioactive compounds, encompassing phytochemicals, antioxidants, polyphenols, flavonoids, terpenoids, and alkaloids. These compounds exhibit diverse health-enhancing characteristics and contribute to the therapeutic capabilities of nutraceuticals. The distinctive chemical composition of medicinal plants offers a diverse array of bioactive molecules that can be extracted, refined, and integrated into nutraceutical formulations.

- Traditional Knowledge and Ethnopharmacology: It encompass the utilization of medicinal flora that has been practiced for an extended period within traditional medical frameworks, including Ayurveda, Traditional Chinese Medicine, and Indigenous healing methodologies. The aggregation of traditional knowledge offers valuable perspectives on the potential therapeutic applications of botanical species. Ethnopharmacological investigations facilitate the identification of botanical specimens possessing distinct therapeutic attributes, elucidate the underlying mechanisms by which these properties are manifested, and provide guidance for their utilization in the development of nutraceutical preparations. The integration of traditional knowledge with contemporary scientific research facilitates the identification of novel bioactive compounds and improves the efficacy of nutraceutical interventions.
- Holistic Approach to Health: The utilization of medicinal plants provides a comprehensive and integrated approach to promoting health and well-being. In contrast to traditional pharmaceuticals that frequently focus on singular symptoms or illnesses, medicinal plants encompass a multitude of bioactive compounds that possess the potential for synergistic impacts on diverse physiological systems. Nutraceuticals originating from botanical sources possess the capacity to enhance general welfare, rectify fundamental irregularities, and facilitate optimal health by providing nourishment to the body and its physiological mechanisms.
- Disease prevention and health promotion: Extensive research has been conducted on the potential of bioactive compounds found in medicinal plants for the prevention and management of various diseases. Nutraceuticals derived from botanical sources have the potential to exert preventive effects through their antioxidant, anti-inflammatory, and immune-modulating properties. They play a role in mitigating the likelihood of developing chronic ailments, such as cardiovascular diseases, diabetes, neurodegenerative disorders, and specific forms of cancer. Through the integration of botanical species with medicinal properties into nutraceutical formulations, individuals have the opportunity to actively promote and enhance their overall health and well-being.
- Natural and sustainable methodologies: Medicinal flora provide a natural and sustainable approach to promoting health and well-being. In contrast to synthetic pharmaceuticals, which frequently exhibit accompanying adverse reactions, nutraceuticals sourced from medicinal plants are regarded as safe and well-tolerated when administered appropriately. Furthermore, the cultivation and sustainable harvesting of medicinal plants play a crucial role in promoting environmental conservation, preserving biodiversity, and implementing sustainable agricultural practices.
- Personalized Nutrition: Personalized nutrition approaches are founded upon the utilization of medicinal plants. Various botanical species possess distinct bioactive compounds that exhibit diverse physiological effects on human health. Through comprehensive analysis of an individual's distinct health requirements, genetic predispositions, and biochemical indicators, customized nutraceutical suggestions can be formulated to maximize health outcomes. Medicinal plants possess a wide

array of bioactive compounds that can be selectively combined or tailored to meet specific individual needs.

Hence, medicinal plants are of significant importance in the advancement and application of nutraceuticals. They function as a plentiful reservoir of bioactive substances, provide valuable traditional knowledge and ethnopharmacological perspectives, advocate for a comprehensive approach to well-being, assist in the prevention of diseases and the promotion of health, offer a natural and sustainable methodology, and enable the implementation of individualized nutritional strategies. The integration of botanical species with medicinal properties into nutraceutical compositions amplifies their therapeutic efficacy and aids individuals in attaining an optimal state of health and overall well-being (Srivastava et al. 2018).

8 Applications of Medicinal Plant-Based Nutraceuticals

- ***Human Health and Disease Management***: The utilization of nutraceuticals derived from medicinal plants plays a crucial role in the prevention and management of diverse chronic diseases in human health. The bioactive compounds found in the subject's composition, namely polyphenols, alkaloids, and terpenoids, exhibit characteristics of being antioxidants, anti-inflammatory agents, and anticarcinogens. These nutraceuticals have the potential to serve as supplementary therapies to bolster conventional treatments and enhance overall well-being (Devaraj et al. 2021).
- ***Nutritional supplements***: Medicinal plant-derived nutraceuticals are recognized as valuable reservoirs of vital nutrients, encompassing vitamins, minerals, and dietary fibers. Nutritional supplements are formulated to effectively target and rectify specific nutrient deficiencies, thereby enhancing overall well-being. Illustrative instances encompass botanical extracts abundant in vitamins C and E, omega-3 fatty acids obtained from botanical origins, and plant-derived protein supplements (Ruchi 2017).
- ***Traditional Medicine***: Medicinal plants have been employed in traditional medicine systems across various cultures for an extended period of time. Nutraceuticals derived from these botanical sources persistently find application in traditional medicinal practices on a global scale. In Ayurvedic practice, formulations frequently incorporate plant-derived nutraceuticals with the aim of reinstating equilibrium and fostering well-being. Traditional Chinese Medicine utilizes herbal preparations as therapeutic interventions for a multitude of health conditions (Ruchi 2017).
- ***Cosmeceuticals***: Medicinal plant-derived nutraceuticals are widely employed in the cosmetics sector due to their potential advantages in promoting skin and hair well-being. Skincare products, hair care formulations, and anti-aging treatments often utilize plant extracts that contain bioactive compounds such as polyphenols,

flavonoids, and essential oils. These nutraceuticals exhibit antioxidant, moisturizing, and anti-inflammatory properties, thereby contributing to enhanced skin tone, texture, and overall appearance (Carvalho et al. 2016).

- ***Functional Foods and Nutraceutical Beverages***: Medicinal plant-derived nutraceuticals are integrated into functional foods and beverages to augment their nutritional composition and confer targeted health advantages. Functional foods encompass a range of fortified consumables, such as breakfast cereals, energy bars, and yogurts, which are enriched with nutraceuticals derived from plants. Nutraceutical beverages may comprise of botanical extracts or herbal infusions that exhibit potential health benefits (Pinela et al. 2016).
- ***Animal Nutrition and Feed Additives***: Nutraceuticals derived from botanical sources are employed in animal nutrition to enhance animal well-being, growth, and productivity. These nutraceuticals may comprise of botanical extracts, volatile compounds, or distinct phytochemicals possessing antimicrobial, anti-inflammatory, or growth-stimulating attributes. They function as organic substitutes for synthetic feed additives, promoting the implementation of sustainable and environmentally-friendly farming methods (Hajam et al. 2020).
- ***Agricultural Applications***: Medicinal plant-derived nutraceuticals exhibit potential in agricultural settings as biopesticides and plant growth promoters. Medicinal plants, such as Azadirachta indica (neem) or Chrysanthemum cinerariifolium (pyrethrum), contain bioactive compounds that demonstrate insecticidal, antifungal, or herbicidal activities. These naturally occurring alternatives mitigate dependence on artificial pesticides and facilitate the adoption of ecologically sustainable agricultural methods (Tlak et al. 2021).
- ***Environmental Sustainability and Biodiversity Conservation***: The cultivation and utilization of medicinal plants for nutraceutical purposes have the potential to make a positive impact on environmental sustainability and biodiversity conservation. The conservation of medicinal plant biodiversity can be effectively ensured by implementing sustainable practices, such as organic farming, responsible harvesting, and cultivation of endangered or threatened species. This methodology facilitates the sustainable preservation of botanical species with medicinal properties and ensures the conservation of natural habitats (Chen et al. 2016).

9 Challenges and Opportunities in Using Medicinal Plants for Nutraceuticals

9.1 Challenges

Using medicinal plants for nutraceuticals poses challenges in terms of quality control, standardization, efficacy determination, regulatory framework, sustainability, intellectual property rights etc. Piccolella et al. (2019). Some are listed below:

- ***Phytochemical diversity***: Medicinal plants exhibit a wide range of chemical constituents, encompassing alkaloids, flavonoids, terpenoids, and phenolic compounds. Nevertheless, the chemical composition of these plants exhibits considerable variation contingent upon factors including plant species, geographical location, climatic conditions, soil characteristics, and the timing of harvest. The presence of variability presents a significant obstacle in maintaining uniform levels of bioactive compounds in nutraceutical products derived from medicinal plants.
- ***Quality control and authentication***: The assessment and verification of the quality and genuineness of medicinal plant materials utilized in nutraceuticals are of utmost importance in ensuring their safety and effectiveness. The phenomena of adulteration, substitution, or misidentification of plant species can manifest, resulting in discrepancies in the composition and potency of the ultimate products. The implementation of rigorous quality control measures, such as accurate botanical authentication, comprehensive chemical profiling, and standardized active constituent analysis, is imperative in order to guarantee product uniformity and establish consumer confidence.
- ***Safety considerations***: Although medicinal plants are generally regarded as safe for consumption, certain plants may contain toxic compounds or have the potential to interact with medications. Evaluating the safety profile of medicinal plants and their bioactive constituents is of utmost importance in order to identify potential hazards and establish appropriate dosage guidelines. Moreover, the existence of impurities such as metallic elements with high atomic mass, chemical substances used for pest control, or microscopic disease-causing organisms in botanical specimens can potentially endanger human well-being if adequate measures are not implemented for regulation.
- ***Variability in standardized regulations***: The regulations pertaining to the manufacturing, labelling, and promotion of nutraceutical products derived from medicinal plants exhibit heterogeneity across various countries and regions. The lack of standardized norms and regulations can pose difficulties for manufacturers, leading to variations in product quality, safety, and effectiveness. The implementation of uniform regulations and guidelines is imperative to guarantee the efficacy and safety of nutraceuticals derived from medicinal plants.

9.2 Opportunities

The use of medicinal plants as a source of nutraceuticals opens up a number of promising avenues. Nutraceuticals are bioactive compounds obtained from food sources that exhibit physiological benefits surpassing their fundamental nutritional value. Medicinal plants, due to their wide array of bioactive compounds, present a bountiful reservoir of natural constituents for the advancement of nutraceutical research and development (Sen et al. 2011). Below are several potential avenues for harnessing the potential of medicinal plants in the development of nutraceuticals:

- ***Phytochemical characterization***: The field of phytochemical characterization has witnessed significant progress due to the development and application of advanced analytical techniques, including chromatography, spectroscopy, and mass spectrometry. These techniques enable the thorough determination and measurement of bioactive compounds found in medicinal plants. Thorough phytochemical characterization enhances the process of selecting suitable plant species, guarantees consistent levels of essential compounds, and aids in identifying the most effective extraction and processing techniques for nutraceutical manufacturing.
- ***Pharmacological Research***: The implementation of meticulous pharmacological examinations, encompassing both preclinical and clinical trials, yields scientific substantiation regarding the effectiveness and safety of nutraceuticals derived from medicinal plants. These investigations provide clarification on the mechanisms by which bioactive compounds exert their effects, explore their potential for therapeutic applications, and examine potential interactions with other substances. Pharmacological research additionally contributes to the establishment of optimal dosage regimens, the identification of target populations, and the investigation of potential synergistic effects with other medications or therapies.
- ***Bioavailability augmentation***: Numerous bioactive compounds found in medicinal plants exhibit suboptimal bioavailability, indicating limited absorption and utilization within the human body. Techniques such as nanotechnology, liposomal encapsulation, microencapsulation, or complexation with specific carriers can be employed to improve the solubility, stability, and bioavailability of these compounds. Enhanced bioavailability facilitates the transportation of the active components to their designated locations within the body, thereby augmenting the efficacy of nutraceutical interventions.
- ***Sustainable cultivation and sourcing***: The utilization of medicinal plants can exert stress on natural resources and ecosystems. By advocating for sustainable cultivation methodologies, such as organic farming, agroforestry, and the cultivation of endangered species, we can effectively guarantee the continued accessibility of medicinal plants in the long run, all the while mitigating any potential adverse effects on the environment. Furthermore, the endorsement of fair trade principles and ethical sourcing has the potential to positively impact the conservation of traditional knowledge and the welfare of indigenous communities engaged in the growth and collection of medicinal flora.
- ***Synergistic combinations***: Medicinal plants frequently possess numerous bioactive compounds that have the potential to demonstrate synergistic effects when employed collectively. Exploring the synergistic interactions among various plant constituents can potentially result in the creation of nutraceutical formulations that exhibit heightened effectiveness and a wider range of health advantages. Many micronutrient serving as phytochemicals also act in synergies for long lasting effects (Singh et al. 2022).
- ***Personalized nutrition and precision medicine***: Medicinal plants possess a broad spectrum of bioactive compounds that exhibit various health-promoting properties. The concept of personalized nutrition and precision medicine endeavours to customize nutraceutical interventions by considering individual genetic

variations, health status, and specific requirements. The integration of genetic profiling, biomarker analysis, and clinical data enables the identification of individuals who would derive the greatest advantages from particular medicinal plant-based nutraceuticals, thereby facilitating personalized and precisely targeted interventions.

10 Conclusion

Medicinal plants serve as a valuable reservoir of bioactive compounds that possess noteworthy nutraceutical properties. These plants exhibit a diverse array of health-promoting properties, encompassing antioxidant, anti-inflammatory, anticancer, cardiovascular, neuroprotective, and gastrointestinal effects. Nevertheless, the application of botanical species for their medicinal properties in the form of nutraceuticals poses certain obstacles, including the need for standardization, quality control measures, and adherence to regulatory guidelines. However, the continuous progress in technology, the synergy between traditional knowledge and modern science, personalized nutrition strategies, and the implementation of sustainable practices present potential avenues for addressing these obstacles. Through comprehensive study, quality control, and appropriate application, the nutraceutical potential of medicinal plants can be tapped to improve preventative medicine, supplementary therapies, and individualized diets.

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Comparative Study on Quality Attributes of Vacuum and Atmospheric Fried Bitter Gourd Chips

Savita S. Zambre

Abstract The correlation between increased vegetable consumption and protection against chronic diseases as well as a shift towards sustainable and personalized food choices has motivated interest in production of value-added products from vegetables. In this study bitter gourd slices were vacuum fried at three different temperatures 90, 100 and 115 °C at vacuum pressure 9 kPa. The prepared chips were analyzed for quality attributes such as oil content, total phenolic content, crude fibre, colour, texture, browning index. The sensory evaluation of vacuum fried bitter gourd chips fried at 115 °C and 9 kPa scored highest points 8.02 among all other samples on nine point hedonic scales. The composition of vacuum fried bitter gourd chips showed 21.67% oil, 11.52% crude fibre and 3828 mg/100 gm total phenolic content. The colour was measured using Lovibond RT 300 portable reflectance spectrophotometer, and the colour values L*, a* and b* were 57.67, 10.76 and 34.09 respectively. The scanning electron micrograph of vacuum fried bitter gourd chips reveals the presence of more porous structure compared to atmospherically fried chips. The moisture sorption isotherm for vacuum fried bitter gourd chips at 38 °C showed typical type II sigmoid shape. Sorption isotherm model equations such as Brumauer–Emmet–Teller (BET), Smith, Halsey, Oswin, Henderson, Kuhn, Iglesias and Chirife, and Freundlich applied for the fitting of experimental moisture sorption data yielded high coefficient of determination R^2 ranging from 0.96 to 0.99 confirming the applicability of the equations employed for modelling the process. The study indicates the feasibility of developing vacuum fried bitter gourd chips with high nutritional values and desired quality attributes.

Keywords Vacuum frying · Bitter gourd chips · Total phenolic content · Crude fibre · Browning index · Moisture sorption isotherm

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1 Introduction

Bitter gourd consumption has enormously increased for their nutritional value and therapeutic value. Bitter gourd is considered to be a good source of bioactive compounds and Polyphenols having high antioxidant potential and anti-diabetic activity (Grover and Yadav 2004; Vinayagam et al. 2016; Deshaware et al. 2017; Behera et al. 2010). The application of novel technologies in food processing is encouraged by the growing demand for production of value-added products from fruits and vegetables. To develop food preservation and improve shelf life of product, alternatives to conventional food processing technologies which are sustainable are recognized. In vacuum frying amount of oil used for frying is less as compared to other frying methods. For the production of novel, healthy snacks such as fruit and vegetable crisps vacuum frying is an encouraging technology that produces desired quality attributes and as per new health trends (Song et al. 2007).Vacuum frying is a deep fat frying technique, carried out in a closed system under pressures well below atmospheric levels, considerably reducing the boiling point of water and accordingly the frying temperature (Garayo and Moreira 2002). Actually, most of the benefits of this technology are the result of the low working temperatures and minimal contact to oxygen. The benefits include:

(i) Decrease in the oil content of the fried product and undesirable effects on oil quality
(ii) Retention of natural colour and flavours (Shyu and Hwang 2001)
(iii) Decreased acrylamide content (Granda et al. 2004) and
(iv) Conservation of nutritional compounds (Da Silva and Moreira 2008).

In the present study bitter gourd chips were vacuum fried, its purpose was to remove moisture to a certain level which can avoid microbial growth and slows down the action of enzymes, leading to an extension of shelf-life while maintaining product quality.

2 Material and Methods

From the local market of Nagpur fresh, fully matured bitter gourds were purchased. Bitter gourds were washed with water, dried with tissue paper and cut into thin slices of 2–3 mm thickness. Fresh vegetable oil (sunflower oil) was used for frying and the product to oil ratio was maintained as 1:20 in all the experiments. A laboratory scale vacuum fryer was constructed as shown in (Fig. 1) was used for vacuum frying of bitter gourd.

Bitter gourd slices were vacuum fried at three different temperatures 90, 100 and 115 °C and vacuum pressure 9 kPa whereas atmospheric frying temperature was 170 °C.

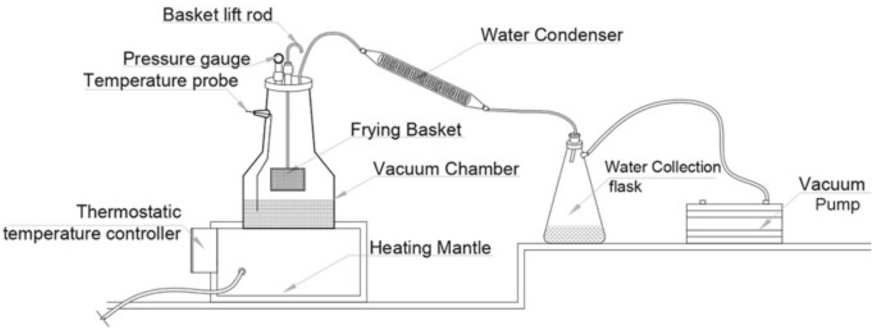


Fig. 1 Schematic diagram of laboratory scale vacuum fryer

2.1 *Vacuum Frying Process for Bitter Gourd Chips*

50 g of bitter gourd slices were loaded in a perforated basket and hanged with a stainless-steel lift rod. The perforated basket suspended through the lift rod above the oil level, closing the lid and then, all the joints were sealed with vacuum grease to avoid leakage. Once the vessel attains the desired temperature, it was evacuated and the basket was inserted into the hot oil. Chips were fried for desired time and temperature. After frying, the basket was raised, stirred manually to remove excess oil adhered on the chips. The sample was kept in vacuum condition for 5 min. The vessel was pressurized up to atmospheric pressure; the samples were removed and blotted dry with paper towels to remove excess oil. To ensure removal of excess oil the sample was centrifuged for 5 min at 800 rpm, and stored in sealed metalized polyester bags in desiccators for further analysis. The data from three repetitions (three batches of 50 g) were used for further process analysis.

2.2 *Chemical Analysis*

The standardized samples of bitter gourd chips were analysed for the moisture content, crude fat, crude fibre, total phenolic content, as per the standard procedure described in AOAC (AOAC 1995).

Soxhlet extraction apparatus was used for extraction the oil from the sample with petroleum ether as a solvent. The determinations were carried out in triplicate and mean value was reported. Crude fibre analyser (FIBRA Plus, Model FES2E Pelican equipment's) was used for analysis of crude fibre. 2–3 g defatted sample was weighed and extracted by 1.25% H_2SO_4 acid. The acid wash was followed by alkali wash with 1.25% NaOH, further with hot distilled water. The crucibles were dried in oven at 100 °C, weighed and were placed in muffle furnace at 500 °C for 20 min. The loss of weight is taken as the weight of crude fibre (Ranganna 2001). Total phenolics contents (TPC) of fresh bitter gourd slices and defatted bitter gourd chips were estimated calorimetrically using Folin-Ciocalteu (FC) reagent (Fang et al. 2011; Maity et al. 2017). 1 ml of the methanolic extract was mixed with 9 ml of distilled water and 1 ml of FC reagent. After 6 min, 10 ml of 7% sodium carbonate solution was added, volume was made up to 25 ml, and incubated at room temperature for 90 min, and the absorbance was measured at 750 nm using a UV–visible spectrophotometer (LABMAN). The results were expressed as gallic acid equivalents in milligrams per hundred gram dry weight (mg GAE/100 g db).

2.3 Colour Measurement

The colour was measured using Lovibond RT 300 portable reflectance spectrophotometer, using CIE $L^*a^*b^*$ (CIELAB) system. Colour was measured for bitter gourd chips of each condition and three readings were taken at different locations on the surface of each chip for each experimental condition. The colour was expressed in terms of L^*, a^* and b^* value. The total colour change ΔE, and browning index (BI) were calculated from L^*, a^* and b^* values (Diamante et al. 2010).

$$\Delta E = \left[\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2\right]^{1/2} \tag{1}$$

where $L_0{}^*$, $a_0{}^*$, $b_0{}^*$ are the initial colour values of fresh samples and L^*, a^* and b^* are the final colour values of the chips.

$$BI = \frac{[100(X - 0.31)]}{0.17} \tag{2}$$

where,

$$X = \frac{(a^* + 1.75L^*)}{(5.645L^* + a^* - 3.012b^*)}$$

2.4 Texture Analysis

The textural properties of the fried chips samples were measured using a texture analyzer (TA XT; Stable Micro Systems, London, UK), by 2 mm Cylinder Probe (P/2) using 50 kg load cell and heavy-duty Platform (HDP/90) with a holed plate. The equipment was set for pre-test speed 1.5 mm/s and post-test speed 5 mm/s. The sample was tested at test speed 0.5 mm/s, and distance of penetration 2 mm. Test results were obtained from 5 samples of each type.

2.5 Scanning Electron Microscopy

The fried chips were defatted by dipping them in petroleum ether of boiling point 40–60 °C for 2 h and powdered sample was directly loaded on carbon coated grid to see images, on SEM instrument, make-TESCAN, and model-Vega 3.

2.6 Sensory Evaluation

Fried bitter gourd chips were analysed organoleptically by a semi trained panel of members for sensory evaluation. Sensory evaluation was carried out using a nine-point hedonic scale for different attributes like appearance, flavour, colour, taste, after taste, texture and overall acceptability. The scores were assigned from liked extremely (9) to disliked extremely (1).

2.7 Statistical Analyses

All the experiments were carried out in triplicates and the values were reported as mean ± standard deviation. Statistical analysis was completed using Graph Pad Prism version 5.00 for Windows, Graph Pad Software, San Diego California USA. Analysis of variance was performed by one-way ANOVA procedure Tukey's and Bonferroni's multiple comparison tests. When $P < 0.05$ mean values were considered significantly different.

3 Moisture Sorption Isotherm Studies

3.1 Determination of Equilibrium Moisture Sorption Isotherm

Standardized samples of fried snacks were used for moisture sorption studies by keeping known weight of the sample in separate desiccators kept at different relative humidity ranging between 20.4 and 91.1% built in desiccators using appropriate saturated salt solutions at 37 °C, until equilibrium was established. The samples were withdrawn at a regular interval of one day and weighed until constant weight. Changes like softness, mold growth, and discoloration were noted on each day. The equilibrium moisture content was calculated by Wink's weight equilibrium method (Ranganna 2001) by plotting moisture sorption isotherm on graph. Critical moisture content and equilibrium moisture content was determined from the sorption isotherm.

Table 1 Sorption isotherm models

S. no.	Sorption model	Equation	Linear equation	Constants
1	Bet	$\frac{\mathrm{a_w}}{(1-\mathrm{a_w})\mathrm{M}} = \frac{1}{\mathrm{M_m}C} + \frac{1}{\mathrm{CM_m}}\left[\frac{(C-1)}{\mathrm{a_w}}\right]$	$\frac{1}{(1-\mathrm{a_w})\mathrm{M}} = \frac{1}{\mathrm{M_m}} + \frac{1}{\mathrm{CM_m}}\left[\frac{(1-\mathrm{a_w})}{\mathrm{a_w}}\right]$	$M_m C$
2	Smith	$M = \mathrm{M_b} - \mathrm{M_a}\ln(1 - a_w)$	$M = \mathrm{M_b} - \mathrm{M_a}\ln(1 - a_w)$	$M_b M_a$
3	Halsey	$\ln(a_w) = \frac{-a}{RT\emptyset_t}$	$\ln(M) = a + r(\ln\{-\ln(a_w)\})$	a, r
4	Oswin	$M = a\left(\frac{a_w}{1-a_w}\right)^n$	$\ln M = \ln a + n\ln(\frac{a_w}{1-a_w})$	n, a
5	Henderson	$\ln M = \frac{\ln[\ln\{\frac{1}{1-a_w}\}]}{B} - \frac{\{lnA\}}{B}$	$\ln M = \frac{\ln[\ln\{\frac{1}{1-a_w}\}]}{B} - \frac{\{lnA\}}{B}$	B, A
6	Kuhn	$M = \frac{a}{\ln a_w} + b$	$M = \frac{a}{\ln a_w} + b$	a, b
7	Inglesias chirife	$M = A + B\left\{\frac{a_w}{1-a_w}\right\}$	$M = A + B\left\{\frac{a_w}{1-a_w}\right\}$	B, A
8	Freundlich	$M = A(a_w)^{1/D}$	$\ln M = \ln A + \frac{1}{b}\ln a_w$	A, b

3.2 *Moisture Sorption Isotherm Model Analysis*

Sorption isotherm model equations such as Brumauer–Emmet–Teller (BET), Halsey, Smith, Oswin, Kuhn, Henderson, Iglesias and Chirife, and Freundlich were used to fit the experimental data of fried chips sorption isotherm. Linear form of equations were used as per Table 1 and appropriate constants by regression analysis using MS-Excel software were determined (Jagadish and Raj 2013). The sorption data were analyzed as per the models and equivalent constants were determined.

4 Accelerated Shelf-Life Studies of Bitter Gourd Chips

4.1 *Determination of Half Value Period*

Determination of shelf life was carried out by Breakdown method as per the procedure in Ranganna (2001). Metalized polyester laminated pouches having WVTR of 2.26 g/m^2/day and Aluminum laminated pouches having WVTR of 4.23 g/m^2/day were used for the determination of shelf life. The samples were packaged in pockets of size 10 cm × 6.5 cm, sealed properly for conducting the shelf stability studies. Accurately weighed packed pouches were placed in two different conditions for storage. Initial moisture content (M_0) before packing was determined and pouches were stored at storage conditions ambient 25 °C, 75% RH and accelerated, 38 °C and 90% RH.

One pouch was withdrawn at an interval of 7 days and analyzed for weight gain and moisture content on the dry basis of the sample and the mean value (M) was measured. Finally, one packet was opened, and the contents were exposed to the storage atmosphere, till equilibrium was achieved, and the equilibrium moisture content (M_e) was noted. The slope of the plot of log (Me–M) against time, days of storage was calculated. HVP was calculated using the expression:

$$\mathrm{HVP} = \log 2/\mathrm{slope.} = 0.3010/\mathrm{S}$$

4.2 Determination of Shelf Life from Half Value Period

Shelf life at ambient or accelerated storage was derived from the graph plotted against log [Me–M] versus time in days. The first point being log [Me–Mo] corresponding to 0 days and second point is log [Me–MHVP] corresponding to half value period. MHVP is moisture corresponding to HVP, and calculated as MHVP = 1/2(Mo + Me). Shelf life is calculated by the time corresponding to the value of log (Me–Mc) on the time scale, where Mc is critical moisture content. Packaging constant k for different product and packaging material was calculated from these observations:

$$\mathrm{HVP\ at\ t\,^{\circ}C} = \mathrm{HVP\ at\ T\,^{\circ}C} \times \left(\frac{\text{Vapour pressure of water at } T\ ^{\circ}\mathrm{C}}{\text{Vapour pressure of water at } t\ ^{\circ}\mathrm{C}}\right)^{k}$$

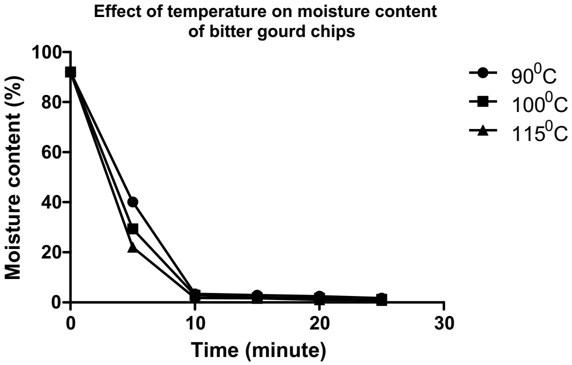
T Temperature used in the determination of HVP.
t Average temperature to which the products will exposed during transit and storage.
k Packaging constant.

5 Results and Discussion

5.1 Moisture Content

Figure 2 shows the moisture loss from bitter gourd slices vacuum fried at 3 different frying oil temperatures (90, 100 and 115 °C). The moisture loss during vacuum frying followed a standard drying curve. Similar findings have been obtained with vacuum frying of potato chips and jackfruit bulb slices. Within the first 5 min, 57, 68, and 76% of moisture was lost while frying at temperatures 90, 100 and 115 °C respectively. At all frying temperatures, moisture content of the bitter gourd slices dropped suddenly just after 5 min. This is due to the fact that in vacuum frying, the sample's water immediately begins to boil and escapes as vapours as soon as it is submerged in the

Fig. 2 Effect of different temperatures on moisture content of vacuum fried bitter gourd chips

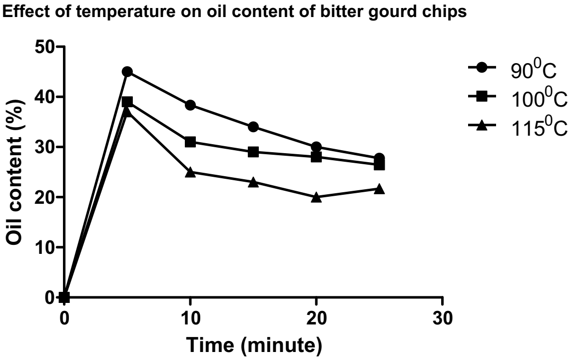


oil. When experiments were conducted, the sample was at room temperature, which reduced the amount of time required for the sample to warm up to the boiling point of water (42 °C at 9 kPa) is minimized. The final moisture content of vacuum fried bitter gourd chips at temperatures 90, 100 and 115 °C was 1.73, 1.23, and 0.83% respectively. The vacuum frying temperature had no significant impact ($P > 0.05$) on the moisture content. It was discovered that the atmospherically fried bitter gourd chips had a moisture content of 2.52%.

5.2 Oil Content

As depicted in (Fig. 3) oil content of vacuum fried bitter gourd chips at 90–115 °C was found to be in the range of 21.67–27.76% which was reasonably less than atmospherically fried products 40% (Sobukola et al. 2013). The vacuum frying at 115 °C produced the lowest oil content vacuum fried bitter gourd chips than the ones at 90 and 100 °C. Similar performance was observed by Garayo and Moreira (2002) in the vacuum frying of potato chips and by Andrés-Bello et al. (2010) in the vacuum frying of gilthead sea bream fillets. They came to the conclusion that more oil absorption resulted from higher oil adherence on the surface of the chips and faster rates of water loss. Together, less oil is absorbed as the product's percentage of free water decreases (Andrés-Bello et al. 2010; Garayo and Moreira 2002). During frying, oil content in the bitter gourd chips increased initially but decreased with time for all frying temperatures. The results are in the same pattern as reported in vacuum frying of breaded shrimp (Pan et al. 2015). Oil content decreased progressively for lower temperature, as compared to higher temperature, 115 °C. Final oil content of bitter gourd chips was not significantly affected ($P > 0.05$) by frying temperature. Oil absorption happens during the pressurisation stage of vacuum frying because the sudden rise in pressure following vacuum release is greater than ambient pressure, which forces the surface oil into the product. In order to maintain a low oil content,

Fig. 3 Effect of different temperatures on oil content of vacuum fried bitter gourd chips



centrifugation is required after vacuum frying. These results are in conformity with the literature observation (Diamante et al. 2015).

5.3 Crude Fibre Content

The crude fibre content of raw bitter gourd was found to be 17.86% on dry weight basis. The reduction of moisture during frying increased the concentration of fibre, resulting in an increase in fibre content in bitter gourd chips. Similar observations were reported for plantain, yam and *Colocasia esculenta* (Agoreyo et al. 2011). As seen from (Table 2) crude fibre contents of vacuum fried bitter gourd chips at 90, 100 and 115 °C were found to be 15.92, 13.46, and 11.52%, respectively. The decrease in crude fibre content of bitter gourd chips was 10, 32 and 38% for chips fried at 90, 100 and 115 °C respectively. The crude fibre content of atmospherically fried bitter gourd chips was found to be 10.57%. The increasing temperature induces breaking of weak connections between polysaccharide chains and glycosidic linkages in the dietary fibre polysaccharides, reducing the crude fibre concentration. The depolymerisation of the fibre leads in its solubilisation (Lola 2009). Significant decrease in crude fibre content ($P < 0.05$) were observed during frying at higher temperature.

5.4 Total Phenolic Content

Phytochemicals that include phenolics contribute significantly to the improvement of health benefits (Simões et al. 2009). Due to their extreme instability, polyphenols are susceptible to degradation during processing. Results for total phenolic content (TPC) for raw and fried bitter gourd chips are shown in (Table 2). From the results, it can be observed that there is an increase in TPC of fried bitter gourd chips. The atmospherically fried chips showed highest TPC 4413 mg GAE/100 g as compared to

Table 2 Values of moisture, oil, crude fibre, and total phenolic content (TPC) of vacuum fried bitter gourd chips

S. no.	Temperature	Time (min)	Moisture (% db)	Oil (% db)	Crude fibre (% db)	TPC (mg GAE/100 g)
1	Raw bitter gourd		90.10 ± 0.85	1.95 ± 0.32	17.86 ± 0.77	2011 ± 1.25
2	90 °C	25	1.73 ± 0.64^a	27.76 ± 0.36^a	15.92 ± 0.29^a	2573 ± 0.54^a
3	100 °C	25	1.23 ± 0.48^a	26.45 ± 0.27^a	13.46 ± 0.36^b	3116 ± 2.82^b
4	115 °C	25	0.83 ± 0.22^a	21.67 ± 0.06^a	11.52 ± 0.45^c	3828 ± 1.69^c
5	Atmospheric fried 170 °C	07	2.52 ± 0.32^b	40.64 ± 0.47^b	10.57 ± 0.86^c	4413 ± 0.83^d

Values are average ± standard deviation, n = 3
Values with the superscripts a, b, c for any given column represents significant differences ($P < 0.05$)

2011 mg GAE/100 g of raw bitter gourd. Vacuum fried chips fried at 115 °C showed 3828 mg GAE/100 g. The increase in TPC was ranged from 127.95, 154.95, 190.35, and 219.44% in vacuum fried bitter gourd chips at, 90, 100, 115 °C and atmospherically fried chips. Similar results were reported by Alloush, S and Salem, A for beans, drumstick and bitter gourd. They reported 202.62 and 260.30% increase in TPC in open cooked and pressure cooked bitter gourd (Alloush and Salem 2014). Vegetables contain phenolic substances in both soluble and cell-wall complexed forms. The overall phenolic content of vegetables changes significantly after cooking (Saikia 2013). There could be an increase or a loss of phenolic compounds. Cooking-related phenolic degradation may be responsible for the loss (Turkmen and Sari 2005). The gain may be due to release of free phenolic compounds from decomposition of some polyphenols bound to dietary fibre of vegetables (Stewart et al. 2000).

Polyphenol oxidase and other oxidising enzymes are typically rendered inactive by heat treatment, which slows down the oxidation of phenolic compounds upon exposure to the environment. Since these enzymes prevent phenolic loss, their deactivation results in an increase in total phenolic content (Yamaguchi et al. 2001).

5.5 Colour

L* is a critical metric for the frying business since it is the first quality attribute that consumers notice and consider when deciding whether or not to buy a product (Dueik and Bouchon 2011). As shown in (Table 3), L^* value decreased from 75.82 to 57.67 as temperature increased from 90 to 115 °C.

Table 3 Mean values of L^*, a^*, b^*, ΔE and BI values of vacuum fried bitter gourd chips

S. no.	Temperature	L^*	a^*	b^*	ΔE	BI	Breaking force (g)
1	Raw bitter gourd	84.27 ± 0.43^a	-2.82 ± 0.42^a	16.47 ± 2.34^a	–	19.97 ± 0.02^e	90.92 ± 0.92^a
2	90 °C	75.82 ± 4.1^b	-2.19 ± 0.52^a	30.24 ± 4.53^b	13.85 ± 0.01^a	42.25 ± 0.06^a	350.6 ± 24.56^b
3	100 °C	68.89 ± 4.33^b	2.41 ± 2.4^b	31.67 ± 2.5^b	23.30 ± 0.05^b	66.97 ± 0.06^b	291.1 ± 11.83^{bc}
4	115 °C	57.67 ± 2.67^c	10.76 ± 0.3^c	34.09 ± 6.5^b	34.54 ± 0.26^c	98.69 ± 0.21^c	167.50 ± 4.91^d
5	Atmospheric frying	41.44 ± 2.19^c	15.31 ± 2.9^d	23.70 ± 5.9^{ab}	46.93 ± 0.16^d	108.24 ± 0.08^d	112.6 ± 20.41^{ad}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c for any given column represents significant differences ($P < 0.05$)

Statistical analysis showed that there were significant differences ($p < 0.05$) for L^* lightness values of raw bitter gourd, vacuum fried bitter gourd chips and atmospherically fried bitter gourd chips. Only for vacuum fried bitter gourd chips, fried at 90 and 100 °C, L* values were not significantly different. There were no significant differences for b* value except for raw bitter gourd and atmospherically fried Bitter gourd. There were no significant differences in L* and b* values of vacuum fried bitter gourd chips fried at 90 and 100 °C. But for the product fried at 115 °C, b* values were not significant whereas L* and a* values were significantly different ($p < 0.05$). Vacuum frying did not affect significantly b^* values ($P > 0.05$) at temperature 90, 100 and 115 °C, however differences were significant ($P < 0.05$) for samples fried at 115 °C and atmospheric frying. (Table 3) depicts the results of a^* value, demonstrates the increase in value from −2.83 to 10.76 for temperature from 90 to 115 °C respectively. The vacuum-fried bitter gourd chips' a* values considerably increased (P 0.05), with an increase in frying temperature having a significant impact on browning reactions.

The difference in colour between raw (L_0^*, a_0^*, b_0^*) and fried (L^*, a^*, b^*) bitter gourd slices was calculated using equation no. 1, to examine the overall effects of the frying procedure on the product's colour. Lower ΔE values obtained for bitter gourd chips vacuum fried at 90 °C, but the change in colour values were affected significantly ($P < 0.05$). With increase in frying temperature and time browning index calculated by formula (2) revealed significant increase. The results of our study were similar to that reported by Diamante et al. (2012) for vacuum fried chips of kiwifruit.

5.6 Texture

Texture of a fried product is an important parameter to decide the acceptability of a product. As shown in (Table 5), breaking force related to hardness was significantly affected by frying process and temperature. The bitter gourd slices' texture changed as a result of the majority of the water being removed during frying. Significant differences ($P < 0.05$) were found between the force required at 90, 115 °C, and the atmospherically fried sample. Texture of bitter gourd chips as evaluated by sensory evaluation illustrate that chips vacuum fried at 115 °C were accepted with the highest score of 7.60 on 9-point hedonic scale.

5.7 Structural Changes

Comparing vacuum-fried bitter gourd chips to chips that were fried atmospherically, scanning electron microscopy showed that vacuum-fried chips had a more porous structure. This may be attributed to the fast removal of water. There were no prominent differences between the structural patterns of bitter gourd chips fried by different processes. This is also supported by the fact that no significant differences

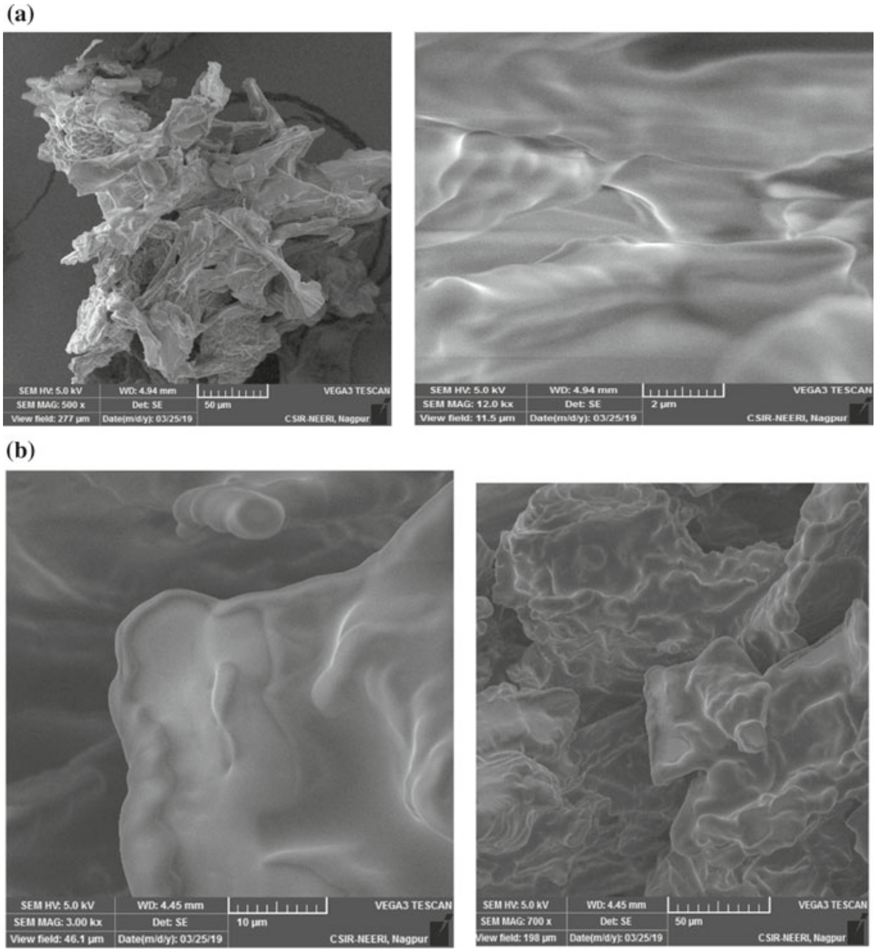


Fig. 4 **a** Effect of frying on microstructure of vacuum fried bitter gourd chips. **b** Effect of frying on microstructure of atmospheric fried bitter gourd chips

were found between the crude fibre content of bitter gourd chips fried by different processes (Fig. 4a, b).

5.8 Sensory Evaluation

The panellists preferred the vacuum-fried bitter gourd chips for colour, texture, flavour, taste and overall quality for the sample fried at 115 °C and 25 min.

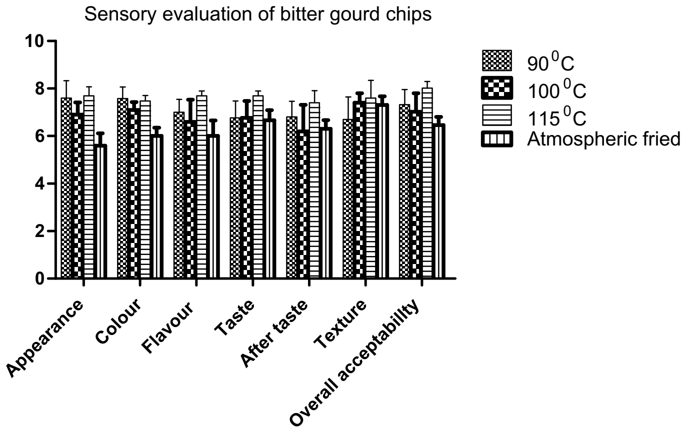


Fig. 5 Sensory evaluation of vacuum and atmospheric fried bitter gourd chips

The sensory evaluation of bitter gourd chips (Fig. 5) showed that chips vacuum fried at 115 °C scored highest points, on nine-point hedonic scales. Significant differences were found for atmospheric and vacuum fried bitter gourd chips. Vacuum fried bitter gourd chips fried at 115 °C scored highest points 8.02 among all other samples. The findings of the sensory evaluation revealed that the majority of the panelists considered the texture of bitter gourd chips as the superior factor. Temperature of the process showed significant effect, $P < 0.05$, on sensory scores of bitter gourd chips. The sensory score for colour of bitter gourd chips was found to increase from 6.0 to 7.58 from atmospheric frying to vacuum frying at 90 °C. The results of colour analysis, lightness and redness determined by colorimeter were also validated by sensory evaluation results provided by panel members.

Crispiness is an important textural characteristic in determining the quality of chips (Krokida et al. 2001). Sensory scores for texture were highest 7.60 on 9-point hedonic scale for chips vacuum fried at 115 °C as compared to 6.7 at 90 °C. The sensory scores for flavour of bitter gourd chips fried at different temperatures were significantly affected ($p < 0.05$). The sensory scores for flavour of bitter gourd chips were lowest, 6.0 for atmospherically fried chips and highest 7.70 for chips vacuum fried at 115 °C. This may be because of volatile nature of flavour compounds which escapes during frying at high temperature. Sensory evaluation results suggested that the overall acceptability of bitter gourd chips fried at 115 °C for 25 min was highest with a score of 8.02 on the scale of 9. These chips with highest acceptability were selected for sorption and shelf life studies.

6 Moisture Sorption Isotherm Studies

6.1 *Equilibrium Moisture Sorption Isotherm Studies of Vacuum and Atmospheric Fried Bitter Gourd Chips*

The moisture absorption isotherm for vacuum fried bitter gourd chips at 37 °C was plotted as represented in (Fig. 6). The isotherm showed typical type II sigmoid shape, common to most food products. Sorption isotherms of vacuum fried carrot chips also showed sigmoid isotherm (Liu-Ping et al. 2005). The critical moisture content was found to be 7.0% which corresponds to Relative Humidity (RH) 20%. Chips gained moisture quickly and become soft when RH was more than 20%. There was a steep rise in the isotherm beyond RH 75%. The absorption isotherm of bitter gourd chips showed three regions of a typical isotherm I, II and III corresponding to RH 0–20%, RH 20–75% and RH above 75%. In region III, water is in free state, held into voids, capillaries and crevices and available to chemical and microbial reactions (Hossain et al. 2002). The absorption isotherm of atmospheric fried bitter gourd chips (Fig. 7) also showed three regions of a typical sigmoid isotherm. Region I correspond to RH 0–40%, region II corresponding to RH 40–75%, and region III corresponding RH above 75%. The critical moisture content was found to be 7.5%. Above this RH chips gained moisture quickly and became soft. At relative humidity above 75%, there was a steep rise in the isotherm.

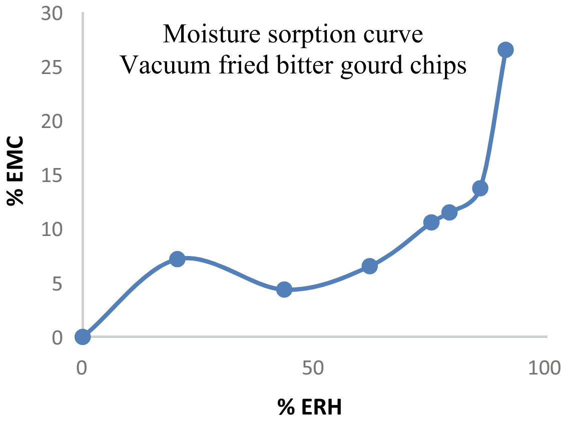


Fig. 6 Moisture sorption isotherm for vacuum fried bitter gourd chips using salt solutions of various RH

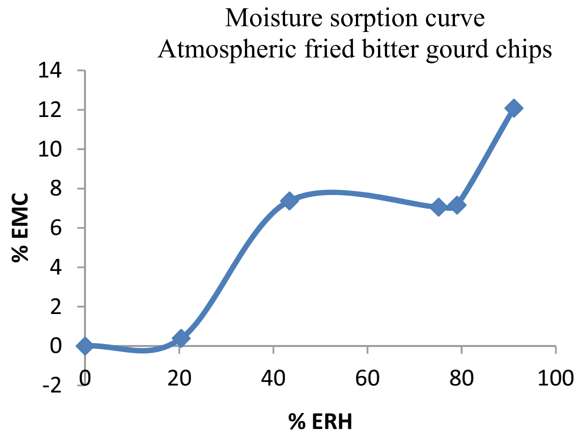


Fig. 7 Moisture sorption isotherm for atmospheric fried bitter gourd chips using salt solutions of various RH

6.2 Moisture Sorption Isotherm Model Analysis of Vacuum Fried Bitter Gourd Chips

Various sorption models were applied for the fitting of experimental moisture sorption data to linear fitting equations and constants of different models were computed. Coefficient of determination R^2 values of linear models were determined as shown in (Table 4). The values of coefficient of determination R^2 ranging from 0.96 to 0.99 confirms the applicability of the equations.

The B.E.T constants, M_m and C were computed from a linear plot. The experimental sorption data applied to BET model for vacuum fried bitter gourd chips was found to fit well for aw in the range 0.2–0.6. Chirife and Iglesias (1978) have demonstrated that the BET equation holds well between water activities for 0.05–0.45, which is comparable to the above findings. The monomolecular moisture parameter of BET equation M_m was found to be 2.12, which is important for shelf-life studies. From a linear regression of M versus ln (1–aw), the Smith constants M_b and M_a were computed from the intercept and slope of the line. The Smith model holds well for aw in the range of 0.4–0.86 for vacuum fried bitter gourd chips with $R^2 = 0.99$. This was in agreement with the result of reported literature (Srinivasa et al. 2003, 2007; Sudhamani et al. 2005).

6.3 Moisture Sorption Isotherm Model Analysis of Atmospheric Fried Bitter Gourd Chips

Various sorption models applied for the fitting of experimental moisture sorption data yielded the results as shown in (Table 5). The high coefficient of determination R^2 ranging from 0.74 to 0.98 confirms the applicability of the equations employed.

Table 4 Sorption isotherm model constants and coefficient of determination (R^2) from linear fitting equations for vacuum fried bitter gourd chips

S. no.	Sorption model	Equation	Range of a_w	Constants by linear fitting of sorption isotherms		R^2
				M_m	C	
1	Bet	$y = -0.0742x + 0.4706$	0.2–0.6	2.124	−6.342	0.96
2	Smith	$y = -7.1341x + 0.183$	0.4–0.86	M_b	M_a	0.99
				0.183	−7.134	
3	Halsey	$y = -0.786x + 1.3147$	0.4–0.91	A	R	0.98
				1.314	−0.786	
4	Oswin	$y = 0.6643x + 1.5942$	0.4–0.91	A	N	0.97
				4.92	0.664	
5	Henderson	$y = 0.9275x + 0.9754$	0.4–0.91	B	A	0.98
				1.078	2.862	
6	Kuhn	$y = -2.2214x + 1.7786$	0.4–0.91	B	A	0.98
				1.778	−2.221	
7	Inglesias Chirife	$y = 2.2331x + 2.7757$	0.4–0.91	A	B	0.98
				2.775	2.233	
8	Freundlich	$y = 1.7011x + 2.8328$	0.4–0.86	A	B	0.97
				14.53	−1.48	

Constants for all 8 models were derived from linear graphs as seen from (Table 5). From a linear plot of 1/[(1–aw) *M] versus [(1–aw)/aw], the B.E.T constants, Mm and C were computed. The monomolecular moisture parameter of BET equation Mm was found to be 6.1, is important for shelf-life studies. Linear models with high R^2 are considered to be statistically acceptable.

7 Accelerated Shelf-Life Studies of Bitter Gourd Chips

For shelf-life studies, metalized polyester packaging material with WVTR of 2.26 g/m^2/day was used. The samples were packaged in sealed pockets of size 6.5 cm × 10 cm, for conducting the shelf stability studies. Accurately weighed packed pouches were placed in two different conditions for storage. Initial moisture content (M_0) before packing was determined and pouches were stored at following storage conditions: (1) Ambient: 25 °C and 75% RH. (2) Accelerated: 38 °C and 91% RH. One pouch was withdrawn at an interval of 7 days and analyzed for moisture, texture, colour, free fatty acids and Peroxide value.

Table 5 Sorption isotherm model constants and coefficient of determination (R^2) from linear fitting equations for atmospheric fried bitter gourd chips

S. no.	Sorption model	Equation	Range of aw	Constants by linear fitting of sorption isotherms		R^2
				M_m	C	
1	Bet	$y = 0.8019x - 0.164$	0.2–0.75	6.10	0.2044	0.87
2	Smith	$y = -4.281x + 1.4705$	0.2–0.91	M_b	M_a	0.74
				1.470	−4.281	
3	Halsey	$y = -0.5064x + 1.2825$	0.75–0.91	A	R	0.98
				1.282	−0.506	
4	Oswin	$y = 0.4659x + 1.3996$	0.75–0.91	A	N	0.98
				4.053	0.465	
5	Henderson	$y = 0.5513x + 1.1511$	0.75–0.91	B	A	0.98
				1.81	8.068	
6	Kuhn	$y = -0.5591x + 5.669$	0.43–0.91	B	A	0.87
				5.669	−0.559	
7	Inglesias chirife	$Y = 0.5628x + 5.915$	0.43–0.91	A	B	0.87
				5.91	0.562	
8	Freundlich	$y = 2.9801x + 2.75$	0.75–0.91	A	B	0.95
				15.642	0.335	

7.1 Vacuum Fried Bitter Gourd Chips Packed in Metalized Polyester at 38 °C, 91% RH

The changes in moisture, texture, and colour values of bitter gourd chips packed in metalized polyester packets and stored at accelerated and ambient temperature conditions, are shown in (Table 6). As seen from this table, moisture content of vacuum fried bitter gourd chips packed in metalized polyester, stored at 38 °C, 91% RH increased from 1.42% to 10.53% after 28 days. Chips crossed critical moisture content after the 7th day and became soft. Significant differences ($P < 0.05$) were observed for the initial moisture content and final moisture content. There were no significant differences between the moisture content of 21st and 28th day. The hardness of bitter gourd chips decreased from 167.5 g to 127.67 g on 28th day. Hardness of bitter gourd chips decreased significantly ($P < 0.05$) right from the 14th day. There was no change in L* value for the first 21 days, after that significant change in colour was observed. Significant differences were found in a* value from the 7th day. Change in b* colour value was not significant between 1st and 28th day. Free fatty acid content of bitter gourd chips increased from 0.12% on the first day to 0.92% on the 28th day of storage, and change significantly. The primary products of lipid oxidation are hydro peroxides therefore, determination of peroxide value can

Table 6 Changes in moisture, texture, colour values, FFA and PV of vacuum fried bitter gourd chips at 38 °C, 91% RH in Metalized polyester packets

S. no.	Metalized polyester		38 °C, 91% RH			
	Parameter	0 day	7 days	14 days	21 days	28 days
1	Moisture %	1.42 ± 0.03^{a}	3.60 ± 0.51^{b}	7.31 ± 0.25^{c}	9.43 ± 0.15^{d}	10.53 ± 0.79^{ed}
2	Hardness g	167.50 ± 4.9^{a}	165.0 ± 5.20^{a}	147.3 ± 9.45^{b}	134.7 ± 6.03^{c}	127.67 ± 6.5^{d}
3	L*	58.95 ± 2.1^{a}	56.16 ± 2.83^{a}	52.93 ± 3.26^{a}	51.10 ± 3.10^{a}	50.02 ± 2.79^{b}
4	a*	10.71 ± 0.11^{a}	13.73 ± 0.10^{b}	14.74 ± 0.66^{cb}	15.10 ± 0.76^{dc}	15.23 ± 0.80^{dc}
5	b*	35.14 ± 0.95^{a}	35.20 ± 0.98^{a}	35.78 ± 1.03^{a}	36.83 ± 1.30^{a}	37.57 ± 1.59^{a}
6	FFA	0.12 ± 0.03^{a}	0.23 ± 0.04^{b}	0.43 ± 0.06^{c}	0.63 ± 0.06^{d}	0.92 ± 0.07^{e}
7	PV	0.86 ± 0.05^{a}	2.65 ± 0.14^{b}	4.47 ± 0.24^{c}	6.88 ± 0.37^{d}	8.55 ± 0.46^{e}

Values are average ± standard deviation, n = 3
Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

be used as an oxidation index for the early stages of lipid oxidation (Amany et al. 2012). The peroxide value changed significantly ($P < 0.5$) from 1st day to 28th day. (Shyu et al. 1998) observed similar results and found that peroxide value increased linearly with frying time for all three oils under investigation during vacuum frying of carrot slices (Shyu et al. 1998).

7.2 Atmospheric Fried Bitter Gourd Chips Packed in Metalized Polyester at 38 °C, 91% RH

As seen from (Table 7) moisture content of atmospheric fried bitter gourd chips packed in metalized polyester pouches, stored at 38 °C, 91% RH increased from 2.52% to 7.76% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content on day one and final moisture content on 28th day. The hardness of bitter gourd chips decreased from 112 g on day one to 90 g on 28th day. For the first 14 days hardness does not reduce considerably. Significant changes in hardness of bitter gourd chips were observed from 21st day ($P < 0.05$) onwards. No significant differences were observed for L* values till the 21st day. L* value decreased significantly ($P < 0.05$) after 3rd week. The a* value did not change till 14th day, after 21st day a* value change significantly ($P < 0.05$). The b* value does not change significantly throughout the study. Free fatty acid content increased from 0. 35% to 1.64% and change significantly. During frying, fats and oils are oxidized to form hydro peroxides, which further decomposes to produce the secondary oxidation products, such as aldehydes, alcohols, ketones, and acids. In deep-fat frying, by the reaction of fat with water resulted to form free fatty acid (Shyu et al. 1998). The peroxide value increased from the initial value 1.22 to 9.48 meq/kg on the 28th day. The peroxide value changed significantly ($P < 0.05$).

Table 7 Changes in moisture, texture, colour values, FFA and PV of atmospheric fried bitter gourd chips at 38 °C, 91% RH in Metalized polyester packets

S. no.	Metalized polyester		38 °C, 91% RH			
	Parameter	0 day	7 days	14 days	21 days	28 days
1	Moisture %	2.52 ± 0.09^{a}	3.56 ± 0.13^{b}	5.42 ± 0.21^{c}	6.86 ± 0.26^{d}	7.76 ± 0.29^{e}
2	Hardness g	112.67 ± 5.2^{a}	109.0 ± 5.07^{a}	100.0 ± 4.7^{ab}	96.06 ± 4.5^{b}	90.06 ± 4.19^{b}
3	L*	41.48 ± 2.21^{a}	40.38 ± 2.15^{a}	39.57 ± 2.11^{a}	37.60 ± 2.01^{a}	34.68 ± 1.85^{b}
4	a*	15.32 ± 0.82^{a}	16.57 ± 0.88^{a}	17.46 ± 0.93^{ab}	18.45 ± 0.98^{b}	19.88 ± 1.06^{b}
5	b*	23.72 ± 1.26^{a}	22.89 ± 1.22^{a}	21.36 ± 1.14^{a}	21.25 ± 1.13^{a}	20.47 ± 1.09^{a}
6	FFA	0.35 ± 0.02^{a}	0.54 ± 0.02^{b}	0.90 ± 0.05^{c}	1.23 ± 0.06^{d}	1.64 ± 0.08^{e}
7	PV	1.22 ± 0.06^{a}	3.43 ± 0.18^{b}	5.67 ± 0.30^{c}	7.57 ± 0.41^{d}	9.48 ± 0.51^{e}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

7.3 *Vacuum Fried Bitter Gourd Chips Packed in Metalized Polyester at 25 °C, 75% RH*

As seen from (Table 8), moisture content of vacuum fried bitter gourd chips packed in metalized polyester, stored at 25 °C, 75% RH increased from 1.42% to 5.55% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content on day one and final moisture content on 28th day. Moisture content increased significantly throughout the study up-to 28 days.

The hardness of bitter gourd chips decreased from 167 g on day one to 141 g on 28th day. Significant changes in hardness of bitter gourd chips were observed from

Table 8 Changes in moisture, texture, colour values, FFA and PV of vacuum fried bitter gourd chips at 25 °C, 75% RH in Metalized polyester packets

S. no.	Metalized polyester		25 °C, 75% RH			
	Parameter	0 day	7 days	14 days	21 days	28 days
1	Moisture %	1.42 ± 0.06^{a}	2.65 ± 0.14^{b}	3.73 ± 0.14^{c}	4.86 ± 0.18^{d}	5.55 ± 0.17^{e}
2	Hardness g	167 ± 4.9^{a}	166.6 ± 1.52^{a}	158.66 ± 1.52^{b}	147.6 ± 2.08^{c}	141.0 ± 2.6^{dc}
3	L*	58.96 ± 2.1^{a}	58.45 ± 2.72^{a}	57.70 ± 2.70^{a}	57.82 ± 2.75^{a}	57.24 ± 2.63^{a}
4	a*	10.71 ± 0.11^{a}	11.44 ± 0.27^{b}	11.57 ± 0.26^{cb}	12.23 ± 0.28^{dc}	13.06 ± 0.25^{e}
5	b*	35.14 ± 0.95^{a}	36.54 ± 0.68^{a}	38.54 ± 0.60^{b}	39.59 ± 0.31^{b}	39.82 ± 0.26^{b}
6	FFA	0.11 ± 0.03^{a}	0.18 ± 0.03^{a}	0.24 ± 0.05^{b}	0.34 ± 0.04^{c}	0.48 ± 0.03^{d}
7	PV	0.86 ± 0.05^{a}	1.79 ± 0.18^{b}	3.68 ± 0.16^{c}	5.35 ± 0.22^{d}	6.71 ± 0.26^{e}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

1st to 28th day ($P < 0.05$). No significant differences were observed for L* value for 28 days. The a* value increased from 10.71 to 13.06 after 28 days. The b* value does not change significantly for the first 7 days. Significant difference was observed in b* value from 14th day onward. Change in b* colour value was not significant between 14 and 28th day. Free fatty acid content increased from 0.11% to 0.48% after 28 days. Free fatty acid content does not change significantly for first 7 days and thereafter change significantly ($P < 0.05$). The peroxide value increased from initial value of 0.86 to 6.71 meq/kg. The peroxide value changed significantly from the first day to 28th day. The peroxide value increased linearly with storage days. The rate of increase of PV is less at ambient condition as compared to accelerated condition, i.e., 38 °C and 91% RH.

7.4 Atmospheric Fried Bitter Gourd Chips Packed in Metalized Polyester at 25 °C, 75% RH

As seen from (Table 9) moisture content of atmospheric fried bitter gourd chips packed in metalized polyester pouches, stored at 25 °C, 75% RH increased from 2.52% to 5.46% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content on day one and final moisture content on 28th day. The hardness of bitter gourd chips decreased from 112 g on day one to 100 g on 28th day. No significant changes in hardness of bitter gourd chips were observed ($P < 0.05$). No significant differences were observed for L* values. The a* and b* value does not change significantly up-to 28 days. Free fatty acid content increased from 0. 35% to 0.98%. There was no significant difference ($P > 0.05$) between FFA of 21st and 28th day. Peroxide value increased from 1.22 to 8.34 meq/kg after 28 days.

Table 9 Changes in moisture, texture, colour values, FFA and PV of atmospheric fried bitter gourd chips at 25 °C, 75% RH in Metalized polyester packets

S. no.	Metalized polyester		25 °C, 75% RH			
	Parameter	0 day	7 days	14 days	21 days	28 days
1	Moisture %	2.52 ± 0.09^{a}	2.85 ± 0.04^{b}	3.94 ± 0.06^{c}	4.65 ± 0.22^{d}	5.46 ± 0.01^{e}
2	Hardness g	112.67 ± 5.2^{a}	111.57 ± 5.2^{a}	109.63 ± 5.11^{a}	105.44 ± 4.91^{a}	100.07 ± 4.66^{a}
3	L*	41.48 ± 2.21^{a}	41.36 ± 2.21^{a}	40.47 ± 2.16^{a}	40.02 ± 2.13^{a}	39.66 ± 2.12^{a}
4	a*	15.32 ± 0.81^{a}	15.88 ± 0.85^{a}	16.45 ± 0.88^{a}	16.86 ± 0.90^{a}	17.69 ± 0.94^{a}
5	b*	23.73 ± 1.27^{a}	23.36 ± 1.25^{a}	22.90 ± 1.22^{a}	23.52 ± 1.25^{a}	24.69 ± 1.32^{a}
6	FFA	0.35 ± 0.02^{a}	0.58 ± 0.03^{b}	0.68 ± 0.04^{c}	0.89 ± 0.04^{d}	0.98 ± 0.53^{e}
7	PV	1.22 ± 0.06^{a}	2.42 ± 0.13^{b}	4.56 ± 0.24^{c}	6.23 ± 0.33^{d}	8.34 ± 0.45^{e}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

Table 10 Changes in moisture, texture, colour values, FFA and PV of vacuum fried bitter gourd chips at 38 °C, 91% RH in Laminated Aluminium packets

S. no.	Laminated aluminium		38 °C, 91% RH			
	Parameters	0 days	7 days	14 days	21 days	28 days
1	Moisture %	1.150 ± 0.44^{a}	3.43 ± 0.13^{b}	6.62 ± 0.25^{c}	9.45 ± 0.35^{d}	11.12 ± 0.42^{e}
2	Hardness g	167.50 ± 4.9^{a}	146.09 ± 6.8^{b}	138.09 ± 6.4^{c}	130.0 ± 6.0^{dc}	125.08 ± 5.82^{e}
3	L*	58.95 ± 2.1^{a}	56.93 ± 3.24^{a}	53.37 ± 3.7^{a}	50.08 ± 2.9^{b}	48.36 ± 2.80^{b}
4	a*	10.71 ± 0.1^{a}	12.66 ± 0.67^{a}	13.44 ± 0.72^{b}	14.90 ± 0.79^{cb}	15.92 ± 0.85^{c}
5	b*	35.14 ± 0.95^{a}	36.77 ± 0.47^{a}	37.44 ± 0.48^{b}	38.64 ± 0.49^{cb}	39.04 ± 0.50^{c}
6	FFA	0.11 ± 0.01^{a}	0.35 ± 0.02^{b}	0.58 ± 0.31^{c}	0.74 ± 0.04^{d}	0.90 ± 0.04^{e}
7	PV	0.86 ± 0.05^{a}	3.05 ± 0.16^{b}	5.65 ± 0.3^{c}	7.76 ± 0.42^{d}	9.45 ± 0.51^{e}

Values are average ± standard deviation, n = 3

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

7.5 *Vacuum Fried Bitter Gourd Chips Packed in Laminated Aluminium at 38 °C, 91% RH*

As seen from (Table 10), moisture content of vacuum fried bitter gourd chips packed in aluminium pouches, stored at 38 °C, 91% RH increased from 1.15% to 11.12% after 28 days. The bitter gourd chips gain moisture from the 7th day. Significant differences ($P < 0.05$) were observed for the initial moisture content on day one and final moisture content on 28th day. The hardness of bitter gourd chips decreased from 167.5 g on day one to 125.08 g on 28th day. Significant changes in hardness of bitter gourd chips were observed from 1st to 28th day ($P < 0.05$). No significant differences were observed for L* values till the 21st day. L* value decreased significantly ($P < 0.05$) after 3rd week. The a* value increased from 10.71 to 15.92 on 28th day. The a* and b* value change significantly from 14th day. Free fatty acid content increased from 0. 11% to 0.90% and does not change significantly. The peroxide value increased from 0.86 to 9.45 meq/kg on 28th day. Peroxide value of chips packed in Laminated Aluminium increased faster as compared to metalized polyester when stored at same conditions.

7.6 *Atmospheric Fried Bitter Gourd Chips Packed in Laminated Aluminium at 38 °C, 91% RH*

As seen from (Table 11) moisture content of atmospheric fried bitter gourd chips packed in laminated Aluminium pouches, stored at 38 °C, 91% RH increased from 2.52% to 9.39% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content and final moisture content on 28th day. The hardness of bitter gourd chips decreased from 112 g on day one to 85 g on 28th day. Hardness

Table 11 Changes in moisture, texture, colour values, FFA and PV of atmospheric fried bitter gourd chips at 38 °C, 91% RH in Laminated Aluminium packets

S. no.	Laminated aluminium		38 °C, 91% RH			
	Parameters	0 days	7 days	14 days	21 days	28 days
1	Moisture %	2.52 ± 0.09^{a}	3.76 ± 0.14^{b}	5.48 ± 0.21^{c}	7.43 ± 0.28^{d}	9.39 ± 0.36^{e}
2	Hardness g	112.67 ± 5.25^{a}	102.38 ± 4.77^{a}	96.38 ± 4.49^{b}	90.40 ± 4.21^{b}	85.62 ± 3.97^{b}
3	L*	41.48 ± 2.22^{a}	39.70 ± 2.12^{a}	37.70 ± 2.02^{a}	34.83 ± 1.8^{b}	33.71 ± 1.80^{c}
4	a*	15.32 ± 0.82^{a}	17.55 ± 0.94^{a}	18.99 ± 1.02^{c}	19.79 ± 1.06^{c}	20.07 ± 1.07^{c}
5	b*	23.72 ± 1.27^{a}	22.69 ± 1.21^{a}	21.44 ± 1.15^{a}	20.90 ± 1.12^{a}	20.26 ± 1.08^{b}
6	FFA	0.35 ± 0.02^{a}	0.68 ± 0.36^{b}	0.96 ± 0.05^{c}	1.15 ± 0.06^{d}	1.531 ± 0.08^{e}
7	PV	1.22 ± 0.06^{a}	3.78 ± 0.20^{b}	6.88 ± 0.37^{c}	8.78 ± 0.47^{d}	10.13 ± 0.54^{e}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

reduced considerably, and significant changes in hardness of bitter gourd chips were observed from 14th day ($P < 0.05$). No significant differences were observed for L* values till 14th day. L* value decreased significantly ($P < 0.05$) from 41.48 to 33.71 on 28th day. The a* values increased from15.32 to 20.07. The difference in b* values was not significant up-to 21 days. Free fatty acid content and peroxide value change significantly ($P < 0.05$) from the 7th day.

7.7 *Vacuum Fried Bitter Gourd Chips Packed in Laminated Aluminium at 25 °C, 75% RH*

As seen from (Table 12), moisture content of vacuum fried bitter gourd chips packed in aluminium pouches, stored at 25 °C, 75% RH increased from 1.42% to 6.66% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content on day one and moisture content on 28th day. The hardness of bitter gourd chips decreased from 167 g on day one to 132 g on 28th day. Significant changes in hardness of bitter gourd chips were observed from 1st to 28th day ($P < 0.05$). No significant differences were observed for L* and b* values. The values of a* increased significantly ($P < 0.05$) from 10.71 to 14.65. Free fatty acid content increased from 0. 11% to 0.68% and change significantly. The peroxide value increased from initial value 0.86 to 7.87 meq/kg on 28th day. The peroxide value changed significantly ($P < 0.05$) from 1st day to 28th day. Changes in all parameters were lesser in the bitter gourd chips at 25 °C, 75% RH as compared to 38 °C, and 91% RH irrespective of packaging material used.

Table 12 Changes in moisture, texture, colour values, FFA and PV of vacuum fried bitter gourd chips at 25 °C, 75% RH in laminated aluminium packets

S. no.	Laminated aluminium		25 °C, 75% RH			
	Parameters	0 days	7 days	14 days	21 days	28 days
1	Moisture %	1.42 ± 0.013^{a}	3.42 ± 0.032^{b}	4.88 ± 0.046^{c}	5.62 ± 0.05^{d}	6.66 ± 0.06^{e}
2	Hardness g	167.50 ± 4.9^{a}	157.0 ± 1.47^{b}	146.0 ± 1.37^{c}	139.0 ± 1.3^{d}	132.0 ± 1.24^{d}
3	L*	58.95 ± 2.1^{a}	57.19 ± 2.63^{a}	56.415 ± 2.59^{a}	55.38 ± 2.5^{a}	55.59 ± 2.55^{a}
4	a*	10.71 ± 0.11^{a}	12.48 ± 0.16^{b}	13.76 ± 0.17^{c}	14.05 ± 0.18^{d}	14.65 ± 0.18^{e}
5	b*	35.14 ± 0.95^{a}	35.616 ± 1.9^{a}	36.016 ± 1.9^{a}	36.59 ± 1.9^{a}	37.90 ± 2.02^{a}
6	FFA	0.11 ± 0.01^{a}	0.24 ± 0.003^{b}	0.47 ± 0.01^{c}	0.54 ± 0.01^{d}	0.68 ± 0.01^{e}
7	PV	0.86 ± 0.011^{a}	2.56 ± 0.03^{b}	4.67 ± 0.06^{c}	6.45 ± 0.08^{d}	7.87 ± 0.10^{e}

Values are average ± standard deviation, $n = 3$

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

7.8 Atmospheric Fried Bitter Gourd Chips Packed in Laminated Aluminium at 25 °C, 75% RH

As seen from (Table 13) moisture content of atmospheric fried bitter gourd chips packed in laminated Aluminium pouches, stored at 25 °C, 75% RH increased from 2.52% to 7.65% after 28 days. Significant differences ($P < 0.05$) were observed for the initial moisture content and final moisture content on 28th day. The increase in moisture content is remarkably higher as compared to moisture content of bitter gourd chips packed in Metalized polyester at same storage conditions. The hardness of bitter gourd chips decreased from 112.67 g on day one to 88.07 g on 28th day. Hardness of bitter gourd chips reduced considerably from 14th day ($P < 0.05$). No significant differences were observed for L* and b* values. The values of a* increased from 15.32 to 18.69 after 28 days. Free fatty acid content and peroxide value changed significantly ($P < 0.05$). The increase in FFA and PV was less as compared to the values when packed in same packaging material at accelerated condition.

8 Estimation of HVP (Half Value Period)

HVP is defined as the time required for the moisture content of the product to move half way between the initial value and the value that would be obtained at equilibrium under storage conditions. It has a logarithmic relation to uptake of moisture, related linearly with time and is a constant dependent on the nature of product and packaging material (Ranganna 2001; Table 14). From the slope of the linear graph of log (Me–M) against time, the half value period was calculated by the Break down method as per 15.4.1. The slope of the plot of log (Me–M) against time, days of storage was calculated. HVP was calculated using the expression:

Table 13 Changes in moisture, texture, colour values, FFA and PV of atmospheric fried bitter gourd chips at 25 °C, 75% RH in laminated aluminium packets

S. no.	Laminated aluminium		25 °C, 75% RH			
	Parameters	0 days	7 days	14 days	21 days	28 days
1	Moisture %	2.52 ± 0.09^{a}	3.34 ± 0.13^{b}	4.89 ± 0.19^{c}	5.98 ± 0.23^{d}	7.65 ± 0.29^{e}
2	Hardness g	112.67 ± 5.2^{a}	107.63 ± 5.01^{a}	101.63 ± 4.73^{ab}	96.71 ± 4.50^{b}	88.71 ± 4.13^{b}
3	L*	41.48 ± 2.21^{a}	40.71 ± 2.18^{a}	39.27 ± 2.09^{a}	38.87 ± 2.07^{a}	37.99 ± 2.03^{a}
4	a*	15.32 ± 0.82^{a}	16.74 ± 0.17^{bc}	17.68 ± 0.55^{cd}	18.29 ± 0.73^{d}	18.69 ± 0.57^{d}
5	b*	23.72 ± 1.26^{a}	24.06 ± 1.29^{a}	24.71 ± 1.32^{a}	25.10 ± 1.34^{a}	25.32 ± 1.35^{a}
6	FFA	0.35 ± 0.02^{a}	0.64 ± 0.03^{b}	0.88 ± 0.05^{c}	0.98 ± 0.05^{c}	1.22 ± 0.06^{d}
7	PV	1.22 ± 0.06^{a}	3.22 ± 0.17^{b}	6.35 ± 0.34^{c}	8.35 ± 0.45^{d}	9.34 ± 0.49^{d}

Values are average ± standard deviation, n = 3

Values with the superscripts a, b, c, d, e for any given row represents significant differences ($P < 0.05$)

Table 14 Half value period in days of fried bitter gourd chips

S. no.	Storage condition	Vacuum fried				Atmospheric fried			
		Metalized polyester		Laminated aluminum		Metalized polyester		Laminated aluminum	
		Slope	HVP (Days)	Slope	HVP (Days)	Slope	HVP (Days)	Slope	HVP (Days)
1	38 °C, 91% RH	0.03	10	0.038	8	0.014	22	0.028	10
2	25 °C, 75% RH	0.009	33	0.0128	23	0.01	30	0.02	21

$$\mathrm{HVP} = \log 2/\mathrm{slope.} = 0.3010/\mathrm{S}$$

8.1 Estimation of Shelf Life from Half Value Period

For the estimation of shelf life, the graph was plotted against log [Me–M] versus time in days as per 15.4.2 Shelf life at ambient and accelerated storage was derived from the graph by calculating the time corresponding to the value of log [Me–Mc] on the time scale as shown in (Figs. 8, 9, 10, 11, 12, 13, 14 and 15).

From the (Fig. 15) the shelf life was calculated graphically. Predicted shelf life of vacuum fried bitter gourd chips packed in Metalized polyester and stored at 25 °C, 75% RH was maximum, 72 days as compared to 67 days of atmospheric fried chips. The shelf life of vacuum fried chips packed in Laminated Aluminium was found to be 31 days. Packaging material Metalized polyester was found suitable as compared to Laminated Aluminium.

Fig. 8 Shelf life of vacuum fried bitter gourd chips at 38 °C, 91% RH, metalized polyester

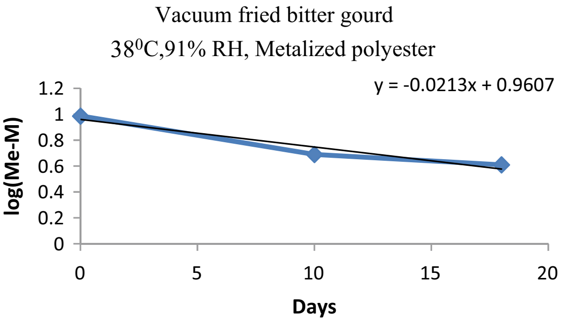


Fig. 9 Shelf life of vacuum fried bitter gourd chips at 25 °C, 75% RH, metalized polyester

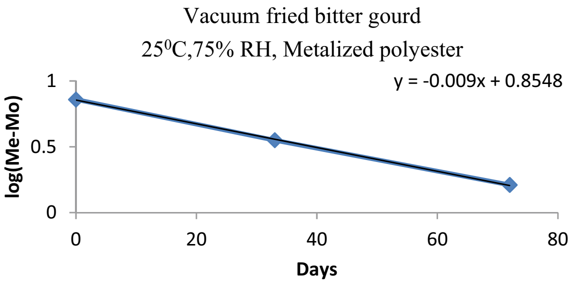


Fig. 10 Shelf life of vacuum fried bitter gourd chips at 38 °C, 91% RH, laminated aluminium

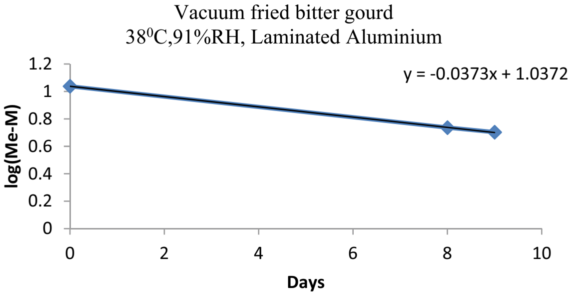


Fig. 11 Shelf life of vacuum fried bitter gourd chips at 25 °C, 75% RH, laminated aluminium

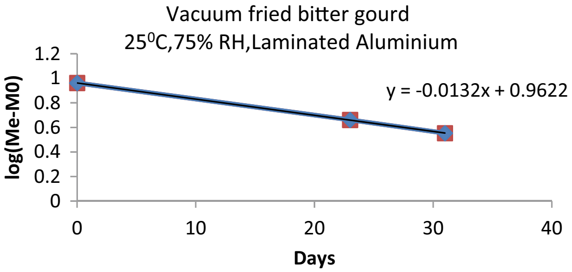


Fig. 12 Shelf life of atmospheric fried bitter gourd chips at 38 °C, 91% RH, metalized polyester

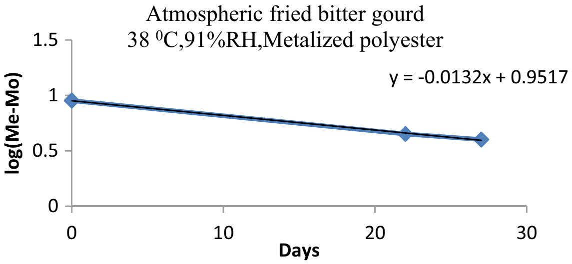


Fig. 13 Shelf life of atmospheric fried bitter gourd chips at 25 °C, 75% RH, metalized polyester

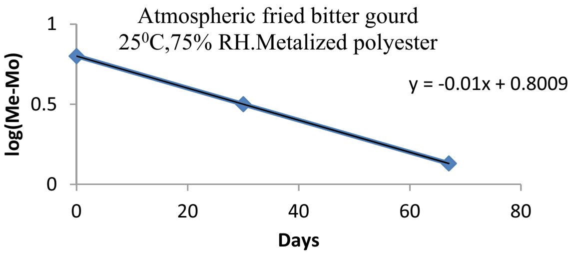


Fig. 14 Shelf life of atmospheric fried bitter gourd chips at 38 °C, 91% RH, Laminated Aluminium

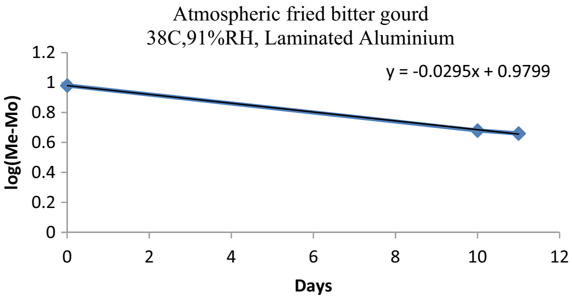
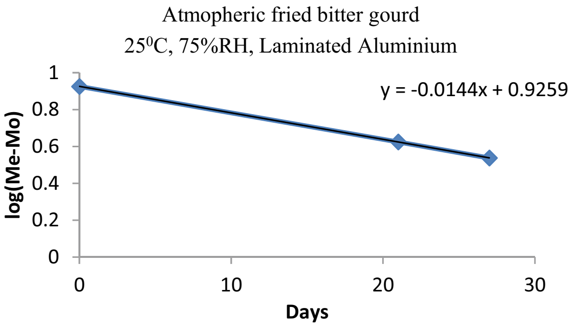


Fig. 15 Shelf life of atmospheric fried bitter gourd chips at 25 °C, 75% RH, laminated aluminium



9 Conclusion

The main purpose of this research was to study the process for increasing the use of bitter gourd by producing vacuum fried bitter gourd chips. It contains a significant amount of fibre and total phenolic compounds which can be beneficial in terms of nutrition. Oil content of vacuum fried bitter gourd chips was significantly lower than atmospherically fried bitter gourd chips. The colour change and browning index of vacuum fried bitter gourd chips increased with increase in frying temperature and time. Sensory scores were highest for bitter gourd chips vacuum fried at 115 °C for 25 min. The moisture absorption isotherm for bitter gourd chips showed typical type II sigmoid shape, common to most food products. Various sorption models applied for the fitting of experimental moisture sorption data yielded high coefficient of determination R^2 ranging from 0.96 to 0.99 which confirms the applicability of the equations employed for modelling the process. Shelf life of vacuum fried bitter gourd chips at 25 °C, 75% RH was found to be 72 and 67 days for atmospherically fried bitter gourd chips. The study indicates the feasibility of developing vacuum fried bitter gourd chips.

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Pectin—Structure, Specification, Production, Applications and various Emerging Sources: A Review

Ragini Surolia and Anuradha Singh

Abstract Pectin, a complex polysaccharide found in the cell walls of fruits and vegetables, has gained significant attention in recent years due to its remarkable functional properties and diverse applications in various industries. This article provides an overview of pectin's structure, production techniques, and emerging sources, highlighting its wide-ranging applications in the food, pharmaceutical, and biomedical sectors. Pectin's unique properties stem from its structural characteristics, such as degree of esterification (DE), molecular weight, and branching patterns. However, variations in pectin composition and gelling properties among different sources pose challenges for commercial manufacturing. It is worth mentioning that pectin is not only limited to food, pharmaceutical, and biomedical applications, it has also been used in other industries, such as the cosmetic industry Recent research focuses on enhancing pectin's functional performance through modification techniques and blending with other biopolymers. Moreover, pectin shows promise in environmental remediation and sustainable packaging, such as wastewater treatment, heavy metal ion removal, and development of eco-friendly films and coatings. Pectin's health benefits are being explored in tissue repair, drug delivery systems, and anticancer processes. It exhibits mucoadhesion, controlled drug release, and potential anticancer characteristics. Commercial pectin production primarily relies on citrus fruits and apple pomace, with emerging sources aiming to utilize waste materials and novel plant sources. Future research focuses on sustainable extraction methods, including eco-friendly solvents and acids, to optimize resource efficiency and reduce environmental impact. Overall, pectin's unique properties and wide-ranging applications make it a versatile biopolymer with significant potential in various industries. Further advancements in extraction techniques and exploration of emerging sources can contribute to a more sustainable and resilient pectin industry.

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1 Pectin

1.1 General Description

A complex polymer called pectin is present in the cell walls of many fruits and vegetables, serving as a key structural component. It is composed of a linear chain of α-(1 → 4)-linked D-galacturonic acid residues, which may be partially methyl-esterified. Pectin has gained significant attention in recent years due to its remarkable functional properties and wide-ranging applications in the food, pharmaceutical, and biomedical industries. This article explores the structure, specification along with pectin production techniques, and shedding light on its diverse applications and providing an overview of various emerging sources.

Pectin, a polymer present in plant cell walls, plays a crucial role in plant structure. It is primarily found in the middle lamella of the cell wall, gradually decreasing towards the plasma membrane (Wicker et al. 2014). While citrus peel and apple pomace are commonly used as industrial sources of pectin, other fruits also contain significant amounts of this compound. However, the challenge lies in the fact that pectin composition and gelling properties vary among different sources, limiting their suitability for commercial manufacturing (Venkatanagaraju et al. 2019). The unique structural modifications in pectin make it a versatile biopolymer with applications as a gelling agent, stabilizer, emulsifier, and substitute for sugar in low-calorie food products (Surolia and Singh 2022a, b). Additionally, pectin is being explored as a prebiotic in functional meals and for the development of edible thin films and coatings (Venkatanagaraju et al. 2019). Currently, researchers are placing considerable emphasis on utilizing industrial food waste as a source for isolating pectin. This approach aims to increase the availability of this highly sought-after biological compound while addressing organic environmental concerns (Freitas et al. 2021).

1.2 Chemical Structure of Pectin

Pectin's unique properties stem from its structural characteristics as: DE, molecular weight, and branching patterns. The DE determines the degree of methylation, which in turn affects the gelation and rheological properties of pectin. Extraction methods play a crucial role in obtaining pectin with desired functionalities.

Plant cell walls are made of proteins and polysaccharides. The majority of the wall is constructed by polysaccharides, and present in varying levels in almost all cell walls. Pectin is a class of polysaccharides with a high concentration of galacturonic acid (Harholt et al. 2010). The source of pectin, the level of ripeness, and the biochemical reactions that occur during plant growth highly affect the structure (Schols and Voragen 2002) and functions of the pectin. Pectin is a versatile polysaccharide due to variability in its molecular structure that has potential for different applications (Fig. 1). Pectin is a complex biopolymer mostly made up of chains of galacturonic acid units, connected by α-1, 4 glycosidic bonds. The carboxyl group of galacturonic acid is present at one end in which some are methyl esterified (Sundar Raj et al. 2012) and an aldehyde group on the other. The structural family of pectin comprises rhamno-galacturonan I (RGI), rhamno-galacturonan II (RGII), homo-galacturonan (HG), and xylo-galacturonan (XG) (Ma et al. 2020) with side chain consist of mainly galactose, arabinose, and xylose sugars and smooth region with no side chain. The proportions of HG, RGI, RGII and XG vary, but usually, HG is the most prevalent polysaccharide, making up about 65% of the pectin, while RGI makes up 20–35% (Debra et al. 2008). Variation in the structure of pectin was observed by using different plant sources for the isolation of pectin. Many other factors influence the structure of pectin such as the growth of plant tissue, method, solvent, and, conditions used for extraction (Rury et al. 2017). It is possible to see differences in pectin structure between the different plant samples and within the plant sample (Sundar Raj et al. 2012). The pectin extracted from the Peel and pulp of the same fruit can show structural variation therefore it's difficult to illustrate the structure of pectin that is affected by numerous factors.

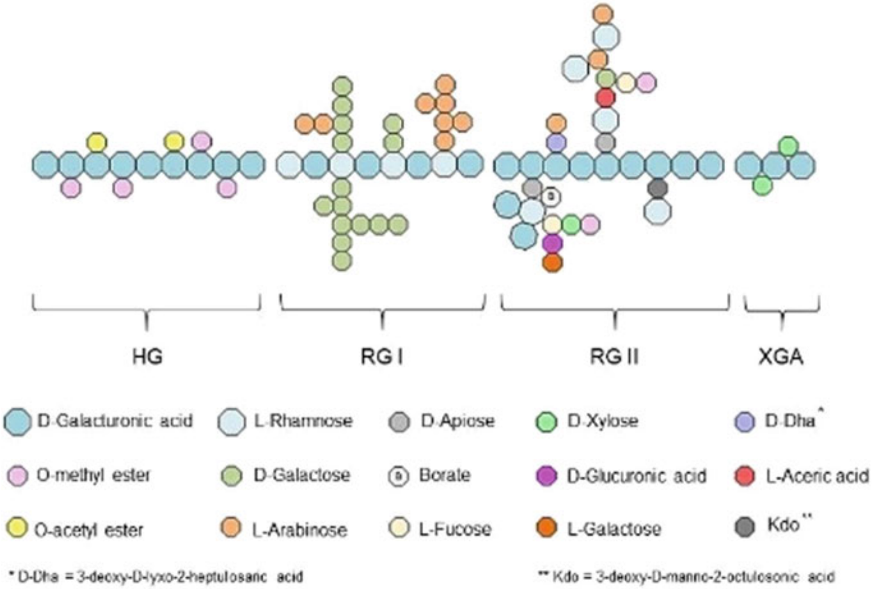

Fig. 1 Structural family of pectin. *Source* Freitas et al. (2021)

The detailed structure of pectin can vary based on the plant source and the specific region of the cell wall from which it is extracted. Here is a general description of the structure of pectin:

- ***Homogalacturonan (HG)***: It is the major component of pectin and consists of a linear chain of α-(1 → 4)-linked galacturonic acid residues. The degree of methylation and acetylation can vary, resulting in different properties. Methylation refers to the addition of a methyl group ($-CH_3$) to the carboxyl group of galacturonic acid, while acetylation refers to the addition of an acetyl group ($-COCH_3$).
- ***Rhamnogalacturonan I (RG-I)***: It is a branched region of pectin attached to HG. It contains alternating residues of galacturonic acid and rhamnose, with various side chains. The side chains can include arabinan, galactan, and arabinogalactan, which contribute to the structural diversity of pectin.
- ***Rhamnogalacturonan II (RG-II)***: It is a highly complex and structurally diverse region of pectin. It consists of a backbone of alternating galacturonic acid and rhamnose residues, with numerous side chains and cross-linking structures. RG-II is known for its high degree of complexity and its role in cell wall integrity and intercellular adhesion.
- ***Xylogalacturonan (XGA)***: It is a minor component of pectin that contains galacturonic acid residues linked to xylose residues. It is found in certain plant tissues and contributes to the structural diversity of pectin.

The detailed structure of pectin can vary not only between different plant species but also within the same species and even within different parts of the same plant. This variability is influenced by factors such as plant maturity, tissue type, and extraction methods.

2 Pectin Specification

Pectin is mainly used in the food and beverage industry and provides natural gelling, thickening, and stabilizing qualities to the product. Pectin is harmless, very valuable, incredibly customizable, and economical. Different international organizations and local regulatory bodies set the specific standard for commercial pectin for e.g. according to EU/Germany, loss on drying should be maximum 12%, whereas, USP stated that it should not be more than 10% (Endress 2011). Despite being safe, pectin from any source cannot be used as a food additive if it does not match the minimum standard set by regulatory bodies. As a result, citrus peel and apple pomace are the only commercial pectin sources; however, numerous other sources have recently been researched, and their specifications are likely to fulfill commercial pectin specifications.

2.1 Galacturonic Acid

One of the most significant factors affecting pectin's functional properties and ability to gel is its galacturonic acid concentration. Galacturonic acid is a food acidifier and its sub-unit forms a chain to constitute the structure of pectin (Belafi-Bako 2007). The % of galacturonic acid in pectin molecules varied depending on the sources and other factors. The galacturonic acid content, which is stated at a minimum of 65% in the specification of pectin as a food ingredient, is the percentage of galacturonic acid in the whole molecule (Flutto 2003).

2.2 Neutral Sugar

Pectin act as major component of plant cell walls, also the most versatile biomolecule in nature, as it can be constituted of up to 17 different monosaccharides with over 20 different linkages (O'Neill et al. 2004). Some neutral sugars may be present as side chains consisting of mainly galactose, arabinose, and xylose sugars (Kertesz 1951), including mannose, glucose, and fucose. A sequence of "smooth" homogalacturonic regions and branched "hairy" regions containing the majority of the neutral sugars (De Vries 1983).

2.3 Molecular Weight (MW)

The cell wall of all the plants contains pectin, whose MW ranges from 110 to 150 kDa (Chen et al. 2022). The source and the extraction procedures have an impact on the molecular weight of extracted pectin. Other factors which influence pectin aggregation are ionic strength, pH, and, the carrier present in the solvent (Sawayama et al. 1988).

2.4 Degree of Esterification (DE)

Pectin is classified by DE as either high or low methoxyl pectin. This categorization determines its ability to form gels and its wide range of applications in the food industry (Daud et al. 2019). If the DE is more than 50% then pectin is used as high methoxyl pectin and if the DE is less than 50% then pectin is used as low methoxyl pectin (Mesbahi et al. 2005). The distribution of esters is particularly significant because it influences the polymer's local electrostatic charge density and, consequently, how well it interacts with other charged molecules, including calcium ions, proteins, and other pectin molecules (Flutto 2003).

2.5 Equivalent Weight (EW)

EW is an essential parameter to define the functional action of pectin (Siddiqui et al. 2021). The equivalent weight of pectin indicates the gelling properties of pectin. The amount of free galacturonic acid may influence the increased or decreased equivalent weight (Nazaruddin 2011). Pectin with high equivalent weight has more ability to form a gel (Vaclavik and Christian 2008), which is significant in the food industry. The higher partial breakdown of pectin during isolation could account for the decreased equivalent weight (Kulkarni and Vijayanand 2010).

2.6 Methoxyl Content (MeO)

The MeO of pectin influences its functional properties as well as the composition and appearance of the gel formed by the pectin. MeO is the amount of methyl alcohol in hundred moles of galacturonic acid. MeO has a significant role in regulating the rate at which pectin sets and form gels (Constenla and Lozano 2003). When the MeO exceeds 7%, the pectin is categorized as high methoxyl pectin otherwise low methoxyl pectin. High MeO is responsible for strong gel formation (Pagarra et al. 2018).

3 Pectin Solubility

Pectin is soluble in pure water although pectin solubility is also influenced by the degree of polymerization, quantity and arrangements of the methyl-ester group on a galacturonic acid chain. The other factor which influences the pectin dissociation rate is temperature, pH, and ionic strength of the solvent (Flutto 2003). Monovalent cation of dried pectin powder is generally soluble in water while divalent and trivalent cations are poorly or undissolved in water. Pectin powder when mixed with water results in the formation of clumps due to rapid hydration of the pectin molecule, which can be overcome by mixing the dried form of pectin with a water-soluble catalyst (Pornsak 2003).

4 Stability of Pectin

High methoxyl pectin is unstable at more than 4.5 pH due to β-elimination which depolymerizes the galacturonic acid chain. It is more stable at less pH and low methoxyl pectin remains stable at higher pH. Both types of pectin are almost resistant to heat and addition of sugar increases the heat stability of the pectin (Flutto 2003).

5 Gelling Properties

The most significant property of pectin is its capacity to form gels. High MeO pectin requires the addition of sugar and acid to form a gel while low MeO pectin forms a gel in presence of calcium ions with minimal or no sugar. The DE of pectin also affects the rate of gel formation. In comparison to low DE pectin, high DE pectin has a rapid gel-forming ability. Pectin with more than 70% DE sets rapidly while pectin between 58 to 70% is slow to set pectin (Sundar Raj et al. 2012).

6 Applications of Pectin

Pectin has several applications because it is a safe, non-toxic ingredient that is widely available and has minimal production costs (Martau et al. 2019). Pectin from different sources has structural variation, making it adaptable for a variety of applications.

Pectin's gelling and thickening properties make it a widely used ingredient in the food industry. Recent research has focused on enhancing the functional performance of pectin in different food systems. For example, modification techniques such as chemical cross-linking, enzymatic modification, and blending with other biopolymers have been employed to tailor pectin for specific applications, including the stabilization of emulsions, encapsulation of bioactive compounds, and development of functional food products.

Pectin has a structural variation because of which it can use as a multifunctional ingredient. In the food processing sector pectin is mainly used as a thickener, gelling agent, stabilizer, and water-binding component (May 1990). Other than this pectin also plays an essential function in confectionery and dairy products (Severian 2004). In low-calorie edible products, pectin work as a fat and/or sugar alternative (Thakur et al. 1997). The pectin has an antioxidant activity that can improve a variety of functions as an emulsifier while reducing artificial ingredients and achieving a clean brand product (Celus et al. 2018). Pectin gelling and stability are governed by different mechanisms for different types of pectin. The pectin that creates the oil/water emulsions does not form a good gel but works well as an emulsifier. Pectin works by covering the lipid molecules by separating them from water and preventing them from aggregating to avoid hydrogen atoms (Nakauma et al. 2008).

In the current scenario, there has been growing interest in utilizing pectin for environmental remediation and sustainable packaging. Pectin-based materials have shown promise in wastewater treatment, heavy metal ion removal, and oil spill cleanup. Additionally, pectin films and coatings can be employed as environmentally friendly alternatives to petroleum-based packaging materials, reducing plastic waste and environmental pollution.

In order to reduce the environmental issues and minimize the generation of toxic waste, natural and biodegradable materials are starting to become popular in the food processing and packaging industries. Pectin is highlighted as an edible covering in food packaging because it is a natural and organic ingredients. Now a days, researchers are more interested in creating natural thin films and edible coatings. Pectin, a material used to create edible films and coatings, extends the shelf life of perishable food items by shielding them from the surrounding elements, delaying the loss of nutrition, and assisting in the maintenance of physical and chemical qualities for a longer period of time (Surolia and Singh 2022a, b).

Pectin is a polysaccharide that has been investigated as a novel biomaterial with prospective health effects such as tissue repair, fat reduction, and membrane construction for contact lenses, artificial corneas, anticancer activity, mucosal and intestinal drug administration carriers, and bone tissue cell transporter (Cariny et al. 2021). The composition of this polysaccharide and the presence of particular structural specificity with bioactive characteristics contribute to its health advantages (Naqash et al. 2017). Pectin is also associated with anticancer processes such as probiotic activity, immunological boosting, tumor growth suppression, and antimutagenic potential (Zhang et al. 2015).

Natural biopolymers help to encapsulate drugs in microcapsules in a sustainable and nontoxic manner. Encapsulation should prevent drug breakdown while promoting regulated release (Martau et al. 2019). Polysaccharides are commonly utilized in drug delivery systems because of their capacity to experience a variety of chemical and enzymatic interactions, resulting in the formation of novel compounds (Tian et al. 2020). Recently many studies demonstrated pectin as an encapsulating agent in drug delivery systems with a combination of other bioactive compounds due to its specific properties of forming a gel (Cariny et al. 2021). Additionally, due to its non-digestibility in the upper gastrointestinal system, pectin has been investigated as a medication carrier to encapsulate active biomolecules and only release the medicine in the colon (Desai et al. 2006).

The unique physicochemical properties of pectin, such as mucoadhesion and controlled drug release, have led to its use in pharmaceutical and biomedical fields. Pectin-based hydrogels, films, and nanoparticles have been investigated as drug delivery systems for various therapeutic agents. Furthermore, pectin's biocompatibility and biodegradability make it an attractive candidate for tissue engineering, wound healing, and regenerative medicine applications.

It has been demonstrated that low molecular weight pectin helps lessen the discomfort associated with several malignancies (Azmar et al. 2008). It was discovered that the molecular size of thermally altered citrus pectin affected the behavior of cancer cells. There may be anticancer characteristics due to the high concentrations of type I arabino-galactans, less-esterified homo-galacturonan oligomers, and decreased levels of rhamno-galacturonan (Prado et al. 2019).

7 Pectin Production Technique

Pectin is commercially produced through the extraction and purification of pectin-rich materials, primarily from citrus fruits (such as oranges and lemons) and apple pomace (the residue left after juice extraction). The production process typically involves the following steps.

7.1 Harvesting and Preparation

The fruits or fruit pomace are harvested and cleaned to remove any dirt or impurities. In the case of citrus fruits, the peels are separated from the pulp.

7.2 Extraction

The pectin-rich material (fruit peels or apple pomace) is subjected to extraction to release the pectin. There are several methods of extraction, however hot acid extraction is most commonly used technique for pectin production, Recently, new and more efficient methods currently favor a greener or organic extraction process such as enzymatic extraction, microwave heating (Rodsamran and Sothornvit 2019), ultrasonic (Xu et al. 2014), autoclave (Oosterveld et al. 2000), electromagnetic induction (Zouambia et al. 2017), and subcritical water extraction, The choice of extraction method depends on factors such as the desired pectin quality, efficiency, and cost-effectiveness.

- **Hot Acid Extraction**: In this traditional method, the pectin-rich material is mixed with hot acid solution (commonly dilute hydrochloric or sulfuric acid) and heated to extract the pectin. The acid breaks down the cell walls and releases pectin into the solution. The use of acid-based chemical extraction is widely prevalent in pectin production, and it significantly affects both the content and composition of pectin's monomers, as well as its physicochemical characteristics (Pacheco et al. 2019).
- **Enzymatic Extraction**: Enzymes, such as pectinases, are used to break down the cell walls and release pectin. This method is milder compared to acid extraction and is often used for obtaining higher-quality pectin. An alternative and noteworthy approach for pectin production is enzyme-assisted extraction (EAE). This method, helps in eliminating the inevitable existence of minute amounts of chemical solvents in products derived from extraction processes involving solvents (Adetunji et al. 2017). Enzymes are renowned for their remarkable selectivity in catalyzing reactions, such as hydrolysis, which effectively reduces the quantity of solvent/chemical required or enhances the yield for an equivalent amount of solvent (Puri et al. 2012)

- **Microwave-Assisted Extraction**: Microwaves are used to heat and disrupt the cell walls, facilitating the release of pectin. This method is relatively faster and may help in preserving the quality of extracted pectin. Microwave energy is a form of non-ionizing radiation capable of penetrating materials. Due to its non-ionizing nature, it does not alter the target material's chemical composition. Microwaves generate electromagnetic radiation, which is converted into molecular motion, resulting in the release of heat. The heated sample's cell walls are under pressure from the water vapour within, which causes the target components to dissolve in the solvent (Karbuz and Tugrul 2021).
- **Ultrasound-assisted extraction**: The primary characteristics of ultrasound-assisted extraction (UAE) involve selecting the frequency typically in the frequency range of 20–100 kHz and wavelength intensity for the solid–liquid extraction (Mao et al. 2019). The ultrasound waves create cavitation bubbles, which are microscopic bubbles that rapidly expand and collapse. The collapse of these bubbles generates localized high temperatures and pressures, causing physical and chemical effects that facilitate the extraction process (Selvakumar et al. 2021). Ultrasound is widely recognized as a sustainable and environmentally friendly technique for extracting valuable compounds from plant materials. By utilizing ultrasound as a key step in extractive procedures, we can significantly reduce the negative impact on the environment compared to traditional extraction methods (Gerschenson et al. 2021).
- **Filtration**: The extracted solution containing pectin is then filtered to remove insoluble solids, such as pulp or peel residues. Filtration can be done using various techniques, including centrifugation and vacuum filtration.
- **Precipitation**: The pectin is precipitated from the filtered solution by adding alcohol, typically ethanol or isopropanol. The addition of alcohol causes the pectin to separate and form a gel-like precipitate.
- **Washing and Drying**: The precipitated pectin is washed with alcohol to remove impurities and then dried to remove the remaining moisture. Drying can be achieved through various methods, such as spray drying, freeze drying, or air drying.
- **Milling and Packaging**: The dried pectin is milled into a fine powder to improve its flow properties and packaged in suitable containers for storage and distribution.

It's worth noting that different manufacturers may have variations in their production processes, and some may employ additional purification steps to further refine the pectin. Depending on the desired uses, the resultant pectin can be further processed into various forms, such as high methoxy pectin or low methoxy pectin.

Future research is crucial to develop novel extraction methods that prioritize sustainability. In addition to solvent alternatives, eco-friendly acids derived from organic sources or produced by fungi can replace mineral acids traditionally used to lower the pH for effective pectin extraction. This shift not only minimizes the use of harsh chemicals but also promotes the circular economy by utilizing waste streams as valuable resources. By incorporating these sustainable practices, the pectin extraction process can be optimized for resource efficiency, waste reduction, and decreased energy consumption. Furthermore, the use of eco-friendly solvents and acids can contribute to the reduction of greenhouse gas emissions and environmental pollution associated with conventional extraction methods.

Overall, focusing on sustainable approaches in pectin extraction research can pave the way for a more environmentally conscious and socially responsible industry. By developing efficient and eco-friendly extraction techniques, we can enhance the sustainability of pectin production and contribute to a more sustainable and resilient future.

8 Sources of Pectin

A complex polymer called pectin is present in the cell walls of many different fruits, vegetables, and plants. Pectin can be obtained from both conventional and non-conventional sources. Emerging sources of pectin refer to new and innovative ways of obtaining pectin that have gained attention in recent years. These sources explore alternative and sustainable methods to extract pectin, often focusing on utilizing waste materials or novel plant sources. Here are some examples of emerging sources of pectin:

8.1 Conventional Sources of Pectin

Conventional sources of pectin refer to fruits that are traditionally used for pectin extraction. These include: Citrus Fruits such as oranges, lemons, grapefruits, and other citrus fruits are commonly used as a conventional source of pectin. The peels of these fruits contain a high amount of pectin. Apple pomace, which consists of the peels, cores, and other by-products from apple processing, is another common source of pectin (Sandarani 2017). Some other fruits like quince, blackberries, and currants also contain pectin, although their pectin content may vary.

8.2 Non-conventional Sources of Pectin

Non-conventional sources of pectin are alternative sources that have gained attention as sustainable and potentially more abundant sources of pectin (Dranca and Oroian 2018). These sources include, by-products generated during the juice and cider production process, such as apple pomace, citrus peel waste, and grape marc, can be utilized as non-conventional sources of pectin (Virginia and Lucia 2020). Various agricultural residues, such as sugar beet pulp, sunflower heads, and mango peels, can be explored as non-conventional sources of pectin.

8.3 Emerging Sources of Pectin

Emerging sources of pectin refer to new and innovative ways of obtaining pectin that have gained attention in recent years. These sources explore alternative and sustainable methods to extract pectin, often focusing on utilizing waste materials or novel plant sources. Here are some examples of emerging sources of pectin: Agricultural by-products and waste from vegetable processing have been explored as potential sources of pectin (Roman-Benn et al. 2023). For example, sources like carrot peels, potato peels, tomato pomace, and sugar beet pulp have been studied for their pectin content. These by-products offer a sustainable alternative and can potentially reduce waste.

By-products from tropical fruit processing have also been considered as emerging sources of pectin. For instance, mango peels, pineapple waste, and banana peels are being investigated for their pectin content. Utilizing these by-products not only adds value to the waste material but also expands the availability of pectin from diverse sources (Picot-Allain et al. 2022). Current research on pectin extraction from various sources is focusing on underutilized fruits and vegetables, which are abundant in dietary fibers. These often overlooked plant sources are gaining attention due to their high fiber content and potential as valuable sources of pectin (Surolia and Singh 2022a, b). Different parts of Aegle marmelos (bael) fruit such as pulp, shells, and seeds contain good amount of pectin (Surolia et al. 2023).

Seaweed, or macroalgae, is gaining attention as a non-traditional source of pectin. Some seaweed species, such as brown algae (e.g., *Laminaria spp.* and *Ascophyllum nodosum*), contain pectin-like substances. Researchers are exploring methods to extract and purify pectin from seaweed, as it offers a sustainable alternative that doesn't compete with land-based agriculture (Jonsson et al. 2020). It is well-documented that genetic engineering techniques have been used to modify various aspects of plant biology, including the modification of polysaccharides and carbohydrates. Researchers are investigating the genetic modification of plants to enhance their pectin content or alter its properties (Littrell 2014). For example, genetically modifying plants like tobacco, *Arabidopsis*, or flax to produce higher levels of pectin or modify its structure could provide a renewable and controlled source of pectin (Liwanag et al. 2012).

These emerging sources of pectin are being studied for their pectin content, extraction methods, and suitability for commercial production. They hold promise in expanding the availability of pectin, reducing waste, and diversifying the sources beyond traditional fruits. However, it's important to consider factors such as cost-effectiveness, scalability, and potential impacts on the environment and human health during the exploration and development of these emerging sources.

9 Pectin Market Analysis

The most common raw ingredient of commercial pectin is apple pomace and citrus peel powder. However, pectin is a dietary fiber present in the cell of all plants, and the most commonly accessible source are cherries, oranges, carrots, apricot, citrus fruits, and apples.

The production of pectin is a complex process, and pectin industries are actively engaged in the development of innovative technologies for its manufacturing. However, hot acid extraction remains the most convenient and extensively utilized method for large-scale pectin production (Oliveira et al. 2016). The international association for pectin producers also states that pectin is manufactured using mineral acids as a processing aid in aqueous solutions (IPPA 2014). According to a report from Future Market Insight in 2022, the market value of pectin was estimated at approximately USD 998.7 Million, with a projected growth rate of 7.8% and an expected market value of US$ 1.6 billion by 2032. This growth can be attributed to the rising demand for functional food products driven by an increasing awareness of health and wellness among consumers in recent years.

The pectin market in India is anticipated to experience growth due to factors like a growing population and increasing middle-class income. However, despite having abundant resources, India faces challenges in meeting the local demand for pectin, primarily due to the relatively small-scale processing industries for apple and citrus fruits (https://www.futuremarketinsights.com/reports/pectin-market).

10 Conclusion

In conclusion, pectin, a complex polysaccharide found in the cell walls of Plants, offers remarkable functional properties and finds diverse applications in the food, pharmaceutical, and biomedical industries. While citrus peel and apple pomace are commonly used as industrial sources of pectin, researchers are exploring emerging sources and production techniques to increase availability and address environmental concerns. Pectin's unique properties, such as gelling, thickening, and stabilizing qualities, make it a valuable ingredient in the food industry, and its potential extends to environmental remediation, sustainable packaging, pharmaceuticals, and biomedical applications. Future research focuses on sustainable extraction methods to optimize resource efficiency and reduce environmental impact. With the increasing demand for functional food products, the pectin market is projected to experience significant growth in the coming years.

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Studies on the Biogenic Amines Produced During Fermentation, Toxicity, and Techniques in Cereal Based Fermented Foods

S. Rohini Karnat, Simran Dubey, and D. Somashekar

Abstract Recent developments in food security and quality have prompted a greater search for trace substances that can affect human health and health agencies worldwide. Food poisoning has become more common as a result of our modern lifestyle and market globalization. Foodborne sickness and food poisoning can be caused by a variety of organisms (bacteria, viruses, parasites, mould, pollutants, and so on), and certain cases of food poisoning can be traced back to chemical and natural toxins. The biogenic amine is one of the toxic compounds addressed by the Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA). These Biogenic amines are natural amines and anti-nutritional factors, constitute a potential public health concern due to their toxicological effects. Their concentrations typically rise when food is subjected to regulated or uncontrolled microbial fermentation or when food deteriorates. The consumption of foods containing high concentrations of biogenic amines has been associated with health hazards. Cereal grains constitute a major source of dietary nutrients all over the world. Cereal grains are an important source of healthy nutrients all around the world. Although cereals are deficient in some basic components (e.g. essential aminoacids), fermentation may be the most simple and economical way of improving their nutritional value, sensory properties, and functional qualities. Lactic acid bacteria (LAB) are usually considered to be non-toxic and non-pathogenic but some LAB species, however, can generate biogenic amines, although the levels are below the of toxicity limit. Biogenic amines are found in a wide variety of cereal-based fermented foods (rice, wheat, corn, cereals, soya bean, etc.), and biogenic amine formation is regulated by various factors related to the raw material used to make food products, microbes, processing, and storage conditions. Biogenic amines are also essential markers of food quality and/or acceptance. These biogenic amines can be quantified using analytical methods that are mostly based on chromatographic procedures. Hence, biogenic amines must be

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monitored in food to maintain the standard of quality of food and safety. This review will highlight the importance of biogenic amines in cereal foods.

Keywords Lactic acid bacteria (LAB) · Biogenic Amines · Health hazards · Cereal grains

1 Introduction

"Biogenic amines" constitute nitrogenous molecules with low molecular mass, organic bases, and a chemical structure comprising one or more amino groups (NH_2) with biological activity in living organisms (Kalac 2014). The biogenic amines can be classified as aliphatic, aromatic, and heterocyclic compounds (Liu et al. 2018). These biogenic amines can be further classified into monoamines such as PHEN and TYR, diamines-HIM, PUT, and CAD, and polyamines-SPM, SPD, and AGM, depending on the number of amino groups present in the molecule (Fig. 1). DOP, epinephrine (also known as adrenaline), norepinephrine (also known as noradrenaline), and epinephrine (also known as noradrenaline) are catecholamine's, which include a catechol structure (Melnikov et al. 2018). Biogenic amines are formed through the enzymatic decarboxylation of organic compounds (amino acids) and the reduction of amines to ketones and aldehydes (Schwenke et al. 1986). As previously mentioned, biogenic amines are primarily present in fermented foods and beverages made from grain. Fermented foods are becoming more and more popular since they are nutrient-dense and have wonderful sensory properties. Although biogenic amines have been around for a while, they have recently received a lot of attention. It is critical to appropriately manage the biogenic amine concentration in fermented foods (Latorre-Moratalla et al. 2017).

The human body possesses enzymes to detoxify the biogenic amines. However, in some cases, this mechanism may be impaired, leading to the accumulation of biogenic amines, which can lead to major toxicological issues and a high risk of poisoning (EFSA 2011; Ruiz-Capillas and Jiménez-Colmenero 2004). The detoxification process is affected due to consumption of amine oxidase inhibitors, immune deficiency, gastrointestinal disorders, alcohol, and higher biogenic amine levels, such as those found in spoiled or fermented foods (Bardócz 1995; Alvarez and Moreno-Arribas 2014). The implication of making sure that no food has been contaminated with potentially dangerous substances at any step in the food chain. Each person involved in the global food supply chain, from the producer to the end user, has a responsibility to ensure that the food should not get contaminated at any time throughout production, transport, and preparation-consumption. The European Food Safety Authority (EFSA), the Food and Drug Administration (FDA), the Food Safety Commission of Japan (FSCJ), the World Health Organization (WHO), etc. all have food safety as one of their top priorities. The human body has detoxification methods to deal with these biogenic amines which are primarily carried out in the intestine by the enzyme monoamine oxidase, diamine oxidase, and polyamine oxidase (Fig. 1).

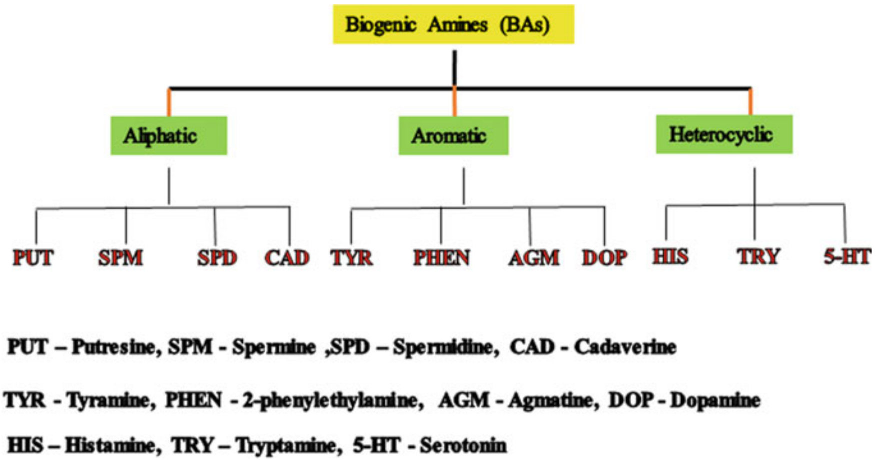


Fig. 1 Types of biogenic amines

The foodborne sickness by biogenic amines may be due to bacteria, viruses, parasites, mould, pollutants, metals, allergies, pesticides, natural toxins, etc. (Table 1). The FDA and EFSA specifically focus on aflatoxins, mycotoxins, HIS, etc., among these poisons. Most meals contain HIS, a biogenic amine, but fish and animal products have higher concentrations. The primary cause of "scombrid poisoning" or "histamine poisoning" is this BA. HIS interacts with receptors on cellular membranes to produce harmful effects. The most common symptoms of HIS poisoning are low BP, skin rashes, headaches, and oedema resembling allergic reactions in many body systems like cardiovascular, gastrointestinal, pulmonary, etc. (Bardócz 1995; Kalac 2014). Additionally, histamine correlates to the health issue known as histamine intolerance, which is connected to an increase in histamine levels in plasma (EFSA 2011). It must be noted that histamine is a mediator of allergic diseases. The biogenic amines are released due to allergic reactions, and also eating foods containing HIS can have a similar impact. In clinical and food chemistry, histamine is a primary source of stress.

Other amines, such as PUT and CAD, are also associated with food allergies (Kalac 2014; Shalaby 1996), though both appear to have less pharmacological activity. But they increase the toxicity of HIS and lower the degradation of this amine and hindering histamine detoxification (Halasz et al. 1994; Ruiz-Capillas and Jiménez-Colmenero 2004). PUT and CAD, which are implicated in various types of food poisoning, such as the creation of nitrosamines, are the toxicological risks associated with secondary biogenic amines that are primarily of concern (Al Bulushi et al. 2009; De Mey et al. 2014). Another important biogenic amine is TYR is a significant biogenic amine linked to food poisoning. In this instance, eating meals with high TYR concentrations (Pegg 2013). Suzzi and Gardini (2003), Stadnik and Dolatowski (2010) have reported finding high quantities of TYR in meat and meat products. TYR stimulates the release of noradrenaline, which causes migraines,

Table 1 Toxic effects caused by biogenic amines

Biogenic amines	Precursor	Disease	Pharmacological effects
Histamine	Histidine	Histamines found in sea foods with spoiled foods	Dizziness, peppery taste sensation, tingling of mouth and lips, itching of the skin
Tyramine	Tyrosine	High mallow poisoning	Headache, migraine, increased blood pressure and blood sugar level, increases respiration, hypersensitivity
Putrescine and cadaverine	Ornithine and lysine	Acute unhealthy effects	Increased cardiac output, lockjaw, paresis of extremities, bradycardia
Tryptamine	Tryptophane	Toxic effects	Increase in blood pressure, hypertension
Spermine and spermidine	Ornithine and diamine putrescine	Food allergies	Hypotension, bradycardia, enhancement of toxicity to other amines
β-phenethylamine	Phenylalanine	–	Increase in blood pressure, dietary-induced migraine

headaches, and elevated blood pressure as typical symptoms of tyramine poisoning (Kalac 2014; Bardócz 1995).

2 Factors Affecting During Fermentation in the Formation of Biogenic Amines

Biogenic amines most frequently occur in the cereal based fermented foods, namely in rice, wheat, corn, cereal and soybean based fermented foods. Biogenic are usually generated by microbial decarboxylation of amino acids. The secondary amines such as PUT and CAD can react with nitrite to produce carcinogenic nitrosamines in foods and beverages (Askar and Treptow 1986). In general biogenic amines will be there in almost all foods that include proteins or are generated due to metabolic activity. The other factors influencing biogenic amine formation are raw material quality, microflora, and processing, and storage conditions (Kim et al. 2009; Gardini et al. 2016).

Bacteria can produce more biogenic amines due to the availability of free amino acids, the presence of bacteria that produce decarboxylase, and other factors like incorrect storage temperatures and fermentation methods that encourage the growth of the microbial load. The *Enterobacteriaceae* family, which includes the genera *Escherichia, Klebsiella, Citrobacter*, *Proteus*, *Shigella*, and *Salmonella,* as well as specialized species including *Pseudomonas*, *Clostridium*, *Bacillus*, and *Photobacterium*, are identified as sources of biogenic amines. Lactic acid bacteria (LAB) create biogenic amines in fermented goods in order to thrive in acidic circumstances. Amino acids in food can be decarboxylated by the genera *Enterococcus*, *Lactococcus*, *Lactobacillus*, *Pediococcus*, *Carnobacterium*, and *Leuconostoc*. The synthesis of biogenic amines in the finished product can be considerably impacted and/or increased by certain variables that arise during the fermentation. The amino acid decarboxylation has been shown to be more active in acidic conditions with pH values between 4.0 and 5.5 and temperatures between 20 and 37 °C. Lower pH correlates with higher biogenic amine content throughout the food processing, but lower temperatures inhibit bacterial growth and decarboxylase activity, and biogenic amine synthesis is dramatically reduced below 5 °C. The proteolytic activity, pH, and temperature during storage also affect the generation of biogenic amines and are influenced by the availability of free amino acids in the food (Sahu et al. 2015).

2.1 Types of Biogenic Amines

The most prevalent biogenic amines detected in food are HIS, TYR, PUT, CAD, and β-phenylalanine, which are formed due to the amino acid decarboxylation.

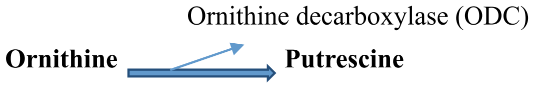
Histamine is formed from histadine by the activity of enzyme histidine decarboxylase (HDC).

$$\textbf{Histidine} \xrightarrow{\text{Histidine decarboxylase (HDC)}} \textbf{Histamine}$$

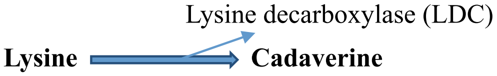
Tyramine is synthesized from tyrosine by the decarboxylase enzyme aromatic tyrosine decarboxylase.

$$\textbf{Tyrosine} \xrightarrow{\text{Tyrosine decarboxylase (TDC)}} \textbf{Tyramine}$$

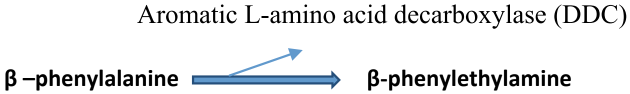
Putrescine is formed from the ornithine by the enzyme ornithine decarboxylase.



Cadaverine is formed from the lysine by the action of enzyme lysine decarboxylase.



β-phenylalanine is converted to β-phenylethylamine by the enzyme aromatic L-amino acid decarboxylase.



3 Formation of Biogenic Amines in Fermented Foods

Foods containing biogenic amine have historically seen as a sign of harmful microbial activity. Generally free amino acids occur in food or are generated during proteolysis. By increasing the availability of free amino acids, microorganisms with strong proteolytic activity may likewise raise the level of biogenic amine production in food. Bacterial growth and amino acid decarboxylase activity are both boosted by the availability of fermentable carbohydrates such as D-glucose. D-glucose concentrations between 0.5 and 2.0% have been found to be ideal, but concentrations above 3% limit enzyme synthesis (Kalac 2014). The redox potential also impacts amine formation. HIS synthesis takes place with a low redox potential, however, in the presence of oxygen, histidine decarboxylase gets inactivated.

Biogenic amines are primarily produced during the production and storage of food by the enzyme amino acid decarboxylase, while some aliphatic biogenic amines are created during the amination and transamination of aldehydes and ketones. In order to distinguish between endogenous and exogenous amino acid decarboxylases, which come from raw materials derived from animals and plants, respectively, but the latter is produced by microorganisms during the fermentation process. According to Liu et al. (2018), a new and promising method for determining the metabolic profile of bacteria is called “microbial metabolomics.” For both Gram-negative and Gram-positive bacteria, it has been demonstrated that external factors can have an impact on the synthesis of metabolites and the metabolite pathway (Liu et al. 2017, 2018). The fermentation metabolites produced primarily by LAB and other microorganisms during the fermentation, as well as storage conditions, determine the desirable features and organoleptic aspects of lacto-fermented foods (Battcock and Azam-Ali 1998). According to Hutkins (2006), LAB produces lactate as well as other compounds such as formate, acetate, ethanol, diacetyl, acetoin, and 2,3-butanediol. Several different end products can be produced by the facultative heterofermentative species *L. plantarum* during fermentation (Kleerebezem et al. 2003). Though food-fermenting LAB are considered non-toxic, and non-pathogenic, but they increase acidity by using catabolic pathways which converts amino acids into amine-containing derivatives (Griswold et al. 2006).

4 Enzymes Involved in the Generation of Biogenic Amines

The enzyme known as decarboxylase functions only on particular amino acids, eliminating the carboxyl groups to create the appropriate amines and carbon dioxide. Diamine oxidase is a enzyme involved in the biosynthesis of PUT, while the decarboxylase pathway is primarily responsible for the creation of biogenic amines (Arena et al. 2008). The production of biogenic amines can activate the proton dynamics of the cell membrane, delivering a net positive charge outside the cell and refueling it with energy (Griswold et al. 2006). As a result, in this instance, the decarboxylation process is a component of the secondary transport system that facilitates the interchange of electrical creatures while supporting primary cellular metabolism in the presence of environmental hazards (Perez et al. 2015). Decarboxylase activity, on the other hand, was revealed to be irrelevant to cell viability (Luo et al. 2020; Tabanelli et al. 2012), and it is particularly resistant to harsh conditions even after cell lysis which is responsible for its production. Decarboxylase-containing strains are now thought to be one requirement for the generation of biogenic amines. Decarboxylase, which supports a particular amino acid decarboxylation pathway, is controlled by a number of specialized operons, of decarboxylase, reverse transport protease, and matching amino acid-tRNA syntheses (Gardini et al. 2012).

LAB, as a result of their excellent acidification, proteolysis, and lipid oxidising characteristics, are the most widely employed starters in fermented goods. These traits are crucial for the development of flavour and colour. During growth LAB produce organic acids and bacteriocins. These substances support LAB and compete with non-fermenting microbes and prevent the growth of microbes that produce amines, which in turn reduces the overproduction of biogenic amines (Ozogul and Hamed 2018). Notably, only some strains of LAB have the ability to degrade biogenic amines; others, such *L. hilgardii* and *L. rhamnosus*, have been shown to create biogenic amines, demonstrating that this ability is strain-specific rather than species-specific (Arena et al. 2008; Fernandez et al. 2007).

The growth of bacteria that produce amino acid decarboxylase during fermentation and storage is the fundamental reason for the increased biogenic amines in traditionally fermented foods (Dimidi et al. 2019). It is challenging to identify the compounds produced by various routes in a complex food system because the types of bacteria engaged in the production of biogenic amines in traditional fermented foods are diverse. The mechanism of biogenic amine generation has to be studied from the gene level and macro-scale quorum sensing (QS) perspectives. The majority of the genes involved in the formation of biogenic amines are of two types. One is in charge of producing and controlling biogenic amines decarboxylase, and the other is in charge of collecting precursors and eradicating biogenic amines. It has also been noted that relatively high levels of some biogenic amines can signal food product degradation or improper manufacturing. Because of their toxicity, it is widely accepted that they shouldn't be allowed to build up in food.

4.1 Cereal Based Fermented Foods

The foods based on cereal fermentation are very important in the nutrition of many people in Asia, Africa, the Middle East, and some parts of Europe (Table 2).

4.2 Rice Based Fermented Foods

4.2.1 Fermented Idli Batter

Idli is a popular breakfast food item of India and nowadays becoming popular worldwide. In fermented Idli batter, HIS, TYR, PUT, CAD, SPD, and SPM were by incorporation of varying ratios of cereals (rice to black gram *dal* at 1:1, 2:1, 3:1 and 4:1 w/w) and stored at room temperature (30 °C) and cold condition (4 °C) for 7 days. CAD and PUT are the predominated amines in preserved Idli batter stored for 7 days at 30 and 4 °C. Increasing the rice content in the batter can reduce the amount of biogenic amines measured, which was 366.87 μg/g. Increased amounts of black gram dal can enhance the free amino acids in the Idli batter, which serve as the precursors of biogenic amines. A rationale for this is that black gram dal contributes a significant amount of protein to fermented Idli batter, accounting for 21.57% of protein. The highest total biogenic amine concentration measured (366.87 μg/g) in the idli (1:1) batter was below the toxic limit (1000 μg/g), it is safe and healthy food to consume.

Black gram contain amino acids such as lysine arginine and tyrosine responsible for the biogenic amines produced during Idli batter fermentation (Padhye and Salunkhe 1979). PUT, SPD, and SPM are all formed as a result of arginine, and lysine is a precursor for the development of CAD (Santos 1996). An increase in PUT and CAD formation in fermented Idli batter after fermentation was due to an increase in the amount of black gram dal. Tyrosine decarboxylase enzyme produced TYR from tyrosine (Collins et al. 2011). Idli batter fermentation increases the level of free

Table 2 Cereal based fermented foods containing biogenic amines

Fermented food and beverages	Source	Biogenic amines	Country
Idli batter	Rice/blackgram	Histamine, tyramine, putrescine, cadaverine, spermidine and spermine	Asian countries
Tarhana	Wheat	Tyramine, putrescine, cadaverine and spermine	Turkey
Soy sauce	Wheat and soy bean	Tyramine, histamine, phenylethylamine, putrescine, cadaverine	Japan, china and far east countries
Kumru	Wheat and chickpea yeast	Putrescine, cadaverine, spermidine, spermine, histamine	Turkey
Kenkey	Corn, maize	Cadaverine, putrescine, tryptamine, tyrammine	Ghana
Boza	Millet, maize, wheat and rice	Putrescine, spermidine, tyramine	Turkey
Beer	Barley	Agmatine, histamine, cadaverine, putrescine, phenylethylamine, spermidine, spermine	All over world
Douchi	Black beans and black soybeans	Histamine, tyramine	China

sugar, amino acids, nicotinic acid, choline, and methionine (Ghosh and Chattopadhyay 2011). Decarboxylase positive organisms required free amino acids to generate biogenic amines (Santos 1996). HIS and SPM were not detected in the batter stored under room temperature (30 °C) for 7 days, however PUT, CAD, TYR, and SPD were present during storage for 7 days at 30 °C (Regubalan and Ananthanarayan 2019). HIS, SPD, and SPM were not found after 7 days of storage at 4 °C; only PUT, CAD, and TYR were identified. The highest quantity of PUT obtained was 140 µg/g for a 1:1 batter ratio. During 4 days of storage at 4 °C, the highest total BA concentration was determined to be 249.13 µg/g in Idli batter of ratio 1:1 w/w. Individual and total biogenic amine concentrations in Idli batter held under refrigerated settings exhibited an increasing trend in the early period of storage (up to 4 days), followed by a slight reduction. Batter samples stored at 4 °C may reduce the enzymatic and metabolic activity of bacteria, which results in lower BA synthesis at 4 °C as compared to 30 °C storage condition.

4.3 Wheat Based Fermented Foods

4.3.1 Tarhana

Tarhana is a popular traditional fermented cereal food consumed in the region of Turkey. Tarhana is a kind of dry powdered food prepared with yeast and LAB that is served as a soup with desired taste. The most frequent BA was TYR. The average TYR concentrations in homemade and commercial Tarhana samples were 92.8 mg/kg and 55.0 mg/kg respectively. Tarhana samples had pH, acidities, total dry materials, and free amino acid values ranging from 3.43 to 5.03, 0.60 to 3.89 g/100 g, 86.42 to 92.32 g/100 g, and 0.035 to 1.427 g/100 g respectively (Tamer et al. 2007).

Tarhana is prepared in four steps: dough mixing, fermentation, drying, and grinding. Tarhana dough is made by combining yogurt, wheat flour, *S. cerevisiae* culture and vegetables, (Ekinci and Kadakal 2005). The prepared dough is fermented for 1–5 days at 30–35 °C. Cultures like LAB (*L. bulgaricus*, *S. thermophiles)* and yeast (*S. cerevisiae*) are commonly used in fermentation (Ibanoglu et al.1995). TYR was found to be the most common of the ten amines examined. The TYR concentration of the samples ranged from 15.7 to 415.4 mg/kg tarhana. Tarhana samples reported an average TYR content of 92.8 mg/kg. Tarhana samples had average PUT, CAD, and SPD concentrations of 46.0, 17.9, and 23.5 mg/kg, respectively. The total amine levels ranged from 73.0 to 1019.9 mg/kg. The amounts of biogenic amines found in 15 distinct types of tarhana samples were much below the maximum allowable limits.

4.3.2 Kumru

Kumru is a traditional Turkish fermented cereal sandwich bread. Kumru made with chickpea (*Cicer arietinum*) and yeast. It is prepared by grinding chickpea into paste and culture (*S. cerevisiae*) baker's yeast, then mixing with wheat flour and kept for fermentation at 25 °C for 9–10 h. Wheat flour, chickpea, and yeast are combined to make the kumru dough. Following dough preparation and fermentation, shaping and cooking are performed. Biogenic amines concentration of fermented kumru meal offer protein and free amino acids that may be utilized by decarboxylase-positive microorganisms. Kumru samples from several producers in Izmir, Turkey were found to contain PUT, CAD, SPD, SPM, and HIS. The total amine content in the samples ranged from 23.9 to 42.2 mg/kg. The highest HIS content found in kumru was 5.9 mg/kg (Özdestan et al. 2012).

4.4 Corn Based Fermented Foods

4.4.1 Kenkey

Kenkey is a fermented maize dough that is popular in Ghana. Popular ready-to-eat traditional meal from Ghana is kenkey is cooked in water while being wrapped in fermented maize dough. LAB are the most important functional microorganisms in fermentation. *L.plantarum*, *L.casei*, *L. brevis*, *B. subtilis*, and *S. cerevisiae* are among the microorganisms responsible for fermentation (Nyarko-Mensah and Muller 1972). Kenkey was added with cowpea to enrich the product with protein, and the levels of biogenic amines were tested. The ranges of biogenic amines in maize-based kenkey were relatively low (total amines < 60 ppm), but increased dramatically with the addition of red cowpea (total amines < 200 ppm, for CAD and TYR) and even more with the addition of white cowpea (total amines < 500 ppm), for PUT and TYR. HIS was absent (<5 ppm) in the samples. Fermentation and cooking influence was less significant on amine content instead of cowpea addition. Cooking for an extended period of time reduced PUT levels but did not significantly reduce TYR levels (Nout 1994).

4.5 Cereal Based Fermented Beverages

4.5.1 Boza

Boza is a traditional beverage in Turkey, also popular in East European countries, including the Balkans, and Egypt. Boza is a fermented product made up of millet, boiled maize, and wheat or semolina or rice flour, yeast and lactic acid bacteria cultures are added. Serap Cosansu (2009) reported on tryptamine, β-phenylethylamine, PUT, CAD, HIS, and TYR contents in boza. The biogenic amines contents of samples varied significantly. Most of boza samples tested for biogenic amines had total amine content ranging between 1.67 and 101.14 mg kg^{-1}. The highest concentrations of TYR, CAD, tryptamine, PUT, β-phenylethylamine, and HIS were 82.79, 17.69, 13.78, 9.80, 4.53, and 4.07 mg kg^{-1}, respectively. The levels of biogenic amines in boza samples were lower than the suggested hazardous limits.

Yeğin and Üren (2008) also reported on boza fermented beverage by evaluating biogenic amines concentrations of boza samples from different manufacturers in Turkey. The most common biogenic amine was TYR. The TYR concentrations in boza samples ranged from 13 to 65 mg/kg. The total amine concentration of samples ranged from 25 to 69 mg/kg. All samples contained PUT, SPD, and TYR. Propylamine was not found in any of the samples tested. Individual BA detected are methylamine, ethylamine, propylamine, isopentylamine, PUT, CAD, tryptamine, SPD, SPM, HIS and TYR with levels of 0.1, 0.3, 0.2, 0.4, 0.2, 0.3, 0.8, 0.3, 0.4, 0.6, 1.8 mg/kg respectively.

4.5.2 Beer

As a result of its relatively high alcohol content (0.5–10% w/w), low pH (3.8–4.7), presence of hop-derived iso-acids, reduced oxygen level (0.1 ppm), and other factors that inhibit the growth of most microorganisms and beer is generally regarded as having low microbiological risk (Schneiderbanger et al. 2020). In general, 100 mg/L of biogenic amines is recognized as a safe dose for the majority of consumers, while this limit is significantly lower in the case of alcoholic beverages. Based on the Nalazek-Rudnicka et al. (2021) and Poveda (2019) literature survey, agmatine (AGM), HIS, CAD, PUT, 2-phenylethylamine (PHE), TYR, SPE, SPD, and HIS are present in beer samples.

4.6 Soybean Based Fermented Foods

4.6.1 Douchi

Douchi is a fermented food, which is prepared from black beans/soybeans and is Chinese fermented food. HIS and TYR can act as a precursor of carcinogenic N-nitroso compound. Bacterial enzymes decarboxylate amino acids to generate N-nitroso compounds (Mitacek et al. 1999). HIS (24.4–814.2 mg/kg) and TYR (53.4–643.5 mg/kg) were identified in douchi products procured from the local market products (Fong et al. 2020).

4.6.2 Soy Sauce

Soy sauce is prepared from a soybean and wheat blend that is mostly used as an all-purpose flavour in Japan, China, and other Far Eastern countries (Yokotsuka 1986). Cooked soybeans are combined with coarse wheat flour. Moulds are inoculated to soybean-wheat flour mixture, and the prepared mixture was kept for fermentation at 25–35 °C for 3 days. The soybean and wheat flour mixture (known as koji at this stage) is immersed in a brine solution (22–25%, with a koji-to-brine ratio of around 1:3 w/v). The salt percentage of the mixture normally decreases between 18 and 21% after mixing. Moromi is a brine solution that contains koji. The moromi kept for a longer duration of fermentation (1–12 months) would enhance soy sauce quality. Biogenic amine levels in soy sauce vary as follows: TYR, 0–525, β-phenylethylamine, 0–31, PUT, 0–205 and CAD, 0–170 mg kg^{-1} (Stute et al. 2002). Some soy sauces have been shown to contain large quantities of vasoactive biogenic amines, such as β-phenylethylamine (up to 121.6 mg/kg), HIS (398.8 mg/kg), and TYR (794.3 mg/kg), are much higher than toxic doses (Chou and Ling 1998).

Soy sauce with different salinity levels showed varied amounts of biogenic amines. Higher salinity levels in soy sauce can lead to the reduction of biogenic amines. The total biogenic amines varied at a range from 102.44 to 1041.43 mg/L. In detail, the ranges of eight biogenic amines contents were TRY, PHE, PUT, CAD, HIS, TYR, SER, and SPD are 6.08–20.89, 9.98–122.49, 6.45–44.82, 6.84–398.56, 2.13–171.82, 0–195.04, 10.62–302.12 and 3.98–402.13 mg/L respectively. The highest contents of biogenic amines were PHE, HIS, and PUT. Brewing process and sanitary conditions influence the amine content in the different types of soya sauces (Guan et al. 2013).

5 Detection of Biogenic Amines in Fermented Food

The detection of amines in food is done for two reasons: first, because of their potential toxicity, and second, because they might be used as indicators of food quality. Monitoring fermentation processes, process control, research and development, and quality control of raw materials, intermediates, and finished goods are a few of the key uses of biogenic amines analysis. Biogenic amines were identified in maize fermented food Kenkey by ion-exchange liquid chromatography and identified with a fluorescence detector after post-column derivatization with O-phthalaldehyde (Walters 1984). Biogenic amines were found in Boza samples by following derivatization with dansyl chloride. The detection limits for HIS, TRY, TYR, PUT, CAD, and PHA were 0.03; 0.04; 0.04; 0.09; 0.11, and 0.05 mg kg^{-1}, respectively, whereas the quantification limits were 0.1; 0.12; 0.12; 0.18; 0.30, and 0.15 mg kg^{-1}, respectively.

5.1 Analytical Methods

In order to meet the growing need for biogenic amines determinations in food matrices, quick, easy, affordable, and reliable analytical approaches are needed. Numerous analytical techniques have been put forth in recent years (Onal 2007; Onal et al. 2013). The necessity to address fresh issues posed in the field of food analysis has led to such a proliferation of approaches. Some developments aim at improving metrics including precision, accuracy, sensitivity, and detection limits.

Various techniques have been developed for the analysis of amines in foods by thin-layer chromatography (TLC), Liquid chromatographic separation, gas chromatography, Ultraviolet (UV) and fluorescence (FL), LC-TOF-MS and LC-Orbitrap-MS, capillary electrophoretic method (CE) and high-performance liquid chromatography (HPLC). Popular and effective techniques for the sensitive and selective determination of biogenic amines in foods include liquid chromatographic separation. The quantification of biogenic amines in dietary samples uses a variety of detection methods. Other straightforward assays can also be identified using flow injection analysis (FIA) and biosensor devices that utilise colorimetric, enzymatic, and immuno-based reactions (Hernandez-Cassou and Saurina 2013).

Particularly for every day and control applications, UV and FL absorption spectroscopies are frequently used to detect biogenic amines. These techniques are based on derivatization reactions (Jia et al. 2012; Berbegal et al. 2016). Due to the simple reason that most biogenic amines lack a chromophore, derivatization is necessary for these kinds of detections. The amino group is used as a catalyst in the derivatization reactions with various tagging reagents, such as o-phthaldialdehyde, dansyl chloride, 4-chloro-3,5-dinitrobenzotrifluoride (CNBF), 1,2-naphthoquinone-4-sulfonate (NQS), 6-aminoquinolyl-N-hydroxysuccinimi. It should be noted that only a select few BAs, like tryptamine and β-phenylethylamine, are easily detected, whereas derivatization is required to get the limits of detection of biogenic amines which display poor chromogenic or fluorogenic properties. Most of the biogenic amines were separated using a one-dimensional TLC method. Densitometry at 254 nm was used to determine the concentration of the amines (Shalaby 1999). For the purpose of identifying biogenic amines, a gas chromatographic-mass spectrophotometric approach with a chosen ion monitoring mode and derivatization was used.

A direct method was used by capillary electrophoretic (CE) for the detection of biogenic amines in food products (Kvasnicka and Voldrich (2006). A CE and a HPLC method for determining biogenic amines in food were compared in Thomas and Wittmann's (2003) report. By using CE or HPLC, the biogenic amines may be separated in less than 9 or 20 min. The development of the LC-TOF-MS and LC-Orbitrap-MS technologies, which both identify a wide range of contaminants in food, including both known and unidentified contaminants, with improved accuracy. Today's UHPLC-HRMS approaches for determining biogenic amines in food matrices use either TOF (42, 45, 65) or Orbitrap technology. For the detection of eight biogenic amines in food samples, LC-APCI-HRMS using an Orbitrap mass analyzer equipped with medium-resolution capabilities (10,000 fwhm) was used (Self et al. 2011; Self and Wu 2012).

5.2 *Detection of Biogenic Amines Producing Bacteria*

In order to reduce the risk of amine creation in the food sector, early detection of biogenic amine-producing bacteria is required. The biogenic amines can be detected by paper chromatography or spectro-fluorimetric methods or for more complex ones, automated systems for the detection of microbial metabolic activities or conductance method are used. A number of techniques have been developed to detect the production of biogenic amine through microorganisms (Marcobal et al. 2006; Linares et al. 2010). In order to identify strains that produce biogenic amines, screening approaches like a differential medium having pH indicator are recommended (Bover-Cid and Holzapfel 1999).

However, numerous studies documented the decline in LAB capacity to generate biogenic amine during extended storage or isolation of strains for culture in selective media or differential medium that contained a pH indicator. For instance, the loss of the histidine decarboxylase plasmid, which is highly dependent on the bacterial growth conditions, is an easy explanation for the instability of the histidine decarboxylase cells of *L. hilgardii* (Lucas et al. 2008). Recent advancements in quick, dependable, and culture-independent molecular methods, typically based on PCR methodologies, have made the ability to quickly and accurately identify bacteria that produce biogenic amine in fermented beverages (Ladero et al. 2008; Nannelli et al. 2008).

Several publications have suggested a connection between the ability to synthesize BA and the existence of the gene encoding the decarboxylase. In order to identify the strains that produce BA in wine and cider, a multiplex PCR approach for the simultaneous identification of LAB that produces HIS, TYR, and PUT has recently been developed (Marcobal et al. 2006). The European Food Safety Agency (EFSA) recently implemented a system to identify pre-market safety of specific taxonomic groups of microbes, resulting in a "Qualified Presumption of Safety" (QPS), which constitutes the European equivalent of the generally recognized as safe (GRAS) status (EFSA 2007). Although some strains of these species have been characterized as BA producers (Coton and Coton 2005), Lactobacillus related to food, such as *L. buchneri, L. brevis, and L. hilgardii*, have gained a QPS designation (EFSA 2007). This could generate discussion on whether "absence of BA production and BA production associated genes" should be added as a qualifying standard in the QPS context.

6 Biogenic Amines and Toxicity

In recognition of the possibility of toxic effects, the BA content of fermented foods has been extensively researched (Table 3). HIS levels of 500–1000 mg/kg food are regarded as possibly hazardous to human health. This amount is based on the concentrations observed in HIS-containing foods. It has been proposed that an acceptable upper limit of 100 mg HIS/kg food and 2 mg/L alcoholic beverage has been proposed. The lethal dosage of the other amines is even less well understood. Taylor (1985) reported that TYR threshold values of 100–800 mg/kg and phenylethylamine 30 mg/kg. TYR and β-phenylethylamine, these two biogenic amines, have been hypothesized as the primary triggers of dietary-induced migraine and hypertensive crises in some people. HIS, another amine, has been linked to a number of incidents of food poisoning. As per Parente et al. (2001), HIS intake range between 8 and 100 mg, and more than 100 mg may result in mild, moderate, and severe poisoning, respectively. The maximum permitted levels of HIS and TYR should be between 50 and 800 mg/kg, according to Nout (1994), who also noted that TYR becomes lethal above 1080 mg/kg. Despite the fact that PUT, SPM, SPD, and CAD have no harmful effects on health, they can react with nitrite to produce cancer-causing nitrosamines and be used as spoilage indicators (Hernandez-Jover et al. 1997). Tryptamine is harmful to humans and raises blood pressure, causing hypertension (Shalaby 1996).

Food poisoning may be due to other potentiating factors such as monoamine oxidase inhibitors (MAOI) medicines, alcoholics, digestive disorders, and other food amines. The most frequent side effects brought on by eating food high in biogenic amines are histaminic intoxication, hypertensive crisis brought on by interactions

Table 3 Levels of biogenic amines in Cereal based fermented foods

Fermented foods	HIS	TYR	PUT	CAD	SPD	SPM	References
Soy sauce (mg/kg)	3.9–398.8	26.8–794.3	2.5–1007.5	0.7–32.3	1.5–53.1	ND-16.1	Tsai et al. (2007)
Douchi (mg/kg)	NF-808	NF-529	NF-596	NF-191	NF-719	NF-242	Tsai et al. (2007)
Fermented idli batter (µg/g)	NF	44.31	35.27	58	25.91	NF	Regubalan and Ananthanarayan (2019)
Dry sausages (mg/kg)	<1–200	3–320	<1–580	<1–790	NF	NF	Eerola et al. (1998a)
Soy sauce (mg/kg)	3.9–398.8	26.8–794.3	2.5–1007.5	0.7–32.3	1.5–53.1	NF-16.1	Cho et al. (2006)
Douchi (mg/kg)	NF-808	NF-529	NF-596	NF-191	NF-719	NF-242	Tsai et al. (2007)

NF-Not found

between food and MAOI antidepressants, and food-induced migraines (Mariné-Font et al. 1995). It has been demonstrated that the diamines (PUT and CAD) and polyamines (SPD and SPM) enhance intestinal absorption and reduce metabolism of the mentioned amines, amplifying their toxicity. The efficiency of each person's detoxification processes significantly impacts the hazardous dose (Halasz et al. 1994), so determining the precise toxicity threshold of BA in individuals is particularly challenging. Low concentrations of biogenic amines are typically converted in the human gut to physiologically inactive breakdown products during the meal intake process. Diamine oxidase (DAO) is one of the specific enzymes included in this detoxifying pathway.

However, the detoxification system cannot sufficiently clear these biogenic amines when ingested in high doses from meals containing biogenic amines. Additionally, even small amounts of biogenic amines cannot be metabolized effectively when there is insufficient DAO activity, which can be brought on by factors like genetic predisposition, digestive disorders, or inhibition of DAO activity brought on by the side effects of drugs or alcohol (Bodmer et al. 1999). HIS and TYR are two examples of biogenic amines that are viewed as anti-nutritional substances. They are harmful to those who are sensitive to them, especially when other substances intensify their effects. One of the most typical types of food intoxication is HIS poisoning, which has allergy-like symptoms and is typically associated with eating scombroid fish like tuna or mackerel (Veciana-Nogue et al. 1997).

7 Conclusion

Amines can accumulate in high concentrations due to microbial activity. Hence one approach to reducing the concentration of biogenic amines is to screen for microbes that lack the enzymes to generate biogenic amines. The study should be focussed on the microorganisms which degrade biogenic amines. There is also a need to develop simple and cost-effective methods to detect biogenic amines in foods. The use of starter cultures that do not generate biogenic amines in fermented foods is recommended. The starter cultures lacking amino acid decarboxylase and the ability to inhibit non-starter organisms should be used in food industries. High levels of biogenic amines could be prevented if the manufacturers adopt good manufacturing practices during the processing of food products. Further research is required on the toxicity of the biogenic amines using animal models. The use of food additives and preservatives and storing the food at refrigerated temperatures may decrease the generation of biogenic amines. There is a lot of scope to study the health risks associated with the consumption of biogenic amines and also to look for methods to minimize biogenic amines in fermented foodstuffs.

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Artificial Intelligence (AI) as a Transitional Tool for Sustainable Food Systems

Kiranbeer Kaur, Priyanka, Gurwinder Kaur, Barinderjit Singh, Shalini Sehgal, and Shalini Trehan

Abstract The expansion of the human population, climate change, the depletion of resources, and pollution all present obstacles to the functioning of our food systems, as well as to our capacity to ensure that future generations will have adequate food and nourishment. The existing methods used in agriculture and the supply chain are one of the primary factors that contribute to these problems. Artificial intelligence (AI) is currently permeating all aspects of food systems, and the methods in which it is doing so point to the possibility of transformative system changes. As intermediaries between people, technology, and the environment, designers have a responsibility to understand and reflect on the various ways in which artificial intelligence (AI) could bring about the change that is required to advance toward sustainable food systems. In the realms of commerce, corporate operations, and governmental policy, the application of artificial intelligence (AI) is quickly pushing the boundaries of what is possible. The intelligence of machines and robotics, empowered with the capacity for deep learning, is bringing about transformative and influential changes across all sectors of society, spanning from business to government. The food system and the various actors involved in it are a key contributor to climate change. They are also to blame for alterations in land use, the depletion of freshwater resources, and the degradation of aquatic and terrestrial ecosystems caused by excessive inputs of nitrogen and phosphorus. The applications of artificial intelligence (AI) are revolutionizing the agriculture industry and contributing to increased efficiency, sustainability, and productivity in farming practices. From using advanced technologies to monitor crop health and optimize interventions to automating various tasks and creating demand-driven supply chains, AI is making a significant impact on agriculture. It is also employed through applications that provide "augmented

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personalized health," which, in turn, may better manage the food and nutrient intake of individuals with the purpose of producing healthier outcomes. There is a possibility that AI will revolutionize food systems, thereby facilitating a move toward reduced environmental consequences, higher resilience, and better health.

Keywords Artificial intelligence · Food safety · Machine learning · Agriculture

1 Introduction

The increased interest in discussions regarding food production methods and their influence on commodity markets in the demand-supply chain. Issues include the dramatic increase in global population, the gradual rise in income levels in developing nations, global warming, and other environmental dangers brought on by mankind over a long period of time. In particular, the increased need for food supplies calls for sustainable production practices and comparable production values. The Food and Agriculture Organization (FAO) of the United Nations estimated that this population could reach over 9.1 billion by 2050 (Godfray et al. 2010) due to the rising trend in population. The problem of 'undernourishment'—the difficulty of obtaining enough food and the degree of insufficient food consumption to meet the necessary dietary energy requirements—remains (Godfray et al. 2010). This estimate severely undercuts the requirement for a 70% increase in global food production and a nearly double increase in poor nations (Misra et al. 2020). New methods of food production and technical food processing are now possible thanks to contemporary advancements in the food sector. Throughout the last 50 years, a variety of food types have been in demand, including some odd ones such as functional foods, which have proven to be essential to leading a healthy lifestyle (Alexandratos 1995). The use of AI in business and industry is increasingly pervasive. Its transformative potential extends to research, learning, daily life, interactions, and work, promising substantial benefits to the economy and society (Habicht et al. 2004). As we move into the Age of Sustainable Development, the 17 Sustainable Development Goals (SDGs) define the global development agenda. A "food system" concept contrasts with views of agriculture, food production, and consumption as a simple, linear path from farm to table. Food systems, on the other hand, are complex networks that encompass all the inputs and outputs related to agricultural and food production and consumption. Food systems can change significantly from place to place and over time, depending on local factors. The notion of food systems provides a complete framework for assessing the social, economic, and environmental components of sustainability. Food is a necessity for humans and is considered the best product of farming. It is created when farmers distribute the various foodstuffs they have produced. Products from the food business are essential for any nation's development (Plan 2016). It also plays a large part in how the national economy and the global economy are developing. Thus, it is crucial to ensure the safety of food sector products and their high quality through appropriate distribution. Artificial intelligence (AI), a recently developed technology, has been successful in achieving the desired goals (Sebastin 2018) throughout the past few decades. Big data is expected to fuel the development of emerging technologies like computer vision and artificial intelligence (AI), enabling advancements in training, real-time operational smart machines, and predictive modelling. The concept of a “computer vision and AI-driven food industry” involves leveraging learning and vision techniques to enhance the food sector. Moreover, AI is forging a new frontier in business, corporate practices, and governmental policy. Deep learning-powered machine and robotic intelligence are already addressing cognitive challenges that were once solely associated with human intelligence.

In this chapter, we will discuss various aspects of artificial intelligence (AI), machine learning (ML), the evolution of AI and ML, the specific applications of AI in the food industry, highlighting its contributions to various aspects of the food sector. Discussing how AI technologies can enhance food safety measures and mitigate potential risks. We aim to provide a deeper understanding of the current state and future potential of AI and ML in shaping the food industry.

2 Different Fields of AI in Food Systems

Food manufacturing is an industry-aligned operation. To maintain competitiveness, businesses must prioritize technology upgrades and seek opportunities for operational improvement through innovation. AI plays a crucial role in enabling intelligent and timely decision-making by leveraging extensive computations and data analysis. In the food industry, artificial intelligence and machine learning contribute to optimizing and automating processes, leading to cost savings and a significant reduction in human errors. Embracing these technological advancements is essential for businesses to thrive in today’s dynamic landscape. Restaurants, bars, and cafés such as Starbucks, as well as food manufacturers, have all expressed support for artificial intelligence and machine learning. The employment of the AI technologies framework in the industry can produce secure and exact product manufacturing lines with better speed and consistency than human workers. AI is also employed in supply chains around the world. AI is used in every step from start to finish, from the production process to the supply chain process, in tasks such as tagging and monitoring stock levels.

3 Machine Learning in Food Systems

Machine learning is one of today’s fastest expanding technical topics, located at the crossroads of computer science and statistics, as well as at the heart of artificial intelligence and data science. Machine learning covers the subject of how to design machines that learn on their own (Jordan and Mitchell 2015). The scientific study of statistical models and algorithms employed by computer systems to efficiently carry out specific tasks without explicit instructions is known as machine learning. It relies on patterns and inference rather than relying on explicit commands (Capitanio et al. 2010). For instance, in the context of recognizing a simple object like an apple, machine learning enables the computer to identify it by learning the steps involved in the recognition process, rather than relying on explicit instructions and coding for the specific details about an apple. This is like how we learn by showing them several examples of the target (Sebastin 2018). Natural language processing, the autonomous processing of natural language, such as text and speech by software, is known as natural language processing. How to design computers to handle and evaluate substantial volumes of natural language data is an area of computer science that addresses the relationship between computer and human languages (Goldberg 2016).

AI and computerized vision constitute a scientific discipline that empowers machines with the capability to perceive the visual world (Fig. 1). Through the utilization of cameras, analogue-to-digital conversion, and digital signal processing, machine vision enables the recording and analysis of visual data. This advanced technology allows machines to interpret and understand visual information, making it invaluable in various applications such as image recognition, object detection, and automated inspection processes (Sonka et al. 2014). Computer vision has integrated its existence in all conceivable sectors within a short period of time, including pattern recognition, machine learning, computer graphics, 3D reconstructions, virtual reality, and augmented reality (Ruckelshaus et al. 2009). AI techniques, including machine learning and deep learning, heavily rely on extensive training data for their effectiveness. To obtain and process the required training data, computer vision techniques are employed (Wettels et al. 2008).

3.1 AI in Robotics

Robotics is a fascinating field that encompasses both science and engineering. It involves the development, manufacturing, usage, and control of robots, in addition to the utilization of computer systems to command these machines, process sensory feedback, and manage information. The aim of robotics is to create machines that can replicate human actions and perform tasks that are challenging or repetitive for humans (Cardello et al. 2007; Leung and Wen 2020). As a result, robots are extensively employed to complete jobs that are difficult or consistently performed by humans.

The advancement of artificial intelligence (AI) has further augmented the potential of robotics. Although the implementation of AI in robotics is still developing, it holds the promise of enhancing efficiency in various industries, including food-related businesses. In the food industry, several robotic technologies have already found practical use. For instance, drones are utilized for food delivery, while robotic arms are employed for food processing tasks. These robotic solutions not only streamline

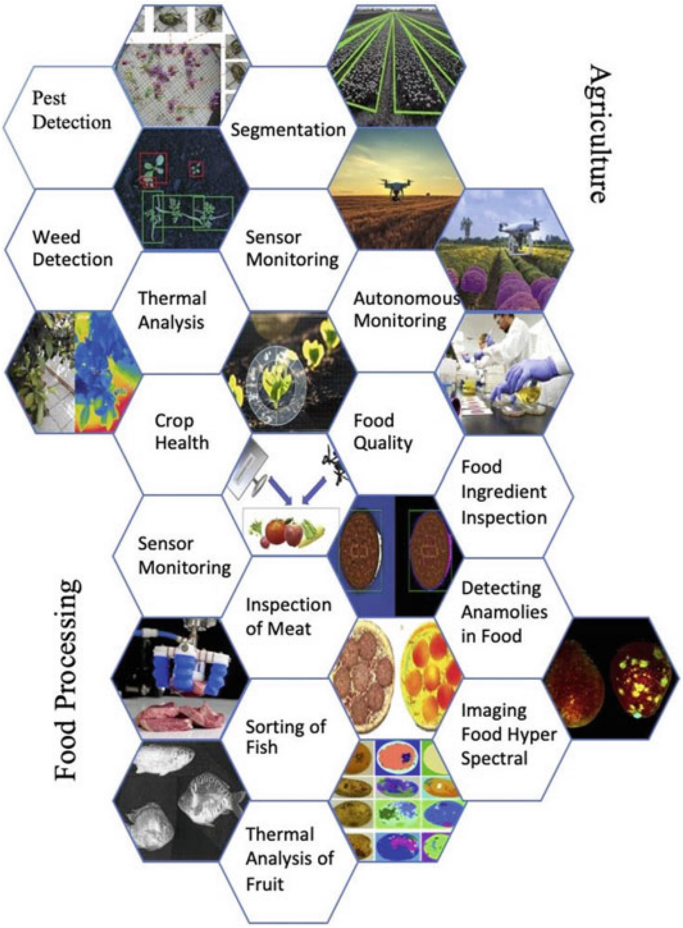


Fig. 1 Application of machine learning in food systems

processes but also offer the possibility of greater precision and consistency in food-related operations (Gulshan et al. 2016).

3.2 AI in Voice Assistants

According to estimates, 27% of users preferred voice search to traditional typing-based search. As a result, voice-based searching is being added to every food and other e-commerce sector, and a brand-new voice commerce platform such as Alexa by Amazon has been created. This functionality allows restaurants to accept quick orders through voice commerce applications without having to seek specifics, which is advantageous for new eateries (Melander et al. 2015).

4 AI Revolution

With the advancement of automation, the manufacturing sector and modern industry have reached productivity peaks in a matter of decades. The industrial sector was the first, and as technology advanced, numerous other industries were shaped. In recent years, artificial intelligence, often known as AI in the scientific community, has excelled, surpassing humans in tasks such as object identification and computer vision. The early 1800s saw the beginnings of automation, which eventually sparked the industrial revolution and current technological advancements. Automation has now permeated every conceivable industry, and the booming market is trading above and beyond estimates (Fig. 2).

Such automation has occasionally occurred since the early 1900s and has since found its way into numerous sectors. However, the most recent developments in AI have forced people to reconsider the value of learning and ask themselves, "What could be the heights of AI when computers are able to learn?" Artificial intelligence (AI) is the culmination of a wide range of techniques and phenomena, and it owes much of its outstanding development to two key ideas known as deep learning (DL) and neural networks (NNs). Neural networks began to perform miracles thanks to the enormous amounts of data, and on top of that, tech behemoths such as Google, Microsoft, Amazon, Facebook, and Apple began their study in AI by gathering enormous amounts of data through their services. This innovation from 2014 demonstrated to the world how quickly machines can pick up complicated skills that took human generations to perfect. Within a few years, DeepMind technology was used for everything from straightforward tasks such as document review and spam email classification to more difficult tasks such as object recognition, context creation, and scene interpretation.

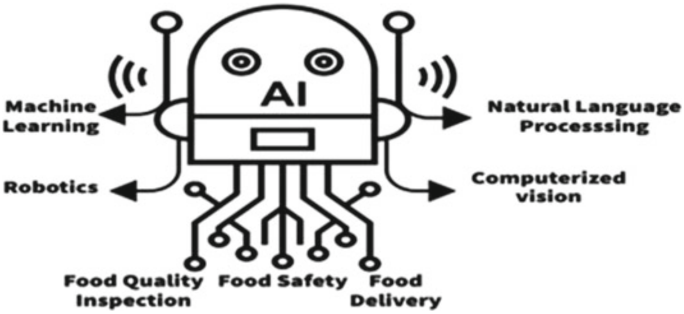


Fig. 2 Different fields of AI

4.1 Big Data, IoT in Agriculture and Food System

The Internet of Things (IoT) generates enormous amounts of streaming data, sometimes known as "big data," which creates new potential for the monitoring of food systems and agricultural activities (Ashton 2018). Big data from social media is also starting to matter for the food system, in addition to sensors. To ease the discussion of several issues within our analysis, we give a graphical summary of the IoT and big data framework in the food system. Here, we should note that the data may come from consumers, the supply chain, food processing or manufacturing, agriculture, or food manufacturing. While sensors are points of data collection on the Internet of Things, consumer data are shared comments on social media platforms. When the information from many sensors and sources is properly combined, it can be used to learn about primary production, processing, or retail activities. Information undergoes transformation into knowledge by means of thorough analysis using computer models. In modern times, data processing frequently occurs at distant locations with the aid of powerful computers, a phenomenon known as "cloud computing." The insights gained from this analysis can then be utilized to make informed decisions about how to execute tasks more efficiently or provide appropriate recommendations.

Artificial intelligence (AI) plays a crucial role in this process, automating the entire journey from data to judgment through self-learning techniques. The term "Industry 4.0," often referred to as the fourth industrial revolution, embodies the concept of high-level automation in industries by integrating cyber-physical systems, the Internet of Things (IoT), cloud computing, and cognitive computing (Lasi et al. 2014). This convergence of technologies has led to revolutionary advancements, enhancing the efficiency and productivity of various industries, and paving the way for new possibilities and innovations.

4.2 System AI-Based Processing Strategies

Even in highly complex fields such as medicine, pharmaceuticals have used AI to perform challenging tasks such as predicting eye diseases from retinal scans alone. In the medical sector, some AI start-ups have made significant strides in predicting cases of malignant tumors in patients by analyzing computerized tomography (CT) scans of the lungs (Mnih et al. 2015). These AI systems have shown remarkable performance, surpassing human radiologists in several aspects. Notably, the AI achieved a 50% better false-positive rate, reducing the chances of unnecessary worry for patients. Moreover, the AI excelled in handling specific complex scan scenarios during testing, where human radiologists had missed 8% of the cases (Völter et al. 2013). This highlights the potential of AI in revolutionizing medical diagnosis and enhancing the accuracy and efficiency of disease detection. Processing food introduces new edible materials with enhanced qualities from raw ingredients (Norvig and Intelligence 2002). Depending on the level of processing, food is divided into primary and deep processing. Primary processing (rough processing) is the initial processing performed on agricultural products after they are harvested to prevent the loss of their original nutrients or to prepare them for transportation, storage, and subsequent processing. Primary processing has straightforward processing principles and technology, and the primary commodity value is low. The primary processing of animal flesh, eggs, and fish involves drying, shelling, milling grains, slaughtering live animals and poultry, and freezing. Following primary processing, deep processing (finishing) refers to much more involved processing techniques used to further enhance the qualities of products. For instance, grains can be transformed into soy sauce, noodles, vermicelli, bread, and cookies. Deep processing is a crucial method for increasing the commercial value of agricultural goods (MacLeod 2002). Traditional food processing involves many labour-intensive processes. The food sector is under much strain because of the growing human population and the diversity of consumer expectations. This is because labour-intensive activities prevent resource optimization, resulting in high labor costs and even raw material waste, which raises costs even further. Thus, this food processing technique cannot produce good quality and low price at the same time (Frohm et al. 2008). Food industry professionals and academics are actively engaged in exploring and implementing cutting-edge and innovative food processing techniques. These advancements aim to achieve several key objectives, including reducing costs, enhancing food quality, and improving overall processing efficiency. Traditional methods still play a significant part in food processing (Bishop 2013). Modern technology is applicable practically everywhere in the food supply chain, from fields to factories to consumers (Van Der Maaten et al. 2009) (Fig. 3). For instance, new MVS technologies can be incorporated into the freezing, drying, and canning processes to lengthen the time that food is preserved. They can also be used to package food and identify foreign items to extend the shelf life of food (Hermann et al. 2015). Certain supplementary procedures are required during the processing of raw food ingredients to distinguish between high-quality and inferior foods. These steps entail evaluating the quality and safety of food, as well as packing and monitoring food processing. This makes it feasible to successfully reduce resource waste and increase productivity. The main criteria used to assess food quality and safety, track food processing steps, and spot foreign objects are appearance, texture, and component parts (Kakani et al. 2020). Techniques for image processing are highly desired options for gathering these data. Additionally, the outcomes of image processing can help the system decide what actions to take next to handle various food categories (Fig. 3).

5 AI Driven Agriculture

AI has rapidly adapted and introduced various farming strategies in the agricultural sector. One of the key concepts utilized in this adaptation is cognitive computing, which revolves around the use of computer models to mimic human thought processes. This leads to tumultuous AI-powered agriculture technology that aids in

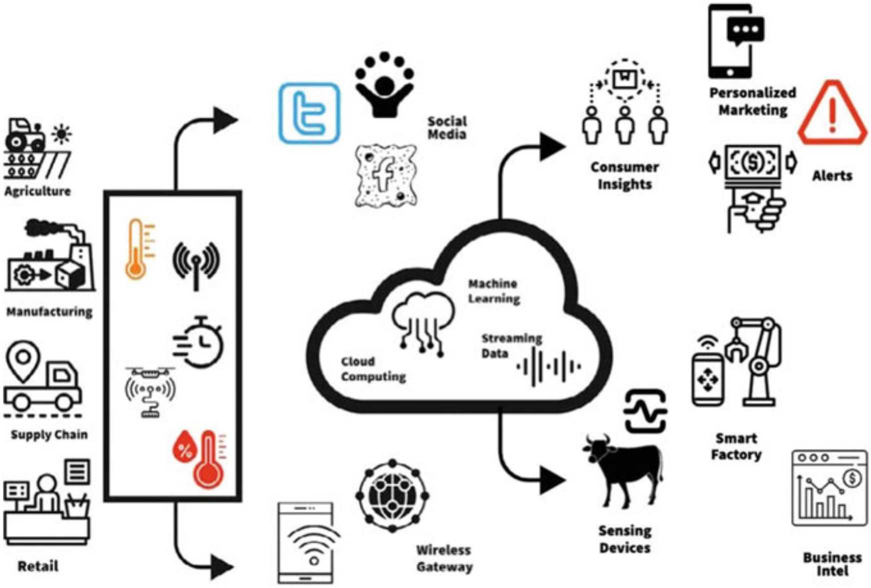


Fig. 3 Representation of the IoT framework within the agricultural and food

interpreting, learning about, and responding to various situations (depending on the learning collected) to increase efficiency (Greenspan et al. 2016). Farmers can interact with these chatterbots to seek advice, obtain weather forecasts, receive updates on market prices, learn about new farming techniques, and access relevant resources for their specific crops or livestock. By leveraging such AI-based platforms, farmers can stay informed, make data-driven decisions, and adapt to changing conditions more effectively. Drone imaging can help with in-depth field analysis, crop monitoring, and field scanning. To assess the ripeness of green fruits, farmers have employed the use of white and ultraviolet A (UVA) light imaging techniques on various crops. Through this investigation, farmers can establish multiple levels of fruit or crop readiness based on the results obtained. Additionally, images of plant leaves are subjected to image sensing and analysis, which facilitates their division into distinct surface areas, such as the background, the diseased region, and the non-diseased portion of the leaf (Cheng et al. 2016). After this segmentation process, the unhealthy or infected regions are isolated and transferred to the laboratory for further diagnosis and analysis. This approach aids farmers in accurately identifying and addressing potential diseases or issues affecting their crops, contributing to better management and improved crop yield.

6 Food Safety and Quality Evaluation

Food safety and quality assessments have received much attention in the past. Food safety is essential to people's lives, protecting their health and acting as a fundamental safety net for the steady growth of civilization (Fellows 2022). Neither the government nor the public accept problems with food safety, such as contamination and deterioration (WHO 2003). Food safety requires ensuring that food does not contain any hazardous ingredients and that it satisfies the necessary nutritional standards. To maintain proper cleanliness during food processing, storage, and sale, as well as to reduce the possibility of biotic and abiotic pollutants that could cause food poisoning, ensuring food safety necessitates a multidisciplinary approach. Because they are time-consuming and harmful, traditional methods for evaluating food safety and quality are frequently unworkable. Consumers and the food business urgently want quick, non-destructive methods to evaluate the safety and quality of food. To classify food, physical characteristics such as size and form are frequently used. This is because products with odd or irregular forms will have lower market acceptance (Zhu et al. 2021). The price of the commodities is correlated with the size, shape, colour, and texture of the fruits, vegetables, meat, and poultry in the food sector. Additionally, when food goes bad, physical changes in its appearance can mirror changes in its underlying chemical state.

Thus, high-throughput, precise technologies are needed for categorizing food into different groups. Foods that do not satisfy the requirements can be identified by MVS through the observation of unfavourable changes, which eliminates foods that should not be sold. Using image processing techniques, it is possible to quantify the size and shape of food, for example, by calculating the projected area and perimeter (Naik and Patel 2017) presented a technique for classifying the mango variety "langdo" that employed maturity and size as defining characteristics. Mango size is predicted using a fuzzy classifier with weight, eccentricity, and area parameters. The ripeness of mangoes is determined using the mean intensity algorithm in the L*a*b* colour space. In this colour space, L* represents perceptual lightness, while a* and b* represent the chromaticity coordinates.

7 Packaging Monitoring

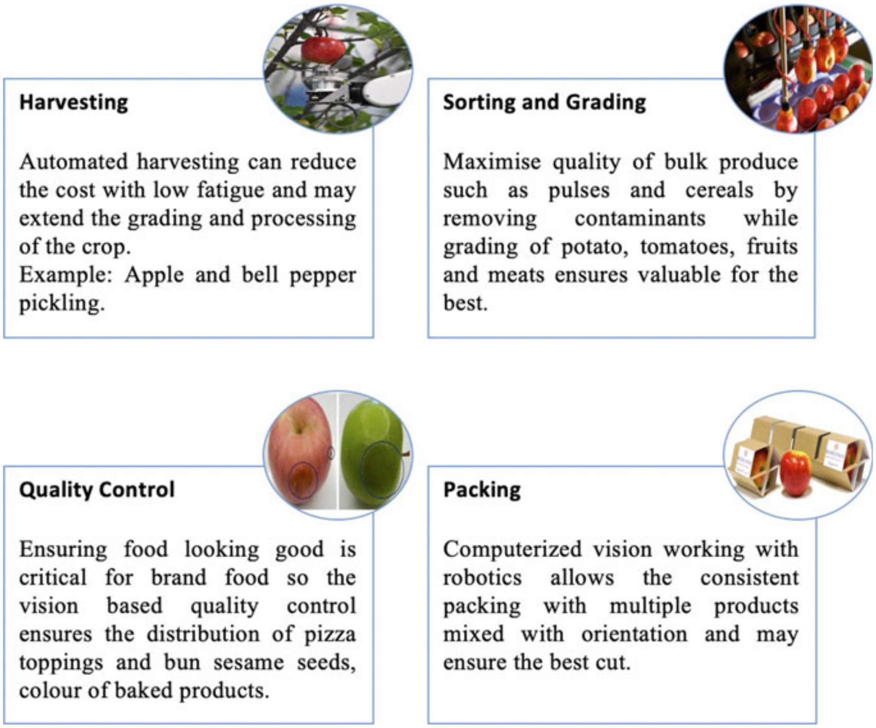
Emerging food processing operations involve many intricate steps that call for strict oversight, adherence to rules, and assurance of worker and food quality. Food processing is the first phase, which frequently entails exposing food to temperature and pressure changes that may alter the state of the food. Conventional control systems call for workers to constantly monitor food changes, which increases the risk of human error (Linko 1998). To ensure quality, food manufacturing must be automated and remotely monitored. During food preparation, food is transported and stored in food packaging to preserve its quality. Effective, high-quality packaging prevents food from rotting too soon, increasing the effectiveness of food marketing and distribution. Sanitation, food protection, product presentation, and simplicity of transportation are the four primary purposes of food packaging (Zhu et al. 2021). Food is protected from deterioration by biological, chemical, and physical forces along the entire food supply chain. Moreover, it can keep the food's quality consistent. Customers can obtain a first impression of the product and the appearance of the meal from the package's aesthetic impact. Food packaging is therefore a crucial part of the food processing process. Nonautomated monitoring of food packaging, such as that of food processing, can result in human error and poor performance (e.g., mixing undesirable objects into the package). By adopting cutting-edge technologies to monitor food manufacturing and packaging, such as a machine vision system, these flaws can be fixed.

8 Foreign Object Detection

One of the biggest causes of food recalls and customer rejection is foreign object contamination (Soon et al. 2020). Customers are harmed by this kind of contamination, which also results in a decline in brand loyalty and high recall costs. For instance, insects, glass, metal, or rubber are examples of foreign items. During any stage of food manufacturing, these items could unintentionally find their way into the food or container. For instance, during any stage of harvesting, processing, handling, or preparation, small pebbles or stones, insects, and twigs may enter (Fig. 4). Although the size, type, hardness, and clarity of the foreign object determine how dangerous it is, eating food that contains foreign objects can still result in choking or other illnesses (Zhu et al. 2021). The prevalence of foreign objects in food is declining as the food industry continues to enhance the quality and safety of food products. Consumers are also becoming less accustomed to thoroughly inspecting food for the existence of extraneous objects and are less likely to tolerate them. It is challenging to find alien things with the unaided eye. In contrast, modern recognition techniques and new technology may quickly identify foreign items. These technologies include, for instance, X-ray, ultrasound, and thermal imaging (Mohd Khairi et al. 2018). For instance, using ultrasound imaging to detect foreign things in meat is made possible by the differential in acoustic impedance between meat and foreign objects (Xiong et al. 2015). This method's employment in the food business is promising because it is precise and non-destructive.

9 Digital Image Processing (DIP)

The initial selection of an input, including evaluation of many aspects defining the categorization process, and how this analysis is productively applied are the main topics of the sections that follow: A thorough division of an input image into



Harvesting

Automated harvesting can reduce the cost with low fatigue and may extend the grading and processing of the crop.
Example: Apple and bell pepper pickling.

Sorting and Grading

Maximise quality of bulk produce such as pulses and cereals by removing contaminants while grading of potato, tomatoes, fruits and meats ensures valuable for the best.

Quality Control

Ensuring food looking good is critical for brand food so the vision based quality control ensures the distribution of pizza toppings and bun sesame seeds, colour of baked products.

Packing

Computerized vision working with robotics allows the consistent packing with multiple products mixed with orientation and may ensure the best cut.

Fig. 4 AI and computer vision driven food system industry, i.e., picking & packing, harvesting, quality control and sorting using vision algorithm. *Source* Frohm et al. (2008)

sections that are each assumed to be similar regarding a particular image quality of interest, such as intensity, colour, or texture, is what is commonly referred to as image segmentation. This procedure is thought of as a crucial part of any image analysis system, and issues related to it have attracted much attention (Valous and Sun 2012). The grey levels of pixels belonging to an object are significantly varied in many image processing applications. Examples of digital image processing activities Classes Operation examples image enhancement, image averaging, frequency domain filtering, and contrast enhancement. Image evaluation Object categorization, feature extraction, and segmentation image compression both lossy and lossless compression Synthesis of images imaging using tomography, 3D reconstruction. The food and beverage sectors' use of vision technology uses different levels of Gray for background-related pixels. Thresholding then turns into a straightforward yet useful approach to distinguish items from the backdrop. A binary image is produced as the result of the thresholding operation, with things in the foreground appearing above the threshold and those in the background appearing below it.

The thresholding technique is complicated by several factors, including nonstationary and correlated noise, ambient lighting, the activity of the object's and its background's grey levels, insufficient contrast, and object size that is out of proportion to the scene. Processing processes such as morphological filtration, measurement, and statistical evaluation, in a non- destructive environment for inspection and quality control in the food and beverage sector (Sezgin and Sankur 2004). Region-based segmentation techniques typically exhibit lower sensitivity to noise compared to other segmentation methods. These techniques rely on analysing and grouping image regions with similar characteristics to identify distinct objects or regions of interest. Examples of region-based segmentation techniques include region expanding, split and merge, histogram thresholding, random field, watershed, and clustering (Shaaban and Omar 2009). Image processing is the process of altering digital photos to achieve goals such as bettering their quality, lowering noise, or fixing lighting issues. The process of separating areas of interest from uninteresting parts to extract information is sometimes referred to as picture analysis. Low-level, intermediate-level, and high-level processing are all possible divisions. Preprocessing, often known as low-level processing, involves processes. These include noise reduction, focus correction, contrast or sharpness augmentation, and grayscale adjustment. These operations create a fresh image and are used to change the position of the object of interest using geometric transformations or to enhance the image quality (Hornberg 2017). Regions in the image with sudden variations in intensity can be identified using filters such as Sobel, Laplacian, and La-placian of Gaussian. At a given range of direction and frequency, the Gabor filter is selective for image elements. The components of a Haar-type filter are balanced neighbouring rectangular patches that are invariant to changes in illumination and have a mean value of zero. To create a binary image where nonzero values, indicate the presence of an edge in the image, edge detection is used. Further information, including scale and direction in relation to an edge, may optionally be returned by detectors. Edge detectors include Canny, Harris, and SIFT, as some examples. Points of interest can be found using the SIFT (Scale Invariant Feature Transform) detector. Each point discovered during the detection process is associated with scale and orientation information (Prince 2012). The process of acquiring an image begins with the conversion of electronic signals generated by a sensor into a numerical representation. This transformation is achieved using a device like a camera, which captures the visual information and converts it into a digital format. Area and line cameras are the two main types that can be used for scanning. In each exposure cycle, traditional or area-scanning cameras produce an image.

Line scan cameras, in comparison, only record one line of pixels at a time. To capture two- dimensional photos of an object, there are two common methods: moving the object using a conveyor or moving the camera along a fixed object. The lighting employed during the acquisition phase has a direct impact on the quality of the image that a computer vision system captures. Therefore, all the work put into using suitable illumination will boost the system's efficiency and dependability while simplifying the software utilized during the processing stage (Prince 2012).

10 Application of Artificial Intelligence in Food Systems

Future food production will be significantly influenced by artificial intelligence. To fulfil consumer expectations, companies in the food and beverage industry are implementing AI technologies quickly to improve operational and logistical efficiencies. The application of AI has had a significant impact on production, finance, marketing, consumption, packaging, distribution, and storage. Before 2021, the worldwide AI industry is expected to develop at a compound annual growth rate of 42% for food and beverage companies. Artificial intelligence technologies were used by food industries to boost efficiency and income (Fig. 5). The food industry is experiencing remarkable benefits from the latest advancements in AI technology. AI is now being utilized in various aspects of the industry, including sorting fresh produce, ensuring high-quality health standards, and ensuring compliance with food safety regulations. Additionally, AI is playing a crucial role in the development of new products and is enhancing supply chain activities.

The food industry is divided into 4 major segments:

- Agriculture
- Food Technology and Processing
- Supply Chain
- Marketing.

We will discuss the application of AI in each sector individually.

10.1 Application of AI in Agriculture

Artificial intelligence (AI) has recently become widely used in the agricultural sector. To increase production, farmers must address issues with pest control and disease infestation, inappropriate soil treatment, low output, and a lack of technological understanding. The fundamental ideas behind artificial intelligence are its precision,

Fig. 5 Foreign object detection in pizza

efficacy, improved performance, and adaptability. Artificial intelligence is used in crop management, disease management, soil management, and pest management.

10.2 Application of AI in Food Technology and Processing

The management and processing of food can significantly alter the food economy. The food processing industry is significantly influenced by a few variables, including quality control, food type, fashionable trends, consumer psychology, and overall human wellness. This made it necessary to include technologies to raise production standards, reduce waste, and meet consumer demand.

10.3 Sorting of Fresh Food

Food processing facilities face a significant challenge in dealing with the inconsistent supply of feedstock. Manual sifting and sorting of vegetables in these plants are not only time- consuming but also reduce efficiency and increase operational costs. To address these issues, the integration of cameras, lasers, machine learning, and artificial intelligence (AI) has emerged as a game-changer in food processing. By leveraging sensor-based optical sorting technologies and AI, food processing businesses can automate the cataloguing of food products, enabling more effective and efficient food sorting. For instance, laborious and time-consuming processes involved in sorting fresh fruit can be eliminated with the use of AI-driven optical sorting systems, leading to higher yields, improved quality, and reduced waste. AI's capabilities help enhance machine calibration, enabling handling of various product sizes while reducing waste and overall processing costs (Sebastin 2018).

11 Food Safety Compliance

In food processing facilities, the implementation of AI-enabled cameras has proven to be invaluable in monitoring worker compliance with safety regulations. This cutting-edge technology employs sophisticated software for object and facial recognition to ensure that employees maintain proper personal hygiene, as mandated by food safety laws. When a violation is detected, the system captures screen images in real-time, allowing for immediate examination and correction (Kurilyak 2019). Remarkably, this AI-driven approach achieves an impressive accuracy rate of over 96%.

The technology utilized in this context falls under the domain of artificial intelligence, specifically the computer vision system (CVS). The CVS combines pattern recognition and image processing methods to analyse and interpret visual data captured by the digital camera and lighting equipment. In general, AI grants computers the ability to learn and think in a manner to humans. Major tech companies like Facebook and Google have already harnessed AI for various applications, such as search suggestions and photo recognition. However, within the food industry, AI is still in its early stages as a tool for ensuring food quality and safety.

12 Developing a New Product

In the field of AI, machine learning and prediction algorithms play a crucial role in estimating consumer flavour preferences and forecasting how they will respond to new or novel flavours. By categorizing data into demographic groupings, businesses can gain valuable insights into the interests and tastes of their target market. This information is then utilized to create new products that align with consumer preferences, enabling companies to identify potential successful products even before they are launched in the market. An illustrative example of this is Coca-Cola's implementation of self-service soft drink fountains in numerous restaurants and other locations. These innovative fountains allow consumers to personalize their beverages by mixing various flavours and ingredients to create unique concoctions that cater to their specific tastes. The underlying technology in these fountains leverages AI algorithms to understand consumer preferences and tailor the available options accordingly. "Cherry Sprite" was the initial output of these data. Its AI found that consumers produced a lot of cherry-flavoured Sprite on their own and it would sell well as a stand-alone item.

13 Food Waste

Artificial intelligence holds tremendous potential in addressing food waste and alleviating global hunger. The statistics from the USDA indicate that a significant portion of food, approximately 30–40% in the United States, goes to waste. This waste amounts to billions of pounds of food that could otherwise be utilized to feed those in need. Furthermore, projections indicate that the number of hungry and undernourished individuals worldwide will surpass 2 billion by 2050. AI-driven solutions can play a pivotal role in tackling this problem. Food waste AI systems can analyse data on production, supply, and demand to identify instances of overproduction and avoidable waste. By understanding consumption patterns and adjusting production materials based on weather forecasts and changing population needs, AI can optimize resource allocation and minimize excess production. Additionally, AI-powered meal tracking apps can connect farmers' produce directly to food pantries, retailers, and restaurants, reducing waste by enabling the sale of less desirable crops before they become unsuitable for consumption. AI can efficiently sort and classify crops, ensuring proper delivery through optimized transportation routes. Overall, the integration of artificial intelligence and machine learning in the food sector promises to create more efficient systems that benefit the economy, improve customer health, and contribute to a more sustainable planet. By leveraging AI's capabilities, the food industry can take significant strides toward reducing waste, feeding more people, and addressing the pressing issue of global hunger.

14 Application of AI in Supply Chain

In response to the increasing demand for transparency, supply chain management has become a critical focus for all food companies. To ensure compliance with industry and consumer standards, AI is being leveraged across the food industry.

14.1 Efficient Supply Chain Management

AI is used to enhance food safety monitoring and product testing at every stage of the supply chain. Improved inventory and pricing management through forecasting. Products may be purchased more effectively and better thanks to AI-based picture recognition technologies. Moreover, AI facilitates efficient and transparent tracking of produce from the farm to the customer, which boosts consumer confidence.

14.2 AI Used in Food Delivery

Machine learning (ML) plays a crucial role in addressing various challenges in the food industry by providing effective solutions to complex problems which includes delivery routes, supplying raw materials, and forecasting demand for certain food items, and logistics planning. By coordinating the location of the delivery agent with existing or upcoming traffic conditions and then advising them in real time of the optimum path, ML can be used to handle delivery route challenges. It is simpler to supply consistent orders and even handle issues such as running out of delivery agents or late deliveries by assuring efficient and prompt delivery. Additionally, by utilizing ML, the volume of data that is collected grows over time and can then be examined using various artificial intelligence-based algorithms to create a more intelligent system. Advanced AI-based methods such as deep learning (DL), which provide users an edge over rivals, could be used to conduct this analysis (Keeble et al. 2020).

14.3 Anticipating Consumer Preference

Food companies adopt artificial intelligence-based solutions that allow them to precisely model and anticipate the flavour preferences of their target customers, as well as predict how they will react to such novel flavours. Predictive analytics powered by artificial intelligence will assist food producers in creating new food items that are closely matched to consumer preferences and tastes. The Kellogg Corporation used AI-enabled technology in 2017 to assist customers in deciding which 50 granola ingredients should be used to create a specific personalized product. The AI suggests ingredients for your granola and informs you on whether the combination of your ingredients will taste excellent. AI does more than just assist people in producing customized tiny batches of granola. A feedback loop is created by the general information from flavour combinations, information about the choices individuals makes, and information about the combinations people reorder. The parent firm will probably find much valuable information from this source when determining what new goods to launch across its much larger brands (Fig. 6).

15 Application of AI in Marketing

Artificial intelligence-based food discovery and recommendation engines are revolutionizing the way customers make food choices. There are front end or consumer facing applications of Artificial Intelligence in marketing.

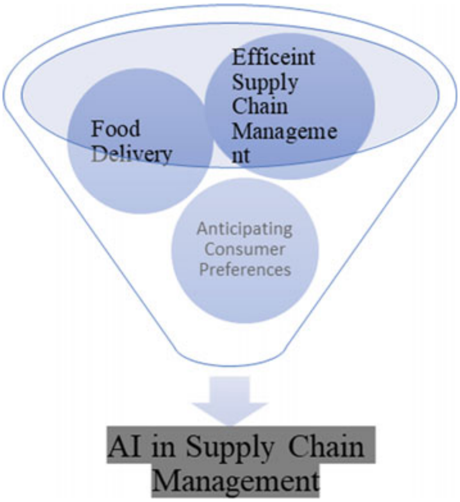


Fig. 6 AI in food supply chain management

15.1 Recommendation Engines

By using apps that learn about the consumer's food tastes, preferences, dietary requirements, and health goals, AI-powered recommendation systems can provide personalized and informed suggestions (Sennaar 2018). It has been seen that customers frequently choose a café, bar, or restaurant based on how well-reviewed its rivals are. As a result, it is critical for a company operating in the food and beverage sector to be aware of any positive or negative consumer experiences to draw in new clients or keep hold of current ones. Currently, Google searches or other online sources are used by most customers to learn about a restaurant.

15.2 Apps and Chatbot

Indeed, artificial intelligence-based virtual assistants, also known as chatbots, are transforming the customer experience in food establishments. By implementing these AI- powered digital assistants, businesses can ensure that clients do not have to endure long wait times when making inquiries or processing and customizing orders. Chabot's are specialized computers that mimic human communication and are designed to comprehend human language and interactions. They can handle user queries, provide accurate information, and respond to customer requests promptly and efficiently. This streamlined procedure improves the overall consumer experience by reducing wait times and enhancing the responsiveness of the service.

15.3 Self-ordering AI-Based Kiosks

Self-ordering devices powered by artificial intelligence can improve the customer experience by decreasing waiting times and the need for customers to stand in line to pay. With integrated card readers, these devices may accept customer orders and enable customers to make payments without human help. Customers appreciate the convenience of point-of-sale systems, commonly known as self-service systems, particularly in reputable restaurants. With the help of AI, these devices can offer customers comprehensive details about the dishes, including information about flavours, spices used, ingredient preferences, and even newly added items. This valuable information assists customers in making informed decisions and enhances their overall ordering experience. Restaurants that have adopted these automated self-ordering systems have witnessed significant improvements in various aspects of their operations. These technologies have been instrumental in addressing challenges such as staffing shortages, enhancing customer interactions, and reducing instances of incorrect orders (Rensi 2018).

15.4 Robots

Robots are starting to appear in restaurants, improving the capacity and speed of food production as well as cutting the duration for food delivery. While the widespread adoption of these technologies is still in its early stages, the advancement of artificial intelligence (AI) has opened possibilities for leveraging robotics' efficiency in the food industry. Various robotic technologies are being explored and applied in the food business, such as robotic arms for food processing and drone for food delivery. However, despite the potential benefits of robotic technologies, their widespread implementation in the food-based economy faces challenges related to cost-effectiveness. At present, the initial investment and maintenance costs of robots might be higher than hiring additional human workers, particularly in labour-intensive regions where human resources are more affordable.

15.5 Voice Assistants

According to estimates, 27% of users preferred voice search to traditional typing-based search. As a result, voice-based searching is being added to every food and other e-commerce sector, and a brand-new voice commerce platform such as Alexa by Amazon has been created. Now that eateries may use this feature, these voice commerce programmes can place instant orders from them even without looking at specifics, which is useful for new establishments (Leung and Wen 2020).

15.6 Revenue Prediction Using AI

The quality of the food and services provided by the owners is crucial for a functioning business such as a restaurant or food outlet. In addition to service and cuisine, a crucial aspect of the restaurant business is forecasting its sales production. For improved business growth and increased profit, the owners of food chains or restaurants must create a solid business strategy for their future operations. A sales forecast can be produced using several fitting algorithms in artificial intelligence. Finding a good fitting algorithm for sales prediction in the food sector, whether for a five-month forecast or a 14-month forecast, takes considerable time and work. Data science has made it possible to have sales estimates at your fingers now. Finding the most appropriate algorithm for a given business and quickly implementing it within that firm with an ideal AI development team are both made possible by data science (Sanjana Rao et al. 2021).

15.7 Advantages of AI

- **Availability 24 * 7**: Artificial intelligence machines can operate continuously without the need for breaks or rest, ensuring round-the-clock availability. Unlike human workers who have limitations in terms of working hours, AI systems can operate non-stop, leading to increased productivity and efficiency.
- **Reduction of Human error**: AI systems are designed to make decisions based on data and algorithms, minimizing the impact of human error. Unlike humans, AI does not get fatigued, distracted, or emotionally influenced, leading to more accurate and consistent outcomes in various tasks and processes.
- **Digital Assistance**: Chabot's and AI-based billing devices in eateries can save users' time while also providing tailored services.
- **Faster Decision**: Artificial intelligence also aids decision-making because our preferences are already loaded into these systems.
- **New Products**: AI is assisting in the creation of new products in practically every sector, including the food business.

15.8 Disadvantages of AI

- High cost of creation: Newer technologies or hardware and software are developed in AI at a rapid pace; therefore, machines must be fixed and maintained to be up to date and fulfil the current specifications, which incurs significant expenditures.
- Making humans Lazy: Most tasks are automated with the help of AI, and humans are becoming addicted to these technologies, which causes them to become lazy.
- Unemployment: Most people prefer robots for repetitive tasks and desire less human interference because AI robots can execute the same work more accurately than humans.
- Lacking out-of-box thinking: Machines just do what is programmed into them and what they are supposed to do; they do not think like humans.

16 Prospects of AI

Currently, the food industry is quickly evolving. According to a McKinsey report, technological advancements in artificial intelligence and machine learning will help the food business achieve a $100 billion worldwide market in the next five years. Technological businesses are utilizing the chance to reinvent how food is prepared and may be planned into a diet. Using artificial intelligence, IBM's chef Whatson with Bon Appetite created an application that can scan the chemical make-up of 100 components and evaluate them to produce thousands of dishes with the simple input of ingredient data. Dieticians are trusted by people with obesity and diabetes to advise them on what foods they should and should not eat. Physiological reports are used to create the diet charts. However, machine learning and data analytics will be utilized to develop strategies for a particular patient in this case, where AI and ML play a significant role. There are more opportunities for AI to develop if the food industry is viewed through the lens of the agricultural sector. According to mechanical engineers from the Britain Institute, crop production wastes 550 billion litres of water every year. Artificial intelligence has the potential to minimize this number and find a solution in the future. Food production might rise by 60% or even more if AI is effective in solving this issue. Due to machine learning, there will be many different wastewater solutions available. According to Nicola Sewell, marketing manager of AI-enabled food waste tracker winnow, “AI technology can now be used to each and every level of the food chain and can be the key transforming these processes, from initial production and farming through to the end product supplied.” AI can be utilized to provide guidance on climate change so that plants are grown in locations where they can grow. Artificial intelligence makes use of and evaluates the enormous amount of data that sensors, marketing, and warehouses acquire. By recognizing data patterns, machines can make judgments on their own with the help of appropriate algorithms. Future workplaces will be automated using AI and robotics and will have a greater prevalence of technology together with high-end vision systems, such as the use of hyperspectral cameras with AI to extend spectral capacities above and beyond human ability.

17 Conclusion

In conclusion, for a variety of purposes, including modelling, prediction, control tools, food drying, sensory evaluation, quality control, and tackling challenging issues in food processing, AI has been playing a significant role in the food business. In addition, AI can improve commercial tactics thanks to its capacity to forecast sales and enable yield expansion. Due to its simplicity, precision, and cost-effectiveness in the food business, AI is well known. In the food sector, the applications of AI, their benefits, and drawbacks, and how the algorithms work with various sensors such as the E-nose and E-tongue are critically compiled. Additionally, a step-by-step procedure for creating the appropriate algorithm has been proposed, which will help and encourage researchers and industry players to use the current technology, which has been shown to produce better results, before using an AI model in a field related to the food industry.

The use of artificial intelligence offers effective solutions that extend the life of farming operations. As a result, artificial intelligence is used in farming, making the job incredibly efficient and straightforward. These computerized frameworks have the advantage of providing consistent data over a range of durations, from hours to months, thus assisting in the development of cycle models that may be explicit to a certain time. The inferred intelligent models are also rather easy to transfer to a business setting, where they can subsequently be refined over the long term because these frameworks can be quickly applied in business nurseries.

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Plant Protein Hydrolysates as Healthier and Sustainable Nutraceutical

Vatsala Sharma and Monika Thakur

Abstract The pursuit of safer and more natural bioactive compounds has led researchers to explore plant protein hydrolysates as potential nutraceuticals. These hydrolysates, derived from different food sources, contain biopeptides with diverse biological functions, including antioxidant, antimicrobial, hypotensive, anticoagulant, cholesterol-lowering, and hypoglycemic effects. Nutraceuticals, which blur the line between food and pharmaceuticals, offer medical or health benefits and have gained interest in disease prevention and management. Plant protein hydrolysates have shown promise in enhancing human health and addressing specific health conditions. Understanding the bioactivity and physiological significance of these peptides presents opportunities for personalized nutrition and targeted health interventions. This review explores the potential benefits of plant protein hydrolysates as health-promoting and sustainable nutraceuticals, emphasizing the need for further research and clinical trials to validate their efficacy, safety, and stability during food processing. The integration of these innovative compounds into functional foods and nutraceutical products holds promise for improving human health and well-being in diverse populations. However, comprehensive research and regulatory scrutiny are essential to fully harness the therapeutic potential of these novel substances.

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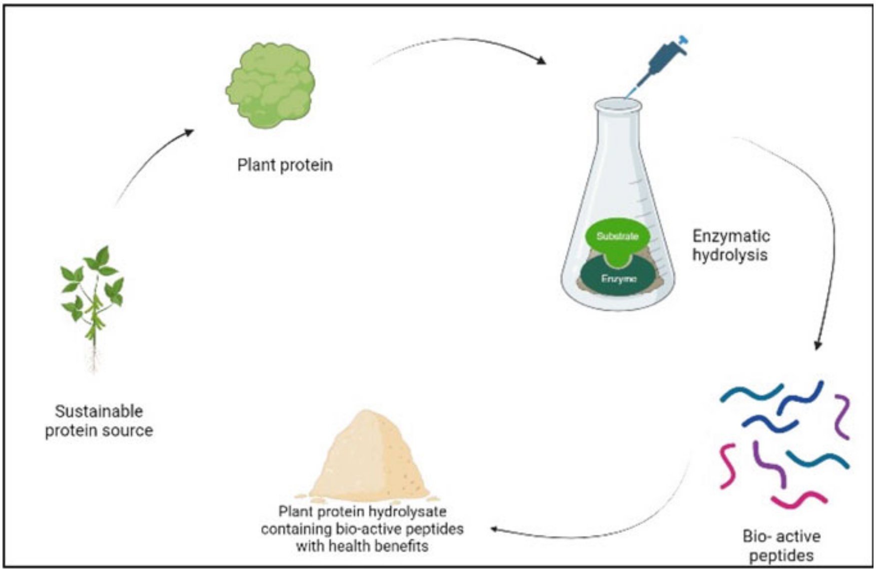

Keywords Plant protein · Enzymatic hydrolysis · Bio-active peptides · Nutraceuticals

1 Introduction

> The doctor of the future will no longer treat the human with drugs, but would rather cure and prevent disease with nutrition
>
> —Thomas Edison

The increasing interest in developing natural and safe bioactive compounds, such as antioxidants, antimicrobials, and antihypertensives, has led researchers to explore various sources with lower potential risks compared to synthetic alternatives (Thakur and Belwal 2022). These compounds show promise in preventing and treating degenerative diseases like hypertension, obesity, and cancer. Over the past few decades, numerous studies have highlighted the multifunctional benefits of protein hydrolysates derived from different food sources. Notably, protein hydrolysates exhibit diverse biological functions, including antioxidant properties (Udenigwe and Aluko 2012), antimicrobial effects (Salampessy et al. 2010), hypotensive activities (He et al. 2013) anticoagulant abilities (Nasri and Nasri 2013), cholesterol-lowering effects (Lassoued et al. 2014; Udenigwe and Rouvinen-Watt 2015) hypoglycemic effects (Nasri et al. 2015), and even antitumor actions (Xue et al. 2012). These beneficial functions are associated with biopeptides found in the protein hydrolysates, consisting of amino acid residues ranging from 3 to 50 in length. Interestingly, most food proteins contain inactive biopeptides within their parent protein sequences, which can be liberated through enzymatic hydrolysis during gastrointestinal digestion, food processing (such as milk fermentation), or exogenous proteolytic processes (Clare and Swaisgood 2000).

Defined as a complex mixture of oligopeptides, peptides, and free amino acids resulting from partial or extensive hydrolysis, protein hydrolysates hold significant potential in the nutraceutical arena (Saadi et al. 2015). On the other hand, biopeptides, or bioactive peptides, are peptides exhibiting beneficial pharmacological properties. The bioactivity of these peptides primarily depends on their unique amino acid compositions and sequences. Additionally, certain peptides have been identified to possess multifunctional activities attributed to their structural features, hydrophobicity, and charge (Meisel 2004).

2 Nutraceuticals

Nutraceuticals are food items or ingredients that provide medical or health benefits. This emerging category of products blurs the distinction between drugs and food, as they do not neatly fit into the legal classifications of either. Instead, they often occupy a grey area, overlapping between the two categories (Cencic and Chingwaru 2010).

In 1989, Stephen DeFelice, MD, the founder and chairman of the Foundation for Innovation in Medicine (FIM) located in Cranford, NJ, coined the term "nutraceutical". DeFelice defined nutraceutical as "a food (or a component of a food) that offers medical or health benefits, while also aiding in the prevention and/or management of diseases" (Santini and Novellino 2017) (Fig. 1).

Stephen De Felice's definition of nutraceuticals raises concerns about its overlap with the description of a food supplement, creating an uneven comparison between the two. While both claim health benefits, nutraceuticals are derived from or are a part of food, whereas food supplements consist of separate substances used to provide micronutrients when the body requires them. Nutraceuticals, whether sourced from

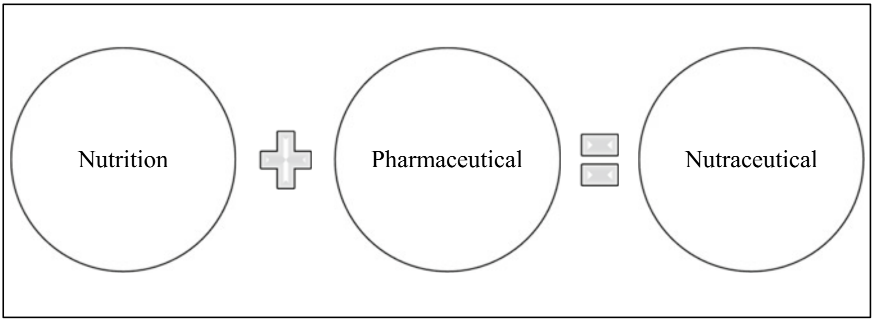

Fig. 1 Nutraceutical was coined from nutrition and pharmaceutical

plants (phytocomplex) or as active metabolite complexes (from animals), should be acknowledged as sets of pharmacologically active substances with inherent remedial, restorative, and curative properties due to their valuable active components. Proper administration of nutraceuticals, in appropriate pharmaceutical forms such as capsules, tablets, or beverages, is crucial, coinciding with the methods employed for drugs and food supplements (Gulati and Berry Ottaway 2006; Thakur and Modi 2020).

3 Benefits of Nutraceutical and Functional Foods

Functional foods and Nutraceuticals offer a myriad of potential benefits in promoting human health:

a. ***Enhancing the health value of our diet***: These specialized foods can provide additional nutrients, bioactive compounds, and other health-promoting substances that contribute to a more balanced and nutritious diet.
b. ***Prolonging lifespan***: Consuming functional foods and nutraceuticals has the potential to extend life expectancy by promoting overall well-being and reducing the risk of chronic diseases.
c. ***Disease prevention***: Functional foods and nutraceuticals may help individuals avoid certain medical conditions by supporting and strengthening the body's natural defense mechanisms.
d. ***Cognitive advantages***: Some functional foods and nutraceuticals have shown promise in providing cognitive benefits, improving memory, focus, and mental clarity.
e. ***Natural appeal and fewer side effects***: Many people perceive functional foods and nutraceuticals as more "natural" alternatives to conventional medicine, with a reduced likelihood of causing adverse side effects.
f. ***Disease treatment and cure***: Certain functional foods and nutraceuticals have demonstrated therapeutic potential in preventing, treating, and even curing specific health conditions and diseases.
g. ***Restoring physiological functions***: Nutraceuticals can help correct or modify physiological functions in the human body, contributing to better health outcomes.
h. ***Supplementing the diet***: Nutraceuticals act as dietary supplements, complementing and augmenting the nutritional content of regular meals.
i. ***Supporting disease management***: Functional foods and nutraceuticals can aid in the prevention and treatment of various diseases and disorders.
j. ***Versatile applications***: Nutraceuticals are designed to be used as conventional foods, as components of meals, or as sole items in specific diets, accommodating diverse dietary preferences and requirements.

Overall, functional foods and nutraceuticals hold great potential in promoting human health and well-being through their unique and multifaceted roles in diet enhancement, disease prevention and treatment, and physiological modulation. The increasing recognition of these benefits highlights their relevance in the quest for improved health outcomes and better quality of life (Pandey et al. 2010).

The growing demand for incorporating nutraceuticals and functional foods into our diet, aiming to promote health and reduce the risk of diseases, has prompted extensive research on amino acids, peptides, proteins, and protein hydrolysates. This research focuses on their precise biological and physiological functions beyond their fundamental nutritional contributions.

In recent times, an increasing number of individuals are seeking alternative approaches to address the effects of medical conditions, such as high blood pressure (BP), through the utilization of natural products obtained from natural sources, commonly known as nutraceuticals. Over the past decade, a growing body of controlled evidence has indicated that various food proteins and peptides exhibit specific biological actions in addition to their traditional nutritional value (Dean 1997).

4 Protein Hydrolysates and Its Characteristics

Protein hydrolysates are described as “combinations of polypeptides, oligopeptides, and amino acids derived from protein sources through partial hydrolysis” (Schaafsma 2009). Protein hydrolysates offer a rich source of functional protein, particularly beneficial in situations that demand additional protein, such as tissue repair after damage. The utilization of protein hydrolysates has demonstrated faster uptake of amino acids compared to whole proteins or free amino acids, with several peptides within the hydrolysates displaying signs of biological activity. Consequently, protein hydrolysates find application in enhancing tissue repair following surgical procedures, ulcers, burns, and muscle-damaging exercises (Thomson and Buckley 2011).

Food allergy affects approximately 5–6% of infants and young children, and its incidence appears to be on the rise, especially in developed nations. This condition leads to substantial morbidity, with severe and potentially life-threatening allergic reactions, placing a significant burden on both patients and their families (Pandey et al. 2010). Historically, hydrolysate formulas have been commonly employed in the management of food allergies and intolerances. These specialized formulas have been instrumental in addressing the needs of individuals who are sensitive or intolerant to certain food components. However, in recent times, hydrolysate formulas have also gained traction as a preventive measure for atopic disease in high-risk infants.

Hydrolysate formulas can be classified into two main categories: extensively hydrolyzed formulas (eHFs) and partially hydrolyzed formulas (pHFs). This categorization is based on the degree of hydrolysis and the length of the remaining peptides in the formula.

Extensively Hydrolyzed Formulas (eHFs) undergo a thorough process of hydrolysis, resulting in the breakdown of protein molecules into smaller peptide fragments.

These formulas contain peptides that are significantly smaller in size, making them less likely to trigger allergic reactions in individuals with food allergies or intolerances. As a result, eHFs have been the go-to option for infants and children with known food allergies or those at risk of developing such allergies. On the other hand, partially hydrolyzed formulas (pHFs) undergo a partial hydrolysis process, resulting in larger peptide fragments compared to eHFs. These formulas are designed for infants considered at high risk of developing allergies. Although they may not be as extensively broken down as eHFs, pHFs still offer a degree of hydrolyzation that can potentially reduce the risk of allergic reactions.

In conclusion, hydrolysate formulas have long been a staple in managing food allergies and intolerances, and their utility has extended to the prevention of atopic disease in high-risk infants. The classification of eHFs and pHFs based on the extent of hydrolysis and peptide length provides healthcare professionals with valuable tools to tailor the right formula to meet the specific needs of infants and children at risk of allergic conditions (Dean 1997).

Protein hydrolysates are produced through the breakdown of purified protein sources, achieved either by heating with acid or, preferably, by adding proteolytic enzymes and further refining the mixture through purification methods. Each protein hydrolysate is a complex composition of peptides with varying chain lengths, along with free amino acids. The extent of peptide bond cleavage in the original protein is represented by a universal value known as the degree of hydrolysis (DH).

The DH value provides insight into the proportion of peptide bonds that have been cleaved during the hydrolysis process. However, it is essential to note that two protein hydrolysates, despite having the same DH value, may have been created using different methods, resulting in distinct compositions. For example, one hydrolysate may contain mostly oligopeptides and significant free amino acids, while another may be predominantly comprised of dipeptides and tripeptides. Consequently, although they share a similar DH value, their absorption characteristics and biological activities are likely to differ significantly.

Hence, it is crucial to recognize that not all protein hydrolysates are created equal. Their specific compositions and peptide profiles can have diverse implications for their functionality and effectiveness. The selection of an appropriate protein hydrolysate should be based on its intended use, target application, and the desired physiological outcomes, taking into account factors such as peptide length and free amino acid content. Understanding these distinctions will enable the formulation of protein hydrolysates tailored to meet spec ific nutritional or therapeutic needs more effectively (Schaafsma 2009).

Protein hydrolysates play a significant role in the development of specialized foods, catering to the unique nutritional needs of various population groups. These targeted food products are specifically designed for children, elderly individuals, and athletes, providing them with tailored nutritional support.

For children, protein hydrolysates are utilized in the formulation of infant formulas and baby food to meet the delicate nutritional requirements during early growth and development. These hydrolysates offer easily digestible and hypoallergenic protein sources, making them suitable for infants with food allergies or intolerances.

For the elderly, protein hydrolysates are incorporated into dietary supplements and functional foods to support their nutritional needs as they age. These hydrolysates are chosen for their improved digestibility and bioavailability, promoting better nutrient absorption for the elderly population.

Athletes also benefit from the use of protein hydrolysates, especially in sports nutrition products. These hydrolysates offer rapid delivery of amino acids to support muscle recovery and enhance performance after intense physical activities.

In addition to special foods, protein hydrolysates find applications in pharmaceutical preparations aimed at convalescent patients and individuals with digestion-related disorders. For convalescents, protein hydrolysates are used to facilitate the healing and recovery process after illness or surgery. The hydrolyzed proteins ensure easy assimilation and provide essential nutrients during the recovery phase.

For those suffering from digestion-related disorders, protein hydrolysates offer a valuable alternative to whole proteins. The hydrolyzed proteins are broken down into smaller peptides and amino acids, which are less likely to trigger adverse reactions, making them suitable for individuals with sensitive digestive systems or certain medical conditions.

In summary, protein hydrolysates are versatile ingredients that find purpose in a wide range of specialized foods and pharmaceutical preparations. Their unique properties, such as improved digestibility, hypoallergenicity, and rapid absorption, make them valuable components in catering to the diverse nutritional needs and health requirements of specific population groups.

5 Absorption of Protein Hydrolysates in Human Body

Conventionally, it is widely acknowledged that dipeptides and tripeptides are typically absorbed intact following digestion by luminal and brush-border peptidases in the small intestine. These smaller peptide fragments are readily assimilated into the bloodstream without the need for further breakdown.

In contrast, tetrapeptides and larger peptides seem to necessitate prior hydrolysis by brush-border enzymes before they can be effectively absorbed. Brush-border hydrolysis involves additional enzymatic cleavage of these larger peptides into smaller fragments, such as dipeptides and tripeptides, which are then absorbed intact.

The process of brush-border hydrolysis plays a crucial role in maximizing the absorption of peptides into the body. By breaking down larger peptides into smaller, more easily absorbable forms, the body can efficiently utilize the amino acids and peptides derived from dietary proteins for various physiological processes. Overall, the digestive system's ability to selectively absorb different peptide sizes reflects its sophisticated mechanism to optimize nutrient absorption, ensuring that essential amino acids and peptides are efficiently transported to where they are needed in the body for growth, repair, and other vital functions (Thomson and Buckley 2011).

Moreover, three key points can be highlighted:

- The breakdown of tetraglycine in the human jejunum is mainly achieved through hydrolysis by brush border oligopeptidases.
- The rate-limiting step in the absorption of glycine from tetraglycine or longer peptides is attributed to the hydrolysis of these peptides into absorbable products, specifically di- and triglycine.
- The rate of glycine uptake is significantly higher from di- and triglycine than from free glycine.

To summarize, the hydrolysis of tetraglycine, facilitated by brush border oligopeptidases, plays a critical role in glycine absorption. The conversion of longer peptides to di- and triglycine is a crucial step in the efficient uptake of glycine, making it more accessible for the physiological processes of the body compared to free glycine (Adibi and Morse 1977).

Therefore, it is commonly accepted that protein hydrolysates, primarily composed of di- and tripeptides, are absorbed more quickly than intact proteins.

6 Plant Protein Hydrolysates with Nutraceutical Potential

Plant protein hydrolysates, derived from various plant sources through enzymatic or chemical processes, have gained substantial attention due to their promising nutraceutical potential. These hydrolysates are composed of smaller protein fragments, peptides, and amino acids, which offer enhanced bioavailability and physiological benefits. The enzymatic hydrolysis of plant proteins breaks down complex structures into bioactive components that exhibit antioxidant, antihypertensive, and anti-inflammatory properties. These attributes make plant protein hydrolysates appealing candidates for the development of functional foods, dietary supplements, and pharmaceutical products aimed at promoting health and preventing chronic diseases. Notably, studies have demonstrated the nutraceutical potential of plant protein hydrolysates from sources like soy, pea, rice, and wheat. However, further research is needed to uncover their full range of bioactivities, optimize production processes, and ensure safety and efficacy for human consumption (Sharma and Thakur 2022).

Protein hydrolysates have been the subject of various recent studies, which have identified individual peptides within them exhibiting specific bioactive properties.

These studies have delved into the intricate composition of protein hydrolysates, uncovering peptides with unique functional properties. These bioactive peptides have demonstrated various health benefits, such as antioxidant, antimicrobial, anti-inflammatory, and immune-modulating effects. They may also play roles in promoting cardiovascular health, improving digestive function, and supporting overall well-being.

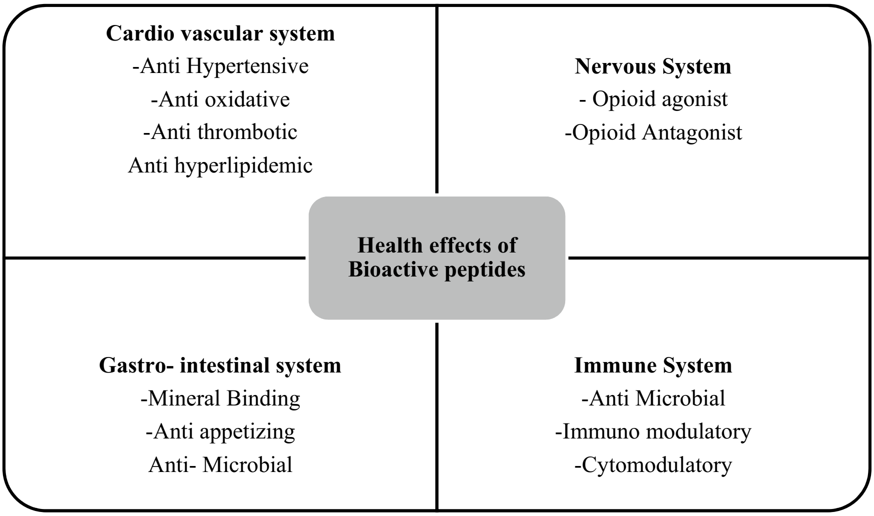

Fig. 2 Physiological effects of food derived bioactive proteins on major body systems

The identification of these bioactive peptides within protein hydrolysates has sparked interest in their potential applications in functional foods, dietary supplements, and pharmaceutical preparations. Researchers are exploring ways to harness these specific bioactivities to target and address specific health conditions (Fig. 2).

As our understanding of protein hydrolysates continues to advance, there is increasing excitement about the possibilities they hold for developing innovative and targeted nutritional solutions. These bioactive peptides have the potential to contribute significantly to the emerging field of personalized nutrition, where individualized dietary approaches can be tailored to meet specific health needs and goals. Moreover, their use in functional foods and dietary supplements can aid in enhancing overall health and well-being in diverse populations.

In summary, recent studies have shed light on the presence of single peptides with distinct bioactive properties within protein hydrolysates. This discovery opens up exciting opportunities for exploiting these peptides in various nutritional and therapeutic applications to support human health and disease prevention (Hori et al. 2001; Jang and Lee 2005; Ma et al. 2006; Adibi et al. 2015). The utilization of food protein-derived peptides is gaining popularity and interest in the pursuit of enhancing health and combating chronic lifestyle disorders to promote overall well-being. Enzymatic hydrolysis, employing enzymes like papain or bromelain, is employed to liberate peptide sequences from proteins. Subsequently, bioactive peptides are isolated from the complex mixture of other inactive molecules through further processing of the obtained enzymatic protein hydrolysates.

The bioactive peptides extracted and isolated from these hydrolysates exhibit medicinal properties that extend beyond the realm of regular and sufficient nutrition. These peptides possess beneficial attributes, demonstrating potential therapeutic effects and health-promoting properties. Emphasizing their bioactivity and physiological significance, they hold promise for interventions against various health conditions and improving overall health and well-being (Darewicz et al. 2011). The substance in question showcases a remarkable array of potent biological activities, encompassing several vital health benefits. Its efficacy has been demonstrated in various scientific studies, revealing its capacity to exert beneficial effects on the human body.

Notably, it possesses significant anti-hypertensive properties, meaning it has the potential to help regulate blood pressure levels, which is crucial for maintaining cardiovascular health. Additionally, it exhibits powerful anti-oxidative properties, acting as a defense against harmful oxidative stress and mitigating cellular damage caused by free radicals. Furthermore, this substance demonstrates immunomodulatory effects, implying that it can modulate and strengthen the immune system, bolstering the body's natural defenses against infections and diseases. Moreover, it shows anti-cancerous properties, potentially impeding the growth and progression of cancer cells, thus representing a promising avenue in cancer prevention and treatment research.

Additionally, its anti-microbial properties make it a valuable asset in combating various harmful microorganisms, helping to protect against infections and contributing to overall health maintenance.

Moreover, the substance has shown anti-cholesterolemic activities, indicating its potential in reducing cholesterol levels, which is crucial for maintaining cardiovascular health and mitigating the risk of heart disease. Overall, the diverse and efficacious biological activities displayed by this substance make it a compelling candidate for further research and potential incorporation into health-promoting products and therapeutic interventions. Its wide-ranging health benefits hold promise in addressing various health conditions and supporting overall well-being (Hartmann and Meisel 2007).

Bioactive peptides are inherently present in plant and animal proteins, initially in an inactive form represented by specific amino acid sequences. However, these peptides can be activated through various means, including fermentation, food processing, and enzymatic proteolysis, either in vitro or during the digestive process within the human body (Hartmann and Meisel 2007; Darewicz et al. 2011). The bioactivity of peptides is influenced by several factors, such as the specific enzymatic process employed for hydrolyzing the parent protein, the processing conditions, and the resultant peptide size. These variables have a significant impact on the absorption and bioavailability of the peptides (Rutherfurd-Markwick and Moughan 2005).

7 Conclusion

Ensuring adequate nutrition throughout all stages of life is paramount for the effective functioning of the body. Nutrients play a vital role in supporting essential life processes, and any deficiency can lead to functional abnormalities with potentially life-threatening consequences. Protein deficiency, especially in the form of Protein Energy Malnutrition (PEM) in children and sarcopenia in adults, poses serious health risks and underscores the importance of maintaining sufficient protein intake.

Premature infants are particularly vulnerable to inadequate protein intake, leading to poor growth and potential complications. Nutraceuticals and functional foods have emerged as promising tools to enhance health, prevent diseases, and address specific health conditions. They offer a range of potential benefits, including improved cardiovascular health, enhanced cognitive function, and disease prevention.

The use of protein hydrolysates, derived from plant and animal proteins, has shown promising results in various studies. These hydrolysates contain bioactive peptides with specific health benefits, such as antioxidant, antimicrobial, anti-inflammatory, and immune-modulating effects. The discovery of these bioactive peptides has fueled interest in their application in functional foods, dietary supplements, and pharmaceutical preparations.

However, the bioactivity of these peptides is influenced by various factors, including the enzymatic process used for hydrolysis, processing conditions, and resultant peptide size. Therefore, further research and clinical trials are essential to validate their biological activity, safety, and efficacy, and to address concerns regarding stability during food processing, organoleptic properties, and the mechanism of absorption in the gastrointestinal tract.

In conclusion, the exploration of protein hydrolysates and their bioactive peptides opens up new avenues for personalized nutrition and targeted interventions to promote health and combat chronic diseases. Harnessing the potential of these bioactive compounds in functional foods and nutraceuticals has the potential to improve human health and well-being. However, continued research and regulatory scrutiny are necessary to fully unlock the therapeutic potential of these innovative products.

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Mycotoxins and Toxic Fungus in Food: Prevention and Sustainable Management Techniques

Deepshikha Thakur and Saiatluri Teja

Abstract Most of the mycotoxin contamination of foods is caused by a few of the prevalent mycotoxigenic fungus such, *Aspergillus*, *Alternaria*, *Fusarium*, and *Penicillium* spp. They seriously jeopardise the quality and safety of food. Due to their toxicity, aflatoxins, ochratoxins, fumonisins, and other mycotoxins are known to raise questions about food safety. Many serious health problems such as carcinogenicity, toxicity, nephrotoxicity, neurotoxicity, hepatotoxicity and many more are associated with these toxins in both humans and animals. The risk of fungal growth and mycotoxin production is further increased by the environmental conditions like high temperature and humidity. Other factors such as pH, fungal strain, and substrates also affect the fungal contaminations and productions of mycotoxins in food. The mycotoxin contamination is controlled by an integrated approach that initiates in the field preceding the planting and continues throughout the food chain. Adoption of the good practices such as good harvest practices, suitable drying measures and safe storage practices help minimize contamination at every step in order to deliver the safe products. Since mycotoxin compounds are extremely persistent, contamination in food is unavoidable. However, there are a number of physical, chemical, and biological strategies that can be used to help reduce contamination. In addition to ensuring that the standards are upheld, the regulations serve to keep food markets free from highly contaminated products. Following control management measures to prevent mycotoxigenic fungus from contaminating food and feed is crucial for ensuring food safety.

Keywords Mycotoxins · Control · Fungi · Food contamination · Mycotoxigenic fungus

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1 Introduction

In the field, during harvest, transportation, or storage, fungi can cause agricultural products to decay, which can lower the production and value of the commodity (Ban Koffi et al. 2017; Russo et al. 2019). Even though there are over 100,000 species of fungi known to exist, only a select few of them, particularly *Aspergillus* spp., *Penicillium* spp., and *Fusarium* spp., are known to produce the majority of the mycotoxins that have a substantial impact on agriculture. Throughout the world, these species can be found in a variety of culinary products. The quality and safety of agricultural products are more at danger from filamentous fungus among the related microorganisms (Adetunji et al. 2020). This is because numerous filamentous fungi create poisons that have detrimental economic effects on a variety of items, such as cereals, almonds, tea, pistachios, and cotton seeds (Alshannaq and Yu 2017). Eltariki et al. (2018) estimate that fungal metabolites are present in 25% of the world's agricultural products. Their relative predominance in West Africa shows that the region's tropical climate (high temperature and humidity) is ideal for their development and the airborne distribution of their spores. It is well recognised that these toxigenic fungi (Fig. 1), which create secondary metabolites known as mycotoxins, have an impact on foods such maize, rice, beans, yam, cassava, peanuts, spices, and chilies (Abiala et al. 2011).

Due to their negative consequences, mycotoxins pose a severe risk to the safety of food around the world. According to Adebo et al. (2021) and Moretti et al. (2019), mycotoxins are thought to be the cause of approximately USD 932 million in annual financial losses in agricultural commodities. Between 60 and 80% of food crops are thought to have them. These mycotoxigenic fungi, such as *Aspergillus, Alternaria, Fusarium*, and *Penicillium spp.*, produce low-molecular-weight toxic metabolites that can contaminate different types of foods and feeds during the pre-harvest, post-harvest, and storage management chains of foods (Emmanuel et al. 2020; Gavahian et al. 2021).

Mycotoxins have been classified as harmful in over 400 occasions. According to Bennett and Klich (2003), mycotoxins made by fungi include:

- AFs–Aflatoxins
- BEA–Beauvericin
- CIT–Citrinin
- DON–Deoxynivalenol
- FBs–Fumonisins
- OTs–ochratoxins
- T2 toxin–trichothecenes
- ZEN–Zearalenone

According to Abd-Elsalam and Rai (2020), the term "mycotoxicoses" broadly refers to conditions that affect people or animals as a result of consuming foods, substrates, or inhaling mycotoxins released by fungus spores. According to Escriva et al. (2015), mycotoxins can cause serious to life-threatening diseases in both people

Fig. 1 Nuts contaminated with *Aspergillus flavus* (**a**), *A. niger* (**b**), *Penicillium sp* (**c**), *Fusarium sp* (**d**)

and animals. Prolonged exposure can impair human immune systems, central nervous systems, and possibly cancer (Denham et al. 2019; Fleurat-Lessard 2017). According to Escriva et al. (2015), short-term exposure to large mycotoxin dosages can occasionally have severe side effects that are fatal. Animal feed contaminated with mycotoxins, like human feed, can result in vitamin shortages, chronic illnesses, impairment to the health of animals, eventual mortality, and lower productivity (Luo et al. 2018).

The likelihood of mycotoxin contamination of food may increase as a result of environmental, agronomic, and socioeconomic variables. However, by monitoring at all stages of processing and creating the appropriate circumstances, the prevalence of mycotoxigenic fungus and, subsequently, mycotoxins in food items, can be decreased. The majority of poor countries adopt the legal systems of wealthy countries, claim Matumba and Poucke (2015). It is crucial to monitor and evaluate fungi and their secondary metabolites, especially in developing nations with lax legal regimes. The roles of fungus and mycotoxins in food spoiling on a global or local scale have been clarified by numerous research (Gruber-Dorninger et al. 2019; Schatzmayr and Streit 2013; Wu and Guclu 2012).

To reduce and/or eliminate mycotoxins from food, we urgently need the right tactics and methods. The bulk of these processes, such as vitamin breakdown, lipid oxidation, and polysaccharide depolymerization and repolymerization, have the potential to significantly alter the color, flavor, texture, and nutritional value of the food substrate (Zhang et al. 2019). This chapter addresses the prevention of mycotoxins and dangerous fungi in food.

2 Factors Affecting the Development and Contamination of Mycotoxin in Food

Infected grains, goods made from grains, and food derived from animals that have been exposed to mycotoxins are the most prevalent ways that people are exposed to them (Persi 2014). Many different types of food and agricultural products can develop mycotoxins. Because mycotoxin contamination is an accumulative process that can begin in the field and intensify during later stages including harvesting, drying, and storage (Richard et al. 2003), it frequently happens at several points along the food chain.

The food safety management system (FSMS), a system of readiness, inspections, and prevention for managing food hygiene and safety in food operations, has been suggested as a feasible strategy to influence or avoid the formation of mycotoxin in agricultural goods and foods (Nada et al. 2022). Due to the diversity of mycotoxin-producing fungi and their target hosts, it is difficult to characterize a single set of characteristics that lead to mycotoxin contamination. The primary factors that affect mycotoxin development are frequently temperature, aw, relative humidity, pH, fungal strain, and substrate (Daou 2021). As a result, it is impossible to identify a certain temperature and water activity range as promoting fungal activity.

Climate factors like temperature, water activity, and relative humidity have a substantial impact on the presence of fungus (Smith et al. 2016). These factors, according to Doohan et al. (2003), affect the development of mycotoxigenic fungus' hazardous byproducts as well as their growth, survival, dissemination, and frequency. Temperature and humidity have an impact on the growth, well-being, and competitiveness of mycotoxigenic fungi as well (Richard et al. 2003). For growth, germination, and the production of mycotoxin, each variety of fungus has specific needs for temperature and water activity. Variations in the microecosystem and the amount of moisture in the environment have an impact on the production and potency of mycotoxins. When humidity and temperature conditions are favorable for fungal invasion to take place and occur at various stages, whether on the field or later during drying or storage, it is sometimes impossible to clearly distinguish the stage in which fungal growth was initiated (Perdocini et al. 2019; Joubrane et al. 2020). Because Fusarium and other hygrophilic species require a relative humidity of 90% or higher to germinate and thrive, they predominate on the field during the pre-harvest period. Mesophilic and xerophylic species, such as Aspergillus species and Penicillium species, germinate, multiply, and produce mycotoxins at relative humidities of

80 to 90% and 80% and less, respectively (Mannaa and Kim 2017). Hygrophilic fungus disappear after harvest.

It's likely that the production of mycotoxin is not always a result of favorable microbial growth circumstances. However, in general, temperatures between 25 and 30 °C, water activities more than 0.78, and relative humidity levels between 88 and 95% are conducive to fungal growth and consequent mycotoxin production (Thanushree et al. 2019). For instance, it has been discovered that a larger range of environmental factors can support *Aspergillus spp.* germination than those that promote fungal growth, which can happen under more diverse environmental factors than mycotoxin production (Mannaa and Kim 2017). Increased media sugar content has been linked to increased AFB1, and water activities that are induced or easily accessible for breakdown prevent the creation of mycotoxin.

The pH of the environment where the fungus are growing and producing mycotoxin is important. The fungi's growth is influenced by the pH level or the saturation of hydrogen atoms in the surrounding liquid, either directly on the cell surfaces or indirectly on the availability of nutrients. Fungi have the ability to change the pH of their surroundings by secreting acids or alkalis. For instance, *Pennicilium* sp. and *Aspergillus* sp. can acidify their surroundings by doing so (Vykova 2017). The ability to adjust pH increases the fungi's likelihood of surviving inside the host. On the other hand, as pH has an impact on metabolic processes, particularly those connected to sporulation and morphogenesis, it can modify how aw and temperature interact (Wang et al. 2017). As an illustration, according to Brzonkalik, "the genes responsible for OTA production in *P. verrucosum* are expressed at pH 8" (Brzonkalik et al. 2012). pH value has also been demonstrated to alter the expression of the biosynthetic genes. Although the impact of pH on the creation of each type of mycotoxin has not yet been defined, it is generally accepted that acidic circumstances encourage germination and the synthesis of mycotoxin. For instance, a pH of 4.0 is required for the creation of aflatoxin, and in this case, the higher the synthesis, the lower the pH (Perdocini et al. 2019; Reverberi et al. 2010). Similar to this, Aspergillus ochraceus is found at considerably greater levels of OTA when the pH level is lower (Brzonkalik et al. 2012). In contrast, trichothecene production is also stimulated by acidic circumstances (Reverberi et al. 2010), as fumonisin B1 is unstable in an alkaline medium and requires a pH of 4.0−5.0 to be synthesised.

The production of mycotoxins is occasionally restricted to certain types of fungi and frequently even to particular strains within a species, and the toxicity of fungi varies greatly (Nicholson 2004). Additionally, Laubscher et al. claim that "strain specificity, variation, and instability" have an impact on mycotoxin production (Greeff-laubscher et al. 2019). This is obvious because various strains of the same species may create different kinds of mycotoxins and because within the same species, strains might exhibit variations in the ideal conditions required to promote development and toxin generation. In contrast to Aspergillus carbonarius, which thrives at a greater temperature range of 8–40 °C and produces OTA, Aspergillus flavus may grow at a temperature range of 15–44 °C and produce AFB1 (Mannaa and Kim 2017).

Mycotoxigenic fungi may grow on a variety of substrates, but it's still unclear why they prefer certain foods over others. Substrates play a significant part in their growth. Moulds can be found on practically all types of food, though, because the nutrients necessary for their growth—primarily carbon and nitrogen—are generally present in food products, particularly those that are high in carbs (Kokkonen et al. 2005). The conditions that encourage toxin formation are typically more restricted than those needed for growth, therefore substrates that enable fungal growth should not necessarily be thought of as supporters of mycotoxin generation. In general, the interaction of various elements in a substrate, including pH, temperature, and composition, notably the presence of simple sugars, has a major impact on the development of mycotoxins (Zcelik 2004). Limitations on fungal growth, germination, and mycotoxin generation are imposed by the interaction of many elements within a substrate because, even in the presence of all encouraging factors, the absence of one single ingredient may still impair fungal growth and prevent its development. Numerous studies have shown that osmotic pressure in a substrate influences fungal growth and the formation of mycotoxins, and it also plays a role in influencing the physiological responses of the fungus (Duran et al. 2010). According to Liu et al. (2016a, b), increasing the concentration of soluble sugars to 3.0 and 6.0%, particularly sucrose, maltose, and glucose, encouraged the production of AFB1 in cell culture. Similar to this, Uppala et al. (2013) demonstrated that increasing the sugar content of the medium led to an increase in A. flavus AFB1 production.

Environmental changes are anticipated as a result of climate change, including an increase in global temperature that is projected to rise by 1.5−4.5 °C by the end of the twenty-first century (Vander et al. 2016). Precipitation is likely to increase, and extreme weather events including heat waves and long, harsh winters, flooding, and droughts are all predicted. Within the next 25−50 years, the content of carbon dioxide in the atmosphere is predicted to double or triple (Medina et al. 2015), which will accompany this transition. Climate change and global warming can have a significant impact on food security by lowering crop yields, lowering crop quality, and increasing the number of food safety concerns that make some goods unfit for human consumption. Since mycotoxins are primarily influenced by environmental factors, global change is predicted to have an impact on many components of the food chain, particularly in relation to mycotoxins (Miraglia et al. 2008). The majority of fungi are aerobic (Ivarsson et al. 2016); but, a small number of them may be facultatively anaerobic organisms, like yeasts, and as a result, their biomass is not influenced by elevated CO_2 levels (Brzonkalik et al. 2012). Climate change and changes in temperature and humidity may have different effects on mycotoxin production since fungal growth, germination, and production are influenced by environmental factors and occur under a specific set of ideal conditions. For instance, some mycotoxins that are normally produced at low temperatures might not be produced as the temperature shifts to higher levels, while others, like aflatoxins, which are dominant in sub-tropical and tropical regions, might begin to be produced in typically temperate regions as a result of those regions' anticipated increase in temperature. This was previously demonstrated in Italy, where a series of hot and dry episodes in 2003 and 2004 led to the colonisation of *Aspergillus flavus*. Therefore, depending on the frequency of their ideal production conditions, each mycotoxin will be impacted differently. The increase in pest and insect populations, their global spread, and attacks, the early maturation and ripening of crops, the reduction in plant resilience, and the change in host pathology brought on by the presence of CO_2 in the atmosphere are all indirect effects of climate change that can have an impact on the global mycotoxin contamination (Medina et al. 2015, 2017; Paterson 2011).

3 Common Mycotoxins of Food Crops

When foods are contaminated by microbes as a result of improper food processing and storage techniques, mycotoxicoses are common in developing nations (Aasa et al. 2022). It is general knowledge that a variety of common toxins, including AFs, ochratoxin A, FBs, and ZEN, are harmful and raise questions about the safety of food (Chilaka and Mally, 2020; Hamad et al. 2022). In contrast to FBs, OTs, and aflatoxins, which are classified as Group 2B potential human carcinogens, Group 1 human carcinogens, and Group 1 human carcinogens, respectively, Omotayo et al.'s (2019) classification of ZEN indicates that it is not a human carcinogen. Thus, these three toxins (AFs, FBs, and OTs) provide serious health risks and will be more thoroughly examined.

3.1 Aflatoxins

Aspergillus species, such as *A. flavus, A.s parasiticus*, and *A. nomius*, produces toxins known as aflatoxins (Coppock et al. 2018). They may thrive on agricultural plants, stored foods, and animal feed. Aspergillus species, which are typically found in dry grains, nuts, herbs, and spices, are responsible for food spoilage (Paterson and Lima 2017).

3.2 Fumonisins

South African researchers initially defined and described fumonisins in 1988 (Beukes et al. 2017). *F. verticilloides* and *F. proliferatum* have been identified as the most notable producers discovered in feed and food products, and they are created by at least 14 different species of *Fusarium* (Ferrigo et al. 2016; El-Sheikha 2019).

3.3 Ochratoxins

Aspergillus ochraceus produces a group of secondary metabolites known as ochratoxins, which were first discovered in South Africa in 1965 (Hatting et al. 2019). The analogues of ochratoxins include ochratoxin A (OTA), B (OTB), C, alpha, and beta (Aroyo-Manzanares et al. 2017). Numerous articles have demonstrated that *Aspergillus* and *Penicillium* species can create OTs (Koszegi and Poor 2016).

3.4 Emerging Mycotoxins

New *Aspergillus, Penicillium*, and *Fusarium* mycotoxins have been discovered recently thanks to improvements in mycotoxin research (Fig. 2).

4 Control Strategies

Hungaryo et al. (2015) identified two methods for reducing mycotoxins: (1) Detoxification of mycotoxins that are already present in food products (2) Prevention or suppression of fungal development (Hathout and Aly 2014). Crop rotation, tillage, irrigation, and adequate pesticide usage are examples of pre-harvest practices that have been implemented utilizing good agricultural practices (GAP) (Devreese et al. 2013). The growth of fungi and the formation of mycotoxin can be stopped by planting crops that are resistant to fungi (Haque et al. 2020). Other agronomic practices to lower the danger of fungus infection and mycotoxin contamination of agricultural goods include early harvesting, appropriate drying, proper storage, and pest management (Wagacha and Muthoni 2008).

In addition, mycotoxins are frequently managed by applying heat (Fleurat-Lessard, 2017), radiation, and extrusion (Vanhoutte et al. 2016). In order to sterilise or degrade food, cold plasma application (Millan-Sango et al. 2015) and microwave treatment have been suggested (Mai-Pronchnow et al. 2014). To decrease the mycotoxin contamination of foods and feeds, several compounds have been utilised. These include lactic acid (Aiko and Metha, 2015), ammonia, bisulfites, and ozonation (Wyk and Prinsloo 2020) as well as hydrogen peroxide and ozonation. AFB1 in agricultural goods can be decreased with the help of salicyclic, silphamine, sulfosalicyclic, anthranilic, benzoic, boric, and propionic acids (Xing et al. 2017). Although synthetic fungicides are expensive and can degrade food quality, their use is nonetheless encouraged to limit fungal growth (Jard et al. 2011; Loi et al. 2017).

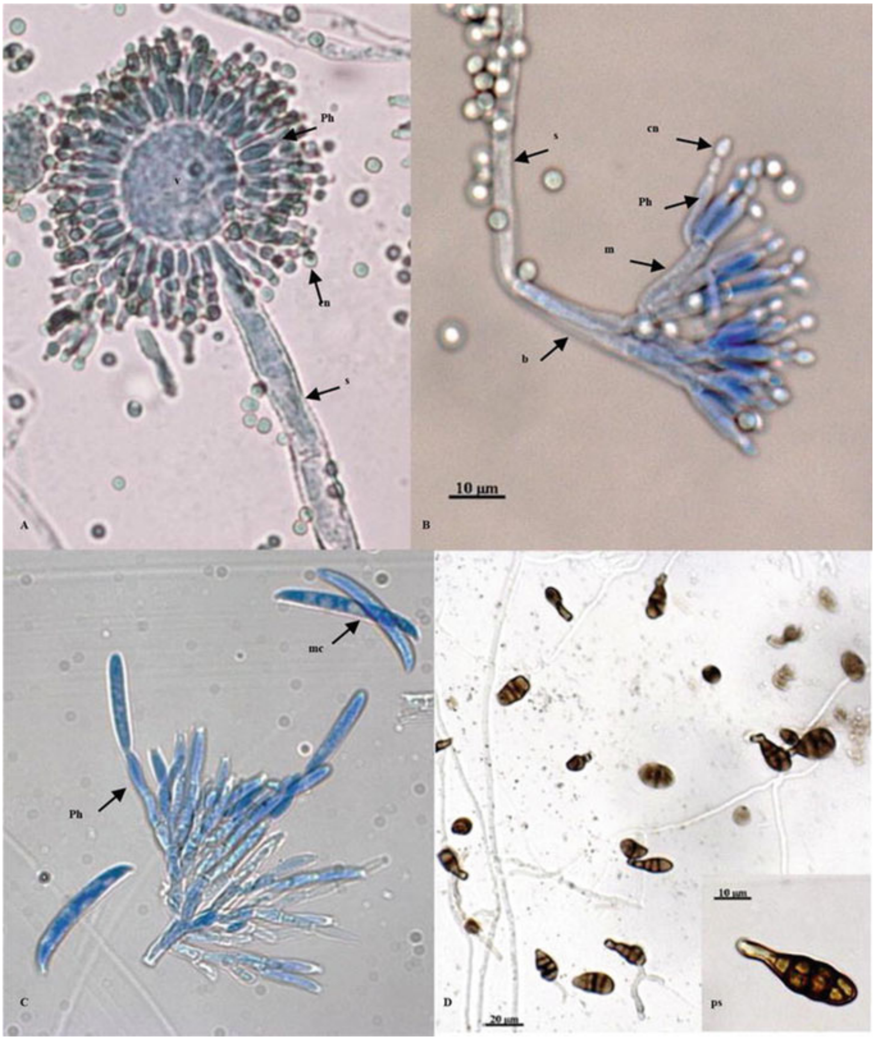

Fig. 2 Microscopic characteristics of *Aspergillus sp.* (**A**), *Penicillium sp.* (**B**), *Fusarium sp.* (**C**), *Alternaria sp.* (**D**). cn = conidia; Ph = phialides; v = vesicle; m = metulae, s = stipe; b = branch; mc = macroconidia; ps = pluriseptate conidium of Alternaria sp. Scale bar: **A**–**C**= 10 µm; D = 20 µm (Mirabile, 2021)

5 Innovative, Modern Techniques to Reduce Mycotoxin Contamination of Food

The desire for sophisticated methods to reduce mycotoxin contaminations, toxicity, and related illnesses without hazardous residues on foods and with little impact on quality is a result of rising consumer awareness of food safety. Among these cutting-edge methods are:

- *Cold atmospheric plasma (CAP),*
- *Polyphenols and flavonoids, magnetic materials and nanoparticles,*
- *Natural essential oils (NEOs).*

It has been demonstrated that ZON generates reactive oxide species (ROS), which can damage a cell's lipid bilayer cell membrane and result in a total cell breakdown (Pietrzak et al. 2015). This was shown by the surface of the fungus hyphae developing strange bulges and distortion after exposure to 12 mmol/L ZON. In another study, it was proposed that the relaxed polysaccharide structure of chitosan in a quercetin (Q)-loaded chitosan (CS) nanoparticle was cross-linked with tripolyphosphate (TPP), with the quercetin entrapped in the CS structure to trigger a hepato-protective cascade that leads to antioxidant protection via the stimulation of nuclear factor E2-related factor 2 (Nrf2)-induced heme-oxygenase-1 (HO-1) production (Sun et al. 2018).

Through the actions of IB kinase (IKK) and p38 mitogen-activated protein kinases (p38MAPK), quercetin reduces the synthesis of NO and the nitric oxide synthase (iNOS) that is stimulated by lipopolysacharide (LPS). The antioxidant response element (ARE), which is located in the promoters of the genes encoding enzyme detoxication, mediates the transcriptional response. Horky et al. (2018) analyzed the key properties of carbon nanoparticles, including fullerenes, carbon nanotubes, and graphene (native graphene, graphene oxide, and reduced graphene) as well as the potential binding relationship with mycotoxins.

Mycotoxins can attach to the surface, bundles, grooves, or channels between these nanoparticles through a variety of binding interactions. However, it is yet unclear how NPs interact with the various components of fungus cells, necessitating additional study.

5.1 Other Recent Innovative Strategies

Food products have been treated to pulsed electric fields (PEF) in order to eliminate mycotoxins produced by fungus, such as aflatoxin B1 and G1 by *Aspergillus* (Gavahian et al. 2020). In another study, PEF was found to be one of the most efficient and reasonably priced novel food processing techniques for the detoxification of aflatoxins, fumonisins, zearalenone, OTA, and trichothecenes in foods; however, it was suggested that a specific food-target assessment be performed before implementation in the food industry. Additionally, it has been looked at if water-assisted microwave therapy (WMT) can lower aflatoxin B1 levels in maize (Zhang et al. 2020). The outcomes demonstrated that WMT efficiently removed AFB1 and could simultaneously prevent the enormous emergence of maize kernels that had been heat-damaged, presenting a novel idea for AFB1 reduction using microwave technique. In order to significantly reduce a number of mycotoxins in juice samples, the use of high-pressure treatment (HP) has also been examined (Gavahian et al. 2020). Active food packaging technology is an effective technique to disinfect and control fungus and associated mycotoxins in a variety of foods, including fruits, nuts, baked goods, cereal grains, and dairy products, claim Jafarzadeh et al. (2022). Biopolymers such polysaccharides, lipids, proteins, and/or their mixtures offer economical and environmentally friendly solutions because of their biodegradable nature.

6 Conclusions

Mycotoxin occurrence and contamination along the management chain of agricultural produce, food, and animal feedstuffs are of concern on a global scale because of their toxicity, the risk they pose to both human and animal health, as well as the financial losses they are associated with. Even with the adoption of precondition programs for food management systems like GAP, GMP, GSP, GHP, and HACCP based procedures at the pertinent phases of pre-harvest, post-harvest, and processing, mycotoxin contamination cannot be avoided (Nada et al. 2022). As a result, quick and early discovery is crucial for eradication, overall food safety, and averting related health problems. The creation of these novel solutions for the effective management requires pertinent analyses and debates on the trends in their use and the overall safety of foods and reduction of mycotoxins. CAP technology, polyphenol and flavonoid inhibitors, magnetic materials, nanoparticles, and NEOs are just a few of the cutting-edge methods that have been used to reduce and detoxify mycotoxin contamination in food.

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Sustainable Solutions on Effect of Roasting Operation in the Reduction of OTA in the Coffee Beans from Different Origins

A. Poovazhahi, P. D. Sanjith, Monika Thakur, and Asmita Singh

Abstract This study represents a continuation of our previous research focused on investigating the presence of Ochratoxin A (OTA) in coffee beans originating from diverse sources. Building upon our prior OTA assessments across various coffee bean origins, we have undertaken a thermal degradation approach, specifically roasting, to further analyze its effects. For this purpose, coffee beans sourced from distinct origins were deliberately contaminated with Aspergillus Ochraceus, after which they underwent roasting at three distinct levels (light, medium, and dark). Following roasting, the beans were ground to a medium consistency, and the levels of OTA were quantified using High-Performance Liquid Chromatography (HPLC) with a Fluorescence detector. The primary objective of this study is to elucidate the impact of roasting on OTA reduction. The roasting process was divided into different points (light, medium, dark) based on color factors, and the roasted beans were then compared in terms of their residual OTA content. Notably, our findings revealed a significantly greater reduction in residual OTA content in dark-roasted beans originating from various sources.

Keywords Roasted coffee · Ochratoxin A · Green coffee · Coffee processing–roasting

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1 Introduction

Ochratoxin A, a secondary metabolite produced by two distinct fungal species, Aspergillus and Penicillium, has been the subject of clinical studies and various research indicating its detrimental effects on human health. The presence of Ochratoxin A in different food items has been documented since 1974. Regulatory bodies have taken stringent measures to reduce its contamination in food products.

Coffee, the second most popular beverage globally, is prepared by infusing properly processed coffee beans (*Coffea Arabica* and *Coffee Robusta*) (Poovazhahi et al. 2020; Thakur 2020; Thakur et al. 2021). Coffee contains specific chemical compounds that create a unique blend of sensory and physiological effects, such as caffeine (Poovazhahi et al. 2020). Throughout coffee cultivation, both coffee beans and cherries are susceptible to contamination by various fungal species. While contamination starting from the field does not usually lead to severe health effects due to the high-temperature roasting process, some fungi can produce mycotoxins resistant to roasting, potentially causing health issues (FAO 2005). Given that coffee is extensively consumed worldwide, its contribution to individual dietary intake of Ochratoxin A could be significant. The European Union (European Commission 2006) has established maximum limits for Ochratoxin A in roasted and instant coffee, but not yet for green coffee. European countries have set their own limits for Ochratoxin A in green coffee, typically around 5.0 mg/kg.

Ochratoxin A, which was initially isolated in 1965 from *Aspergillus ochraceus*, is predominantly synthesized by specific strains of *Aspergillus* (in cooler climates) and *Penicillium* (in tropical and subtropical regions) (Amezqueta et al. 2013; Poovazhahi et al. 2020). Its deleterious impacts on renal and hepatic functions, as well as its potential to cause birth defects, genetic mutations, and suppression of the immune system, have given rise to significant concerns (Visconti Pascale and Centonze 1999). Notably, the International Agency for Research on Cancer (IARC), in 1993, categorized Ochratoxin A as conceivably carcinogenic to humans (Group 2B) (WHO/IARC 1997).

Coffee ranks as a significant source of Ochratoxin A exposure, with reports of its presence in green, roasted, and instant coffee bean (Levi et al. 1974). The contamination levels vary due to changes in coffee production processes. Considering the adverse effects of Ochratoxin A, it is crucial to conduct studies to assess its presence and contribution to human exposure in the Indian coffee market. (Ahmed et al. 2007; Poovazhahi et al. 2020). Various analytical techniques have been developed for Ochratoxin A determination in coffee, including liquid chromatography with fluorescence detection (FLD) (Aresta et al. 2006; Castellari et al. 2000; Gonz alez-Pe-nas et al. 2004; Sugita-Konishi et al. 2006), LC/mass spectrometry (MS) (Leitner et al. 2002; Reinsch et al. 2007), thin-layer chromatography (TLC/FLD) (Dawlatana et al. 1996), capillary electrophoresis (CE/FLD) (Corneli and Maragos 1998) and gas chromatography (GC/MS) (Soleas et al. 2001). Solid-phase extraction using C18 and/or immunoaffinity columns is commonly employed for sample preparation due to the low complexity of matrices and typically low Ochratoxin A concentrations in coffee

(Alvarado et al. 2013; El Khoury and Atoui 2010; Turner et al. 2009; Poovazhahi et al. 2020). In this study, immunoaffinity columns were utilized for a clean step, and an optimized and validated LC-FLD method was employed to quantify Ochratoxin A in coffee beans from different origins.

2 Material and Methods

2.1 Reagents, Standards and Samples

Ochratoxin A (CAS Number: [303–47–9], Molecular Weight: 403.81 g/mol, Purity: 98%) was procured from Sigma Aldrich. The chemicals employed encompassed sodium bicarbonate (Merck, Germany, Purity: 99.0%), potassium dihydrogen phosphate (Merck, Germany, Purity: 99.0%), anhydrous disodium hydrogen phosphate (Merck, Germany, Purity: 99.0%), sodium chloride (Spectrum, USA, Purity: 99.0%), potassium chloride (Merck, Germany, Purity: 99.5%), potassium dichromate (Merck, Germany, Purity: 99.5%), methanol of HPLC grade (Merck, Germany, Purity: 99.5%), glacial acetic acid (Fischer), toluene of HPLC grade (Fischer), benzene (Merck, Germany, Purity: 99.5%), acetone of A.C.S. grade (Merck, Germany), ethyl alcohol of HPLC grade, and sodium hypochlorite (Fischer). A phosphate-buffered saline solution (PBS) at pH 7 was employed, consisting of 0.020% potassium dihydrogen phosphate, 0.110% anhydrous disodium hydrogen phosphate, 0.800% sodium chloride, and 0.020% potassium chloride.

2.2 Standard Solution

An original standard solution (40 μg mL^{-1}) was prepared by combining toluene and glacial acetic acid (99:1) as the solvent mixture. The expected concentration was calculated using UV spectrophotometry, with a molar absorption coefficient of 5440 M^{-1} cm^{-1} at 333 nm, following the guidance of (AOAC 2000). This solution was stored safely in a freezer at –18 °C. To generate a working solution containing 100.0 ng g^{-1}, an appropriate quantity of the stock standard solution was accurately weighed in the mobile phase. This working solution served as the basis for constructing the calibration curve, spanning concentration levels of 3.0, 8.0, 13.0, 18.0, and 23.0 ng g^{-1}, and 3.0, 4.0, 5.0, 6.0, and 7.0 ng g^{-1} for the roasted coffee, respectively. Quantitative analysis was carried out by comparing against a calibration curve tailored to the specific matrix.

2.3 Samples

Batch of green coffee beans underwent roasting at three distinct color levels–light, medium, and dark roast. Color factors were determined using Agtron, while roasting temperatures were maintained at approximately 220–250 °C. The resultant roasted coffee bean powder was stored in a freezer until analysis. Sampling was conducted at various intervals, resulting in a total of forty-two coffee samples.

2.4 Immunoaffinity Column

The immunoaffinity column comprises a gel suspension of monoclonal antibodies covalently attached to a solid support. The antibodies specifically target Ochratoxin A, ensuring high specificity and optimal chromatographic outcomes, free from interfering secondary signals and with high recovery rates. The column's bed is made of a soft gel, covered by a storage buffer containing a preservative. The maximum loading capacity is 100 ng Ochratoxin A, and the columns have a minimum shelf life of 9 months when stored at 4 °C. The column operates based on immunoaffinity principles, utilizing elevated flow rates and reduced elution volume to expedite the evaporation of the sample. The column's internal material is coated with antibodies targeting Ochratoxin A. Upon applying the raw extract onto the column, Ochratoxin A is retained while other matrix components pass through. After washing, Ochratoxin A is quantitatively eluted from the column using methanol and subsequently measured using HPLC.

2.5 Extraction of OTA

To extract OTA, 5 g of the specimen was combined with 100 mL of methanol and a 1% concentration of $NaHCO_3$ (sodium hydrogen carbonate). The amalgamation was vigorously mixed on an orbital shaker for a duration of 40 min. Afterward, the resultant mixture underwent centrifugation for 10 min at 4000 rpm and 25 °C. The obtained extract was subjected to filtration using a Whatman filter 4, and subsequently, a 20 mL portion of the filtrate was transferred into a volumetric flask. The volume was then adjusted to 40 mL by introducing phosphate-buffered saline (PBS).

2.6 Immunoaffinity Column Clean-Up

The extracted samples were passed through an Ochraprep® Immunoaffinity column at a flow rate of approximately 1 drop per second. The column was washed with 20 mL of PBS after removing the bottom cap, followed by drying via air passing through the column. Bound Ochratoxin was eluted using 1.5 mL of desorption solution, and back flushing was employed for complete elution. The column was further washed with 1.5 mL of methanol, collected in a vial. The extract was then evaporated under a nitrogen stream to dryness and reconstituted using the mobile phase.

2.7 Analysis Method

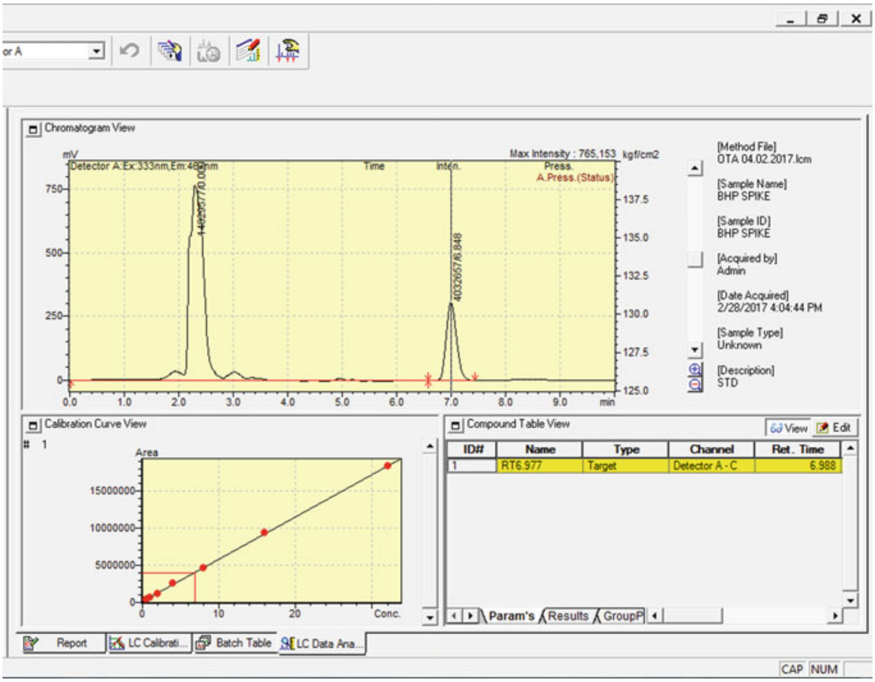
Detection and quantification procedures were conducted using High-Performance Liquid Chromatography (HPLC) employing an RF-20A fluorescence detector integrated into a Shimadzu LC 20AD chromatography system. The specific chromatographic parameters were configured as follows: a safeguard analytical column (ODS, 5 μm, 250 × 4.6 mm) was maintained at a constant temperature of 40 ± 0.5 °C. Fluorometric excitation and emission wavelengths were set at 336 nm and 468 nm, respectively. An isocratic mobile phase consisting of acetonitrile/acetic acid (2% in H_2O, 1:1, v/v) flowed through at a rate of 1 $\text{mL}\cdot\text{min}^{-1}$. A calibration curve with five data points, spanning a range of 0.15–2.15 ng OTA mL^{-1}, was established (with r2 > 0.9999), and 20 μL samples were injected in triplicate. OTA typically exhibited a retention time of around 6.95 min.

2.7.1 Calibration

The OTA standard was diluted with the mobile phase to create a series of working solutions ranging from 0.02 to 10 ng OTA/200 μL. A calibration curve was established by plotting peak areas for each standard against the mass of injected OTA. The slope and intercept of the calibration curve were utilized to calculate the analyte quantity in the sample extracts.

2.7.2 Validation

Validation included analysing samples spiked with varying concentrations of standard solutions. Recovery tests were conducted in triplicate by spiking OTA-free samples at 5 different levels with standards (2, 4, 8, 16, 32 ppb) in coffee. Both the spiked and blank samples were subjected to HPLC analysis. Recovery was determined by comparing the added OTA amount with the detected OTA amount (Fig. 1).



[Method File]
OTA 04.02.2017.lcm

[Sample Name]
BHP SPIKE

[Sample ID]
BHP SPIKE

[Acquired by]
Admin

[Date Acquired]
2/28/2017 4:04:44 PM

[Sample Type]
Unknown

[Description]
STD

ID#	Name	Type	Channel	Ret. Time
1	RT6.977	Target	Detector A - C	6.988

Fig. 1 Chromatogram—Uganda BHP Spike

2.7.3 Statistical Analysis

The data underwent assessment through descriptive statistical methods, encompassing calculations for the mean and standard deviation. To establish calibration, a linear regression model was employed to establish the correlation between OTA concentration and fluorescence emission units (EU). The comparison of OTA content within roasted coffee samples was conducted using an unpaired Student’s t-test. The determination of correction factors was statistically defined using a one-sample t-test, assuming a hypothetical 100% recovery value. All of the aforementioned statistical procedures were conducted at a significance level (denoted as “a”) of 0.05.

3 Results and Discussions

3.1 Quantifying Ochratoxin A in Roasted Coffee Samples

The gathered samples were categorized according to the specified sampling plan. Random selections were made from each product category to represent diverse samples, and subsequently, these selections were subjected to analysis using a 3%

sodium bicarbonate: methanol (50:50) solution as the extraction solvent. A total of 50 samples underwent analysis, with each sample being extracted and analyzed twice. Of these, 91.88% (45 out of 49) exhibited detectable OTA levels, while 2.04% (1 out of 49) surpassed quantifiable limits. Among the samples with measurable OTA, contamination levels ranged from 35 µg/kg to 1 µg/kg. Notably, only a single dark roast sample (13.07 µg/kg) out of the 49 demonstrated OTA contamination exceeding European regulatory thresholds. It is pertinent to mention that all samples under examination were roasted coffee samples.

3.2 Roasting Parameters and Significance

Roasted coffee is acknowledged for its intricate composition, containing diverse classes of compounds including melanoidins. The quantification of OTA in coffee samples presents heightened challenges, necessitating thorough cleaning and OTA concentration enhancement. While roasting is known to reduce OTA levels, comprehensive investigations on the impacts of roasting stages, grinding, and beverage preparation methods are lacking. Contamination of roasted coffee with OTA is intricately linked to the quality of processing across the coffee production continuum, spanning from cultivation to roasting. Coffee beans were intentionally contaminated with Aspergillus Ochraceus procured from Sigma Aldrich. These beans were then subjected to three levels of roasting (light, medium, and dark) and ground to three different consistencies (fine, medium, and coarse). Various origins of coffee beans exhibited the anticipated OTA reduction upon roasting. High-performance liquid chromatography facilitated OTA quantification, revealing the dark roast to have the lowest OTA concentration at 1.025 µg/kg, signifying a remarkable 99.0558% reduction. The findings underscore that the roasting process, in conjunction with roast level, plays a pivotal role in determining the residual OTA concentration in roasted coffee beans. In the proposed methodology, 42 roasted coffee samples were scrutinized. The results revealed a notable OTA presence in all examined coffee samples, with the exception of beans originating from Honduras. However, post-roasting levels remained below the current European limit (European Commission 2006). Various coffee origins such as Uganda BHP, Uganda Arabica, Indonesia robusta, Peru Arabica 30/35, Vietnam robusta, Kenya BHP, and Honduras were assessed for initial OTA contamination. Among these, Honduras displayed significantly lower initial OTA contamination levels, measuring less than 1.0 µg/kg, in comparison to other countries. Although initial OTA contamination levels exceeded EU limits in green coffee beans from Uganda BHP, Uganda Arabica, Indonesia robusta, Peru Arabica 30/35, Vietnam robusta, and Kenya BHP, these levels experienced considerable reduction through husk removal and roasting at 220 °C.

3.3 Analysis of Reduction Levels Based on Roasting Operations

In the case of Uganda BHP raw coffee beans, pre-roasting OTA concentration stood at 9.51 μg/kg, while the artificially spiked sample exhibited a content of 104.26 μg/kg after the introduction of 10 μg/kg OTA. Consequently, the evaluation of roasting effects was predicated on a sample contaminated with 104.26 μg/kg OTA. OTA was detected in all roasted samples (100%) and concentration varied between 104.26 μg/kg and 1.345 μg/kg, with duplicate analyses conducted. The reference sample, consisting of green coffee spiked with ochratoxin A from Sigma-Aldrich, served as an indicator for experimental normalization. Roasting led to a discernible reduction in residual OTA content. Among roast levels, the dark roast exhibited the lowest OTA concentration, averaging at 1.345 μg/kg. This sample displayed an average residual OTA content of 1.2900%, indicating a substantial 98.70% reduction in OTA levels (Table 1).

The initial OTA concentration in unroasted **Uganda Arabica** coffee beans was measured at 0.60 μg/kg, whereas the concentration in the artificially contaminated sample reached 108.33 μg/kg after a 10 μg/kg spike. As a result, the assessment of the impact of roasting centered on the sample contaminated with 108.33 μg/kg OTA. OTA was identified in all analyzed roasted samples, spanning concentrations from 108.33 μg/kg to 1.025 μg/kg; this detection was carried out in duplicate. Among the different roast levels, the dark roast exhibited the lowest OTA concentration, with an average measurement of 1.025 μg/kg. The residual OTA content in this sample averaged 0.9461%, highlighting an impressive 99.0558% reduction in OTA levels (Table 2).

The initial OTA content within untreated **Indonesia robusta** coffee beans measured 7.40 μg/kg, while the concentration in the artificially contaminated sample reached 106.46 μg/kg after spiking with 10 μg/kg. Consequently, the assessment of the roasting influence was predicated on a sample tainted with 106.46 μg/kg OTA. In the analysis of roasted samples, OTA was identified across the board, ranging from 106.46 μg/kg to 2.58 μg/kg; these findings were duplicated for accuracy. Among

Table 1 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time in Uganda Arabica

Uganda BHP					
Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual value (%)
Green coffee		9.51			
Green spike		104.26			
Light roast	68.9	3.075	0.06364	97.054	2.946
Medium roast	50.4	3.2	0.042426	96.93	3.06924
Dark roast	30.5	1.345	0.360624	98.7	1.29

Table 2 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time in Uganda Arabica

Uganda Arabica					
Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual value (%)
Green coffee		0.6			
Green spike		108.33			
Light roast	54.9	3.29	0.113137	96.96	3.037
Medium roast	48.2	2.65	0.183848	97.55	2.446
Dark roast	37.1	1.025	0.13435	99.0558	0.9461

the roast variations, the darkest roast demonstrated the minimal OTA concentration, displaying an average of 2.58 μg/kg. The residual OTA content in this instance averaged at 2.423%, illustrating a significant 97.57% decline in OTA levels (Table 3).

The initial OTA level within untreated **Peru** coffee beans before roasting measured 1.40 μg/kg. Subsequently, the concentration in the deliberately contaminated sample reached 116.40 μg/kg following the introduction of a 10 μg/kg spike. Thus, the assessment of roasting impact was conducted on a sample affected by 116.40 μg/kg OTA contamination. In the analysis of roasted samples, OTA presence was observed in all instances, spanning concentrations from 116.40 μg/kg to 3.345 μg/kg; this analysis was carried out in duplicate. Among the various roast levels, the darkest roast displayed the lowest OTA concentration, averaging 3.345 μg/kg. The residual OTA content in this case exhibited an average of 2.8737%, indicating a substantial 97.126% reduction in OTA levels (Table 4).

The initial OTA level within untreated **Vietnam robusta** coffee beans, prior to roasting, was recorded at 2.80 μg/kg. Subsequently, the concentration in the deliberately contaminated sample reached 109.43 μg/kg after the introduction of a 10 μg/kg spike. Thus, the assessment of the influence of roasting was conducted on a sample with an OTA contamination of 109.43 μg/kg. In the analysis of roasted samples, OTA presence was identified in all instances, with concentrations ranging from

Table 3 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time in Indonesia robusta 30/35

Indonesia robusta 30/35					
Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual value (%)
Green coffee		7.4			
Green spike		106.46			
Light roast	65.6	7.955	0.643467	95.25	7.472
Medium roast	56.9	4.105	0.304056	96.144	3.855
Dark roast	42	2.58	0.565685	97.57	2.423

Table 4 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time in Peru

Peru					
Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual value (%)
Green coffee		1.40			
Green spike		116.4			
Light roast	65.4	9.365	0.0516188	91.95	8.0455
Medium roast	50.4	5.255	0.601041	95.48	4.5146
Dark roast	46.2	3.345	0.643467	97.126	2.8737

109.43 μg/kg to 3.73 μg/kg; this assessment was conducted in duplicate. Among the different roast levels, the darkest roast exhibited the least OTA concentration, averaging 3.73 μg/kg. The residual OTA content in this case demonstrated an average of 23.408%, signifying a notable 96.591% reduction in OTA levels (Table 5).

The initial OTA level within untreated **Kenya BHP** coffee beans, prior to roasting, was measured at 21.9 μg/kg. Subsequently, the concentration in the intentionally contaminated sample reached 110.46 μg/kg following the introduction of a 10 μg/kg spike. Hence, the assessment of the impact of roasting centered on a sample with an OTA contamination of 110.46 μg/kg. In the analysis of roasted samples, OTA presence was identified in all instances, with concentrations ranging from 110.46 μg/kg to 13.07 μg/kg; this analysis was performed in duplicate. Among the different roast levels, the darkest roast displayed the lowest OTA concentration, with an average of 13.07 μg/kg. The residual OTA content in this case demonstrated an average of 11.832%, indicating a significant 88.167% reduction in OTA levels (Table 6).

For further examination, we employed Tukey's test to compare medium roast with dark roast. The means displayed a notable disparity, with dark roast once again indicating the least mean OTA concentration. Concerning the degree of roasting, coffees with larger particle sizes exhibited the most minimal average OTA concentrations. In the case of Honduras beans, the OTA concentration was notably lower

Table 5 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time in Vietnam robusta

Vietnam robusta					
Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual Value (%)
Green coffee		2.8			
Green spike		109.43			
Light roast	68.8	34.14	6.70372	68.202	31.798
Medium roast	57.2	13.445	2.170818	87.71	12.286
Dark roast	436	3.73	0.707107	96.591	3.408

Table 6 Mean OTA values detected in the samples, percent reduction, residual value, temperature and roasting time Kenya BHP

Kenya BHP

Sample type	Colour factor	Mean OTA conc. (μg/kg)	Standard deviation	OTA reduction (%)	Residual value (%)
Green coffee		21.9			
Green spike		110.46			
Light roast	56	34.22	8.189	69.01	30.919
Medium roast	48	21.655	2.171	80.4	19.61
Dark roast	32	13.07	2.475	88.17	11.832

than that of other beans, measuring less than 1.0 (μg/kg) in light roast and falling below the detectable range in medium and dark roasts. The results from Tables 1 through 6 underscored a statistically significant interaction effect based on roasting levels on mean OTA concentration in coffee. The three roasting levels also produced discernibly different mean OTA concentrations, with dark roasting yielding the lowest mean OTA concentration. Substantial distinctions were also observed among the means of the three roasting levels. Similarly, the dark roast demonstrated the least mean OTA concentration, consistent with the outcomes documented in Tables 1–6. Finally, we applied Tukey's test to assess the comparison between dark roast and medium roast, which once again displayed a significant difference, with dark roast revealing the lowest mean OTA concentration. Notably, coffees with coarser particle sizes consistently yielded lower mean OTA concentrations across various roasting levels.

4 Conclusions

The statistical analysis of data reveals a notable reduction in OTA levels across various origin coffee beans based on time and temperature. An evident instance of substantial standard deviation in OTA values was identified during the very light degree of roasting. This variability primarily stemmed from significant differences in moisture loss encountered during this initial roasting phase. While OTA reduction was minimal during light roasting, a pronounced reduction occurred between medium and dark roasting stages. The decline in OTA content during roasting can be ascribed to both thermal degradation and the removal of chaff during the process. In the case of the light roasting phase, the portion of OTA associated with chaff remained intact.

Significant disparities in the remaining OTA content were evident in all investigated treatments. A notable contribution of this study was the assessment of roasting effects, clearly indicating its influence on the final OTA levels in roasted coffee. The nature of roasting significantly influences the residual ochratoxin A content within the coffee. Consequently, this study contributes to the establishment of quality standards for roasted coffee production in alignment with both national and international quality norms, thereby enhancing the value of this traditional product.

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Revisiting the Sustainable Non-thermal Food Processing Technologies and Their Effects on Microbial Decontamination

Reeba Iqbal and Monika Thakur

Abstract Due to the increase in knowledge about the benefits of non-thermal food processing techniques on the nutritional composition and functional potential of the food systems, there has been a significant growth in shifting from the thermal to the non-thermal food processing techniques. The non-thermal food processing techniques are those techniques that work without do not application of heat for the processing and preservation of food. The basic aim of this review study is to throw light on the food processing by thermal and non-thermal techniques, types of different non-thermal food processing technologies and the microbial deactivation achieved by each of the techniques. Hence the study focuses on the different non-thermal food processing technologies currently prevalent in the food industry. The various non-thermal techniques covered in this study are the physical processing techniques namely High Pressure Processing (HPP), Pulsed Electric Field (PFE), Irradiation, Pulsed Light, Ultrasound and Oscillating Magnetic Field (OMF); chemical processing techniques namely Cold Plasma Processing and Ozone Treatment; and separation and concentration techniques namely Supercritical Fluid Extraction and Membrane Separation. The present endeavour revisits and highlights the destruction of specific pathogenic and food spoilage microorganisms and the overall effect on the microbial decontamination, thus ensuring food safety.

Keywords Functional potential · Non-thermal · Microorganisms · Food safety

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1 Food Processing Techniques

Food processing techniques are a series of unit operations that alter the natural state of the food products. They are also used to convert the raw materials into finished food products. The processing of raw materials into foods can be done by subjecting them to either physical processes or chemical processes. Food processing techniques add value to the food products.

The basic principle behind the food processing techniques lies with the simple objective of producing shelf-stable products that are safe for human consumption.

The principal objectives of food processing techniques are described as follows

- To extend the storage life of food products
- To prepare food products that are safe and fit for consumption by humans
- To destroy the pathogenic and spoilage microorganisms present in the food systems and render the food products shelf-stable
- To improve the textural and organoleptic properties of the food
- To meet the rising demand of the consumers.

Based on the objectives, the various food processing techniques prevailing in the food industry can be broadly classified into 2 categories, namely thermal food processing techniques and non-thermal food processing techniques.

2 Thermal Food Processing Techniques

Thermal food processing techniques are those techniques that process the food materials with the application of heat to destroy the pathogenic and spoilage microorganisms. Thermal processing techniques are an effective way of processing as due to increased temperature, the speed of reactions is also increased. This is attributed to the fact that with an increase in temperature, the rate of chemical reactions also increases. Chemical reactions always increase with temperature; biochemical and microbial reactions also increase with temperature, but above a certain temperature enzymes and microorganisms become inactivated. Physical reactions and radical reactions are usually not that much dependent on temperature.

The most commonly used thermal food processing techniques along with their principal objectives are discussed as follows:

1. ***Blanching***: Blanching is a thermal heat treatment process that is used for the inactivation of enzymes and for the microbial destruction in foods prior to other processing methods like drying, freezing, canning, etc.
2. ***Pasteurization***: Pasteurization is defined as the thermal process of heating every particle of a food product to any of the specified pasteurization time–temperature combinations to effectively achieve the destruction of pathogenic microorganisms or reducing their numbers to safe levels.

3. ***Sterilization***: Sterilization is a heat treatment process that aims at the complete destruction of microorganisms present in a food system to render it safe for human consumption.
4. ***Dehydration***: Dehydration of food refers to the process of nearly complete removal of water from foods under controlled conditions in order to reduce the growth of microorganisms by lowering the water activity of the food systems.
5. ***Extrusion***: Food extrusion is a form of thermal food processing method that processes a set of mixed raw ingredients at high temperatures and forces them through an opening or die with a design specific to the food, and is then cut to a specified size by blades. This process inactivates enzymes and reduces microbial contamination in food.

3 Non-Thermal Food Processing Techniques

Thermal processing of foods can cause some unintentional and undesired effects on foods, such as losses of certain nutrients, formation of toxic compounds that can negatively impact the flavour, texture or colour of the food. It is found that thermal food processing techniques can have detrimental effects on the nutritional and functional properties of foods as well. This is attributed to the fact that foods are complex systems and due to the high temperature treatments, some undesirable interactions can occur between the food components. This led to the need of discovering such processing techniques that do not use heat, that is, process the foods without the application of heat. This is how the non-thermal food processing techniques came into existence.

Non-thermal food processing technologies make use of techniques that unmask the foods to treatment conditions for just a fraction of seconds. This reduces the microbial load of the food system. Moreover, as high temperatures are not being utilized in such techniques, they also preserve the functional and the nutritional properties of the food systems. The principle behind the reduction of microbial load by non-thermal food processing techniques lies behind the fact that they alter the membrane structure of the microbial cells and cause the unfolding of the helical structure of the DNA. This results in the death of the microbial cells in a short duration of time. The other benefits of non-thermal food processing techniques are that they inhibit the enzymatic activity, enhance the chemical and physical properties of food systems and lower the water activity of the food materials (Thakur, Modi 2020).

The various non-thermal food processing techniques along with their basic objectives are discussed as under

3.1 Physical Processing Techniques

a. ***High Pressure Processing (HPP)***: HPP accomplishes the inhibition of microbial growth by applying high hydrostatic pressure, between 100 and 1000 MPa, to food products.
b. ***Pulsed Electric Field (PFE)***: PFE destroys the microorganisms by damaging their cell walls by applying pulses of high field intensities of around 25–85 kV/cm for a short duration of time.
c. ***Irradiation***: Radiations of X-rays, high energy gamma rays and high speed electrons are permitted and utilized for the irradiation of food systems. No temperature is raised during the irradiation of food. The radiations cause the unfolding of DNA and destroy the nucleic acid of the microbial cells, and thereby reduce the microbial load.
d. ***Pulsed Light***: This method achieves the decontamination of food by using high intensity light pulses for short durations of time. It includes a wide wavelength range of 200–1100 nm.
e. ***Ultrasound***: Ultrasound is a technique that uses sound waves of frequencies more than that of human hearing frequencies, that is, above 20 kHz. The ultrasounds bring about the desired changes in the food systems.
f. ***Oscillating Magnetic Field (OMF)***: OMF applies magnetic fields in the form of constant amplitude or decaying amplitude sinusoidal waves to the food materials. It helps in microbial inactivation in the food systems.

3.2 Chemical Processing Techniques

3.2.1 Cold Plasma Processing

In cold plasma processing, gases are ionized to form reactive species. These reactive species affect the microbial cells and damage the cellular components and the DNA of cells, ultimately causing the death of the microbial cell.

3.2.2 Ozone Treatment

Ozone is an anti-bacterial gas and causes the death of microbes in a number of ways. It can do so by altering the permeability of cells or by damaging the structural proteins of the microbial cells or by causing the malfunctioning of the microbial enzymes or by affecting the metabolic activity of the microbial cells. All these effects of the ozone result in the destruction of the microbial cells.

3.3 Separation and Concentration Techniques

3.3.1 Supercritical Fluid Extraction

This technique makes use of supercritical fluids for the purpose of extraction of desired components from a food system.

3.3.2 Membrane Separation

It includes techniques like micro filtration, ultra-filtration, nano-filtration, reverse osmosis and electro dialysis. Membrane separation techniques are used for applications like purification, concentration and clarification of various food materials. They are used to separate 2 phases of a food system based on their particle size, electric charges, etc.

The various non-thermal food processing techniques would be discussed in the upcoming sections.

4 High Pressure Processing (HPP)

High pressure processing is a non-thermal food processing technique that uses high hydrostatic pressures for the processing of foods (Singh and Sharma 2023, Thakur and Belwal 2022). HPP makes use of high pressure application to the food product, thereby causing the inactivation of spoilage and pathogenic microorganisms. In this technique, the food is subjected to high pressures ranging from 100 to 1000 MPa, for a few seconds or up to one minute. This can cause a significant decimal reduction in the population of pathogenic Gram positive bacteria, Gram negative bacteria, yeasts and moulds (Jadhav et al. 2021). The main function of HPP is to cause irreversible sterilization for the destruction of cellular structure. This results in disruption of the microbial cell. Moreover, HPP also alters the complex structures present in the cells like proteins and ribosome that ultimately results in the death of the cell by hampering its metabolism.

The treatment temperature, pressure and the type of food being processed majorly define the reduction in the amount of microbial load.

Since during HPP, the food is exposed to high pressure for a very short period of time, it has minimal effects on the sensory, nutritional, textural and functional properties of the food undergoing processing. Therefore HPP finds extensive applications in the food industry and can be used for products like fruit juices, beverages, vegetable products, meat and seafood products, among others.

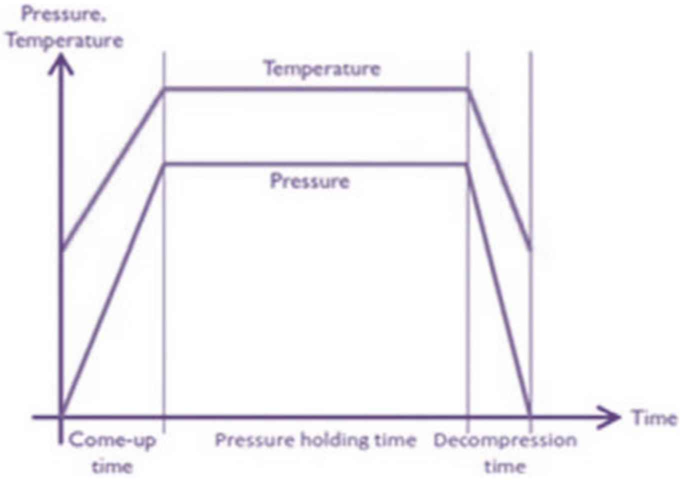

Fig. 1 Pressure, temperature & time during HPP (*Source* Saroya and Kaur, 2017)

4.1 Principle

The basic principle of working of HPP is based on 2 scientific principles, namely Le Chatelier's principle and Pascal's isostatic principle. According to Le Chatelier's Principle, when a system in equilibrium is disturbed, it responds in a way so as to minimize the disturbance. Therefore when the food is processed using HPP, the reactions that result in a decrease in volume are enhanced while reactions that increase the volume are suppressed. This means that any reaction accompanied by a decrease in volume will be enhanced by pressure. The second principle is the Pascal's isostatic principle which states that pressure is instantaneously and uniformly transmitted to a sample when it is under pressure. Since the pressure is transmitted in an isostatic (uniform) manner throughout the sample, the time required for HPP is independent of the size of the sample being processed (Norton and Sun 2008) (Fig. 1).

The picture given below shows time and pressure relationship during HPP process.

4.2 Equipment and Working

HPP is carried out in special equipment's that mainly consist of a high-pressure chamber, closures to seal the chamber, pressure generation and control devices, temperature control device, material handling system and a data collection system (Tao et al. 2014). The HPP can be carried out as a batch process or a semi-continuous process. The batch process is generally used for packaged food products whereas the semi-continuous process can used for the liquid foods.

The batch process is generally used for HPP in industries. It involves the packaging of the food products in flexible packaging materials prior to processing. The packaging material must be designed keeping in consideration the reduction in volume of 10–20% during pressurization and the return to the original volume when the pressure is released. The food products are then placed in the HPP chamber and the vessel is closed. The pressure is then applied in the chamber either by pumping a pressure-transmitting medium into the vessel, like castor oil, silicone oil, sodium benzoate, ethanol and glycol; or by reducing the volume of the pressure chamber by using a piston. After the required hold time is achieved, the pressure from the system is released, the vessel is opened and the food products are unloaded.

The semi-continuous method is recommended for food products that can be pumped, like fruit juices. It involves a free-floating piston in the pressure vessel to compress the liquid foods. The free floating piston divides the vessel into two chambers and thus separates the food product from the pressure medium. Pressurization of the pressure-transmitting medium in the second chamber causes the compression of the food product in the first chamber. After the holding time has elapsed, the pressure is released and the treated product is discharged from the vessel to a sterile hold tank. Following that, the treated product can be filled aseptically into sterilized containers. The packaging also play significant role in reducing the microbial load (Poovazhahi and Thakur, 2022).

4.3 Effect of HPP on Microbial Decontamination

HPP when applied using moderate levels of pressure like 10–50 MPa causes a decrease in the rate of growth and reproduction of microorganisms (Bajovic et al. 2012). However, when applied at higher levels of pressure, it results in the inactivation of microorganisms.

The pressure results in the destruction of cell membrane of the microbial cells, breaks the coiled protein structure of the microbial cells and thereby results in the death of the microbial cells (Van et al. 2010). This is how HPP achieves the microbial decontamination of food systems. It has been found that HPP at high pressures is more effective against Gram negative bacteria, eukaryotes, protozoa, yeast, mould and parasites. It also causes the inactivation of vegetative spores and viruses (Jadhav et al. 2021).

The effect of HPP on specific microorganisms is discussed below

1. ***Bacteria***: Bacteria are single-celled and simple microorganisms. They are basically prokaryotes. The major bacteria targeted by HPP are *Listeria monocytogenes, Staphylococcus aureus* and *Escherichia coli.* Usually, the gram negative bacteria are less resistant to pressure than gram positive bacteria due to differences in their structures (Jadhav et al. 2021). HPP targets the cell membrane of the bacterial cells by altering their membrane properties such as denaturation of the membrane-bound proteins, reduction in fluidity of the membrane and

phase transition of the membrane lipid bilayer. This hampers the integrity of the membrane. Also, the pressure induced by HPP causes various morphological and structural changes inside the cell like aggregation of cellular proteins, compression of gas vacuoles, etc. (Bajovic et al. 2012). The HPP range commonly used for the destruction of microbial cells is 300–600 MPa.

2. ***Spores***: Bacterial spores are highly resistant to heat, pressure, chemicals and radiations. This is attributed to their structural conformities of having thick spore coat (Reddy et al. 2006) HPP at moderate levels causes the activation of the nutrient germinant receptors and initiates germination of the spores. But the resultant germinated spores are pressure sensitive and get inactivated as high pressure ranges are achieved (Black et al. 2007). The HPP pressure ranges used for the inactivation of bacterial spores is greater than 800 MPa (Jadhav et al. 2021).The 2 major species of bacterial pores responsible for food borne diseases are targeted by HPP. These are namely the *Bacillus* and *Clostridium* species.
3. ***Fungi***: Fungi are broadly classified into 2 groups—yeasts (unicellular fungi) and molds, mushrooms, etc. (that produce hyphae). HPP causes higher amount of destruction at low pressures in yeasts, molds and mushrooms as it is more effective on organisms that have higher level of structural complexities (Jadhavet al. 2021).

   HPP affects both the cell membrane permeability and the cellular structure of the yeasts (Black et al. 2007). It can also affect the mitochondria of the cells and leads to the death of the yeast cells. Pressures ranging in the values of 300–400MPa for a few minutes can effectively achieve the inactivation of the yeast cells (Daryeai et al. 2008).In the case of molds, HPP affects the mycelia of the molds. Most of the molds are destroyed at pressures ranging from 300–600 MPa, however variations can be seen in the case of heat-resistant molds (Smelt 1998). Higher pressures are hence required for the destruction of such heat-resistant molds.

   Although fungi are not prominent pathogens but HPP is required for the inactivation of the molds that are toxic in nature.
4. ***Viruses***: Viruses are organisms that have a very simple structure. They consist of a protein coat (capsid) that encloses a central core of nucleic acid. Some enzymes may also be present inside the capsid. The viruses can be classified as enveloped and non-enveloped viruses (Jadhav et al. 2021).HPP targets the viruses by destruction of the capsid proteins of the virus, thereby hampering the binding of the virus to the cellular receptors of the host and ultimately preventing the viral infection. HPP affects the enveloped viruses more than the non-enveloped viruses as enveloped viruses are less resistant to pressure (Rivalain et al. 2010; Rendueles et al. 2011).

5 Pulsed Electric Field (PEF)

Pulsed Electric Field (PEF) is an emerging non-thermal food processing technique that is gaining much popularity in the food industry (Jadhav et al. 2021). PEF technique makes use of high voltage short electricity pulses for the microbial inactivation in food systems while having minimum detrimental effects on the food quality parameters. It makes use of electric field of around 5–85 kV/cm applied to food systems for a few milliseconds or nanoseconds (Vorobievand and Lebovka 2019). This is done by placing the food system between 2 electrodes that generate short, high voltage pulses that are hence applied to the food system for the microbial inactivation (FDA 2000). This allows the destruction of microorganisms at temperatures lower than those utilized in the thermal processing methods. During the PEF process, the energy is stored in the capacitor and it is retrieved from the capacitor and discharged to the food material that is placed in the treatment chamber.

This method is more commonly used for liquid and semi-solid food systems that can flow easily. It has been found in several studies that PEF is one of the most efficient and superior technique among non-thermal food processing techniques as it can cause microbial inactivation at low temperatures without causing negative effects on the functional and the organoleptic properties of the food systems. The fact that PEF can be carried out at low temperatures also makes it an energy efficient option with minimum negative impacts on the environment.

5.1 Principle

PEF is based on the principle of application of pulses with high electric fields, having intensities in the range of 5–85 kV/cm, for a few milliseconds or nanoseconds, to food material placed between two electrodes. During this process, high voltage is applied between the electrodes that results in the destruction of microorganisms present in the food material placed between them. The pulses can be applied in various different forms like oscillating pulses, bipolar waves, exponentially decaying waves or square waveforms.

Food systems are heterogeneous in nature and contain several components. That is why they contain several ions that are responsible for providing electrical conductivity to the food systems. This forms the basis of the transfer of electrical pulses through the food system. The food product thus, when kept between the 2 electrodes, experiences a force per unit charge and the microbial cell membranes get ruptured. When the microbial cell is subjected to high voltage electric field pulses, the temporary destabilization of proteins and lipid bilayer starts occurring. This leads to formation of pores in the microbial cells. However, once the electric field is removed, the pores seal back. During this process of perforation and resealing, since the intensity of electric field is intense, the microorganism becomes unable to repair itself and starts undergoing lysis which ultimately leads to the death of the microbial cell.

5.2 Equipment and Working

PEF is carried out in equipment's that typically consist of a number or components like a high voltage power source, energy storage capacitor, treatment chamber, switch, pump, temperature probes, cooling devices and a control unit.

An amplified and rectified alternating current (AC) is used to generate DC power supply that is utilized to charge the capacitor bank. The switch instantaneously discharges energy from the capacitor to the food held in the treatment chamber. The pump is used to discharge the product to the treatment chamber. The treatment chamber consists of the electrodes that generate the electric field and they are held together by an insulating medium which also forms an enclosure for the food product. The cooling device is used to maintain the food at desired temperature. After treatment, the food product is packed under aseptic conditions.

The effectiveness of PEF is dependent on various factors that affect its ability to inactivate microorganisms. These factors are identified as the product characteristics, type of microbe to be inactivated and process parameters like intensity of electric field, pulse length, pulse shape, number of pulses and temperature of operation.

5.3 Effect of PEF on Microbial Decontamination

The general mechanism of the effect of PEF on microorganisms involves the instability of microbial membranes due to pore formation in the microbial membrane by induction of electrical field and electromechanical compression. Variability in mechanical strength of membranes is a result of the action of the electrical field. There is a considerable increase in the membrane rupture due to electroporation and also in the membrane permeability. The membrane permeability is increased with an increase in electric field. This increase in membrane instability causes an equivalent increase in the inactivation of microbial cells.

The effect of PEF on specific microorganism species is discussed as follow-:

1. ***Bacteria***: PEF is found to affect the bacterial cells. Gram-positive bacteria and Gram-negative bacteria are found to be more resistant to PEF treatment. The PEF treatment affects the different bacterial strains at different rates. *Salmonella* and *E.Coli*are found to be more susceptible to PEF treatment in comparison with species like *Listeria* and *Bacillus* (Amiali 2012).
2. ***Spores***: Bacterial and mold spores are found to be recalcitrant to the PEF treatment (Raso et al. 2000). However, according to certain studies, it has been found that an increase in the application of the electric pulses may cause a reduction in

the viability of spores. According to a study conducted by Marquez et al. (1997), electric field strengths from 20 to 50 kV/cm with pulse numbers ranging from 15 to 50 when applied to *Bacillus* spores in 0.10 to 0.15% NaCl solution, resulted in the lowest count of viable spores at 50 kV/cm with 30 and 50 pulses for B. subtilis and B. cereus, respectively. The log(No/N), that is, the logarithmic ratio of initial count before treatment to surviving spores after treatment, increased with an increase in treatment temperature.

3. ***Viruses***: PEF can affect the virus cells by damaging the core of the virus cells containing DNA or RNA. It has been found in several studies that PEF with electric field ranging around 30 kV/cm can effectively inactivate the viruses.

However, studies conducted on the effect of PEF on virus inactivation in foods are rather less in number. It is still not established that whether viruses can be inactivated in foods unlike in laboratory media. Khadre and Yousef (2012) reported that rotavirus of various concentrations was not inactivated by a PEF treatment of 20−29 kV/cm for 145.6 μs. The failure of PEF treatment against viruses in foods can be attributed to the presence of the capsid proteins of the viruses as compared to the lipid membranes of bacterial cells.

6 Irradiation

Irradiation or Ionizing Radiation technique is one of the ultimate minimal processing technologies that is used to render the food products safe with minimal quality losses. Irradiation of food is a process of utilizing radiant energy in the form of electron beams, X-rays or gamma rays to destroy the harmful and pathogenic microorganisms present in the food system and thereby retarding spoilage of the food system. One of the salient features of irradiation is that it does not make the food radioactive. It is only lethal to the microbes present. In addition to this, irradiation does not even cause an increase in the temperature of the food system and hence is suitable for heat-sensitive food systems as well (Bashir et al. 2021).

According to the standards and regulations, high energy gamma rays and X-rays, and high speed electrons are permitted to be used in food processing. For producing gamma rays, elevated energy photons are generated using radioactive substances like 60CO and 137Cs. For the generation of X-rays, high energies up to 5 meV are utilized. High speeds up to 5 meV are applied to get high-speed electron beams (Farkas 2006; Bashir et al. 2021).

6.1 Principle

The objective of irradiation, irrespective of the type of radiation used, lies in the motive of impairing the microbial cells in order to extend the product shelf life.

The ionizing radiations used in the irradiation process have penetration ability. They penetrate into the food system and result in the unfolding of DNA and the destruction of nucleic acids. They also cause the ionization of water molecules which further leads to oxidative damage to the microbial cells (Castell-Perez & Moreira, 2021). All these changes result in a significant reduction in the microbial load of the food system. This forms the basis of principle of working of the irradiation technique.

The penetration power of the radiation varies with the type of radiation source being used. While high speed electrons of 10 meV can cause penetration of 39 mm into food product, the X-rays and gamma rays have greater penetration powers and hence can even penetrate into the dense food products (Farkas 2006; Jan et al. 2021). The ionizing energy of each dose of irradiation is different. The dose of radiation is measured in Grays (Gy). A gray can be defined as a unit of energy equivalent to 1 J per kilogram. By this, it can be inferred that 1 kiloGray (kGy) is equal to 1000 Grays (Gy).

6.2 Equipment and Working

The different types of radiations are generated in different ways and work in specific manner. They are discussed as follows

1. Gamma rays: The gamma rays utilized in food processing are obtained from either 60CO or 137Cs. Generally this type of radiation is monoenergetic. The dose distributions for the food systems can be computed using analytical techniques like point kernel method or Monte Carlo method.
2. It can be done from 2 sides to increase the uniformity of dose in the processing step.
3. Electrons: High energy electrons are emitted by accelerators having narrow spectral energy limits. The range of the electrons in a medium is finite unlike that of photons. The energy of the electrons can further be controlled by bending magnets of the beam handling device.
4. X-rays: X-ray source is achieved by distributing the primary electron beam over an X-ray convertor of sufficient size.

6.3 Effect of Irradiation on Microbial Decontamination

In order to preserve the functional and the organoleptic properties of the food systems, it essential to determine the threshold dose levels to maintain the efficacy of the radiation treatment along with achieving microbial sterility. Differences in sensitivity to radiation in the microorganisms are related to the differences in their chemical and physical structure, and in their ability to recover from radiation injury. The amount of radiation energy required to control microorganisms in food varies according to the resistance of the particular species and according to the numbers present. Similar to heat resistance, the radiation sensitivity in microorganisms can be expressed by the decimal reduction dose (D_{10}-value) (Farkas 2006).

The effect of irradiation technique on various microorganism species is discussed as under.

1. ***Bacteria***: In case of vegetative cells, several factors such as composition of the medium, the moisture content, the temperature during irradiation, presence or absence of oxygen, the fresh or frozen state influence radiation resistance (Farkas 2006).
2. ***Fungi***: It has been found in various studies that fungi with melanised hyphae are resistant to irradiation (Saleh et al. 1988). Yeasts are also found to be more resistant that bacteria to irradiation. The radiation sensitivity of many moulds is of the same order of magnitude as that of vegetative bacteria.
3. ***Viruses***: According to WHO, viruses are highly resistant to irradiation (WHO 1999).

7 Pulsed Light

Pulsed light technology is one of the emerging non-thermal food processing techniques that has minimal effects on the quality attributes of the food system but is capable of inactivating spoilage and pathogenic microorganisms in food systems. Pulsed light technique has also been proven to extend the shelf life of the food products, to reduce the content of allergens and to cause in-package microbial decontamination. The pulsed light technology was approved for the production, processing and decontamination of food systems and food contact surfaces by the U. S. Food and Drug Administration in the year 1996. It has thereby recommended the use of pulsed light with wavelengths between 200 and 1100 nm with the cumulative treatment not being more than 12 J/cm^2 and not more than 2 ms pulse width. The pulsed light technique makes use of short duration and high power light pulses to cause the inactivation of microorganisms (Mandal et al. 2020a, b). It involves the generation of short duration and high power pulses of light having an intense broad spectrum, covering the frequency regions of ultraviolet light (UV), visible light (VL) and infrared light (IR), with frequency region covered in the range varying from 200–1000 nm (John and Ramaswamy 2018). This is achieved using inert gas flash lamps that are responsible for producing these types of light pulses.

Principle

The basic principle behind the use of pulsed technology lies behind the fact that the inactivation of microorganisms is achieved by the broad spectrum pulsed light by a combination of photo-chemical, photo-thermal and photo-physical effects. The photo-chemical effect on the microbial cells is due to the effect of high intensity light pulses on the constituents of the microbial cells. The photo-thermal effect on the microbial cells can be attributed to the heat dissipation of light pulses penetrating the product, which results in an increase in the temperature of the product. However, only a thin outer surface gets heated and there is no overall temperature rise in the product and hence it is considered a non-thermal technique only. The photo-physical effects of the pulsed light technology can be attributed to the destruction of the cell structure of the microorganisms by the high intensity light pulses.

However, the major lethal effect of the pulsed light technique is indebted to the photo-chemical effect due to which the light photons of high wavelengths, usually in the range of UV light are absorbed by the microorganisms and affect their DNA, thereby resulting in an anti-microbial effect. When the DNA absorbs UV light through the highly conjugated carbon–carbon double bonds, the essential reproductive system of the microorganism is at risk which is the DNA. This absorbed energy by the DNA results in the breaking up of the molecular bonds of the DNA of the microbe, further causing the rearrangement, cleavage and the destruction of DNA. The photo-chemical reactions also result in the production of some DNA reproduction inhibitory substances.

Thus, these mechanisms can be individually or in combination, are responsible for the microbial inactivation in the food systems by pulsed light technique.

Equipment and Working

The basic working of a pulsed light system can be explained in an elaborate manner. Pulses of light are produced by concentrating electrical energy in a capacitor by multiplying electrical power by many folds. This process takes even less than a second and this energy is then released in a very short duration of time to flash lamps. The flash lamps are filled with inert gases and give out light in the form of flashes (Barbosa-Canovas et al. 2000). The pulses obtained per second, that is, pulse frequency is generally in the range of 1–3 Hz (Gómez-López et al. 2012).

A typical pulsed light system consists of a power unit, a pulse generation device, a storage capacitor and a gas-discharge flash lamp (Mandal et al. 2020a, b).The power unit consists of an electrical power supply that converts low voltage AC power into high voltage direct current (DC). The pulse generation device is responsible for determining the shape of the pulse and the spectrum characteristics. It basically consists of high voltage capacitors that are joined in parallel to concentrate energy in the charge cycle, coming from the power unit, and then discharges it in the discharge cycle in the form of high electrical current. The lamp unit is responsible for the transition of the high electrical power to lower energy or ground states, during which they release energy in the form of high intensity light pulses. These high intensity light pulses are then delivered to the product by various lamp configurations.

The pulsed light system can deliver pulsed light in the form of a single pulse, in the form a burst of pulses or as a continuous array of pulses or in random sequences, as per the requirements.

Effect of Pulsed Light on Microbial Decontamination

The effect of pulsed light technique on different microbial species can be depicted as follows

1. Bacteria: According to certain studies, it has been found that Gram negative bacteria are more susceptible to pulsed light than the Gram positive bacteria (Gómez-López et al. 2007) This can be attributed to the loss of DNA repairing tendency of the bacteria due to the continuous application of high intensity light pulses, especially UV pulses.
2. Spores: Spores are less susceptible to the pulsed light than the bacterial vegetative cells (Anderson et al. 2000). This is due to their inherent repair mechanisms which get severely affected and lose their ability to repair themselves due to the pulsed light application.
3. Fungi: The yeast and mold populations have been found to get significantly affected by the pulsed light treatment. The proliferation of yeast in pulsed light treated samples is less rapid as compared to the untreated samples.
4. Viruses: Viruses have also been found to get affected by pulsed light due to the physical changes occurring in them like the breakage of single-strand of RNA, destruction of the virion structure and denaturation of the viral proteins by the high intensity wavelength pulses of pulsed light technique. There is also the rupturing of the viral capsid associated with the effect of the pulsed light on the viral cells.

8 Ultrasound

Ultrasound is one of the most well established technologies in the industry but continues to be an emerging non-thermal processing technology in the food industry. The ultrasound technology makes use of the ultrasound waves, that is, the sound waves having frequencies greater than the normal hearing frequency of human beings, i.e., above 20 kHz (Mason and Cintas 2007). The process of application of ultrasound waves to bring about the desired changes in a medium is referred to as "ultrasonication". These ultrasound waves travel through any medium and produce cavitation bubbles that eventually explode, releasing energy and causing certain mechanical and chemical reactions (Jadhav et al. 2021).

Ultrasound waves can be used at different frequency ranges and hence are classified as low-frequency, medium-frequency and high-frequency ultrasound waves (Bhargava et al. 2021). The low-frequency ultrasound waves have frequencies ranging from 20 to 100 kHz and produce large shear forces in the medium. The medium-frequency ultrasound waves have frequencies ranging from 100 kHz to 1 MHz and produce radical species in the medium through which they are transmitted to. The high-frequency ultrasound waves have frequencies ranging from 1 to 100 MHz and they produce low shear forces in the medium. For food processing and preservation applications, low-frequency ultrasound waves in the range of from 20 kHz-100 kHz are usually preferred as the medium-frequency ultrasound waves can cause undesirable changes in the food systems like lipid oxidation due to their tendency of formation of radical species (Rastogi and Navin 2011). On the other hand, the high-frequency ultrasound waves can physical damage of the tissues of the food systems owing to their high frequencies.

8.1 Principle

Ultrasound waves travel in a medium and cause a series of compressions and rarefactions. When the power exceeds a certain high threshold power, the rarefaction exceeds the power of attractive forces present between the molecules in the food system, resulting in the formation of cavitation bubbles. The cavitation bubbles eventually become unstable due to the action of the localized field generated by the neighbouring bubbles and eventually collapse. This collapsing of bubbles causes the release of energy due to which the microbial cells present in the food system are subjected to extreme conditions of temperature and pressure. The sudden extreme conditions that are experienced by the microorganisms cause thinning of cell membranes of the microbes, shear disruption of the microbial cells, cavitation in the microbial cells, localized heating of the microbial cells and free radical production in the microbial cells, which ultimately have a lethal effect on the microorganisms.

Ultrasonication is usually carried out for both packaged or unpackaged food materials and the ultrasound waves generated are transmitted through the food system and result in the desirable changes in the food product, causing the death of the microbial cells and thereby enhancing the shelf-life of the food product and ensuring that food safety is not compromised, along with maintaining the nutritional and functional properties of the food system without having any deteriorative effects on such properties.

8.2 Equipment and Working

The major equipment that is responsible for the generation of ultrasound waves is a transducer. A transducer is a device that converts electrical or mechanical energy to sound energy. There are 3 major types of transducers that are used for the ultrasound generation, namely liquid-driven transducers, piezoelectric transducers and magnetostrictive transducers.

Liquid-driven transducers are the ones consisting of a liquid in a vessel in which the food material is forced under pressure across a thin blade and for every vibration, the blade produces a vibration wave and cavitation in the liquid. Magnetostrictive transducers are the ones that use the principle of magnetostriction that utilize the application of magnetic field to generate vibrations, that is, conversion of magnetic energy into mechanical energy. Piezoelectric transducers utilize ceramics containing piezoelectric materials that are responsible for the conversion of alternating electrical energy into mechanical energy in the form of vibrations (Bhargava et al. 2021). The most basic types of equipments that are used for the ultrasonication process are ultrasonic baths and ultrasonic probe systems. The ultrasonic baths consist of a tank that contains a medium through which the ultrasound waves shall pass which are generated by the transducers bound to the base of the tank. On the contrary, the ultrasonic probes consist of metal horns of different shapes that are attached to the transducers. The horns, however, must be designed in such a way so that they resonate at the same frequency as that of the transducer.

The ultrasonic probe systems have a high sound intensity and are therefore utilized more commonly for the inactivation of microorganisms in food systems as the process requires relatively high power density.

8.3 Effect of Ultrasound on Microbial Decontamination

The use of ultrasound technique for the inactivation of microorganisms present in the food systems is one of the most promising non-thermal technologies. The destruction or disruption of microbial cell wall can be achieved by using high power ultrasound waves. However, very high intensities are needed if complete sterilization is to be achieved.

The inactivation of microorganisms is owed to the physical damage caused by the ultrasound waves to the microbial cells like rupturing of cell membrane, release of intracellular constituents and the inability of the cells to repair them. The effectiveness of ultrasonication on the lethality of microbial cells is dependent upon the shape and size of the microorganisms as bigger cells are more sensitive than the smaller ones. It also depends on the amplitude of the ultrasonic waves, time of exposure, volume of food being processed, the composition of food and the temperature of the process.

The effect of ultrasounds on the various types of microorganisms is discussed as under

- ***Bacteria***: It has been found in studies that the rod-shaped bacteria are more sensitive to the ultrasonication process than the coccal forms of the bacteria. Moreover, the bacterial spores are found to be more resistant to the process as compared to the vegetative cells (Piyasena et al. 2003).
- ***Fungi***: Ultrasound waves are shown to cause leakage of nucleic acids and proteins and changes in the structure of the cell membrane in case of fungi like *R. stolonifer.* Moreover, the free radicals produced by the ultasonication process like hydrogen and hydrogen peroxide from water molecules present in the food system, break the fungal DNA by making bonds with the sugar-phosphate site of DNA and destroy them.
- ***Viruses***: Ultrasonication is known to have only a marginal effect on the reduction of viral load in the food systems.

9 Oscillating Magnetic Field (OMF)

The use of magnetic fields in the food processing and preservation techniques is increasing day by day. The magnetic fields utilized for the purpose can be static, oscillating or pulsed magnetic fields. One of the most commonly used types of magnetic fields in the food industry is oscillating magnetic field (OMF). OMF is widely being used for the inactivation of microorganisms and for destroying the microorganisms in order to make the foods safe and to extend their shelf-life without the application of heat to them. OMF involves the incorporation of food in sealed plastic bags and their exposure to pulses having frequency ranging from 5 to 500 kHz in numbers 1−100 for a very less treatment time of 25−100 ms at temperatures not exceeding 50 °C.

9.1 Principle

Direct or alternating currents are used to generally generate the magnetic fields. They can also be generated with the help of permanent magnets. According to their behaviour, they can be classified as static, oscillating or pulsed magnetic fields. In the case of OMF, magnetic field is applied to the food systems in the form of pulses which are in the form of decaying or constant amplitude sinusoidal waves.

OMF, applied in the form of pulses, is capable of reversing the charge on each pulse, which in turn decreases the intensity of each pulse with time. The inhibition of the microbial growth by the OMF technique can be owed to the fact that the microorganisms are affected by the magnetic fields they are exposed to or by the magnetic fields induced. The magnetic field intensities that are capable of inactivating the microbes range from 5 to 50 T. It has been found in studies that when a food product is subjected to a single oscillating magnetic field at frequencies above 5 kHz and intensities above 5 T, the number of microorganisms in the food system reduces by about 2 orders of the magnitude of the pulse applied. Therefore, complete sterilization of the food product can be achieved if the product is subjected to a greater number of such magnetic field pulses. Since the time of exposure of each pulse is very short, even a higher number of pulses do not significantly raise the product temperature, thereby preserving the nutritional and the functional properties of the food product. Thus, OMF achieves the nearly complete or complete sterilization of the food product, depending on the number and intensity of the magnetic field pulses, without any increase in the temperature of the product.

9.2 Equipment and Working

The magnetic fields are produced when an electric current is passed through a coil. The intensity of the magnetic field depends upon the number of loops of the coiled wire as it decides the amount of current flowing through the wire. The magnetic field is produced by the coil which is connected to a capacitor that supplies the current. When the oscillating current is induced by the capacitor to the coil, it produces an oscillating magnetic field within the coil. The frequency of the oscillating magnetic field depends on the capacitance of the capacitor and the resistance experienced by the current.

9.3 Effect of OMF on Microbial Decontamination

The OMF is known to cause the inactivation of microorganisms by inducing energy into the magneto-active parts of substantially large molecules of the microbial cells, like DNA. With such several oscillations, the local energy generated can cause the destruction of certain bonds present in the molecules, which would either cause it to become reproductively active or might lead to the destruction of the molecule and hence the microbial cell. Thus, OMF traumatizes the genetic material of microbial cells or damages the structure of microbial cells, both of which render a lethal effect on the microorganisms.

In the case of bacterial cells, their surfaces have net negative charges, which when exposed to the external magnetic fields, experience charge reversal, leading to the structural damage of the bacterial cells.

The inactivation of microorganisms by OMF has been achieved in food products like milk, yogurt, orange juice, etc. It has been reported that even one pulse of OMF was adequate to reduce the bacterial population between 102 and 103 CFU/g in such products.

10 Cold Plasma Processing

Plasma is the fourth state of matter that is a state of gas which is in either partially or fully ionized state. Cold plasma processing is widely used in the food industry for the microbial inactivation of food systems along with maintaining the quality parameters of the food systems intact. Cold plasma processing technique operates in the temperature range of 25−65 °C. When gases like argon, oxygen, helium or nitrogen are ionized using thermal energy, electrical energy or magnetic field, there is generation of free radicals which is majorly responsible for providing a lethal effect on the microorganisms. Thereby cold plasma processing is used for reducing the microbial load of the food systems and on their surfaces (Jadhav et al. 2021).

10.1 Principle

Cold plasma processing technique shows its effect on the microbial cells by the generation of free radicals that subsequently attack the microbial cells (Phan et al. 2017). They do so by causing the oxidation and denaturation of proteins, by inducing lipid oxidation, by destruction of the DNA of the microbial cells and by damaging the cellular components of the microbial cells, thus leading to death of the cell eventually. The reactive species in plasma are known to have direct oxidative effects on the surface of the microbial cells. Furthermore, these plasma reactive species also damage the DNA present in the chromosomes of the microbial cells.

The cold plasma processing technique is known to be highly dependent on the amount of water present in the microbial cell. It has lowest effect on the microbe that is dry as compared to the higher effect observed in case of moist microbes. The reactive species generated by the cold plasma processing, react with water present in the microbial cell which further results in the generation of hydroxyl (OH^-) ions. These hydroxyl ions are the most reactive and lethal to the microbial cell. These hydroxyl radicals are produced in the hydration layer around the DNA molecules of the microbial cells and are responsible for the major destruction of DNA. These radicals also react with the nearby organic molecules which lead to free radical chain oxidation and thereby eventually leading to the destruction of DNA molecules and other cellular components and the cell membranes. This results in the death of the microbial cell eventually. The presence of reactive oxygen species like oxygen radicals also produces lethal effects on the microbial cells by having significant effects on the different macromolecules present in the microbial cell. The singlet state oxygen leads to the deformation of the microbial cells and produce the lethal effect.

10.2 Equipment and Working

Plasma for cold plasma processing can be produced by passing the gas between two electrodes and subjecting it to electric field. Plasma generation can be done by methods like corona discharge, dielectric barrier discharges, radio frequency plasma and the arc discharge method. In cold plasma processing, ionization is one of the most important steps.

10.3 Effect of Cold Plasma Processing on Microbial Decontamination

It has been reported in studies that the cold plasma processing technique reduces the mesophilic bacterial count by 12–85%. It causes a reduction of 54% in 3 min in the microbial load of one of the most common food pathogen, that is, *E. coli*. It has also been shown that the yeast and mould content declines by 44–95% due to cold plasma processing of food systems.

11 Ozone Treatment

Ozone is a molecule consisting of 3 oxygen atoms. It is a colourless gas and has a typical odour. It is highly reactive in nature and is very much unstable. Ozone treatment involves the use of ozone gas either in the gaseous form or as ozonated water by dissolving the ozone gas in water. Ozone treatment is an emerging non-thermal food processing technology that has the capability of altering the permeability of the microbial cells and damaging their cellular membranes and thus causing the death of the microbial cell. It can also cause a fatal effect to the microbial cells by damaging the protein structure and thereby causing the malfunctioning of enzymatic activity and hence affecting the metabolic activity of the microbial cell, eventually resulting in the death of the cell (Jadhav et al. 2021).

11.1 Principle

For use in industrial purposes, ozone is produced in closed spaces by 2 widely used methods. The first method is the UV method in which low concentrations of ozone of around 0.3 ppm are produced from oxygen present in air using radiations of 185 nm wavelength ranges. The second method is the corona discharge method which involves the application of a high voltage alternating current across a discharge gap in which oxygen or air is present. The current excites the oxygen electrons and causes the oxygen molecules to split that combine with other oxygen molecules to form ozone.

The principal mechanisms involved in the action of ozone on microbial inactivation involve either the direct action of ozone molecules on the microbial cells or the free-radical destruction mechanism of the singlet oxygen. It has been found that the ozone targets the surfaces of microbial cells majorly. This is due to the fact that ozone primarily targets the double bonds of the unsaturated lipid constituents in the cell envelope. Ozone also causes the cellular proteins to flocculate. Ozone also causes the alteration of the pyrimidine bases of the DNA of the microbial cells, thus targeting the genetic material of the microbial cells as well. All of these mechanisms lead to the leakage of the cellular contents of the cell and hence the death of the cell.

11.2 Equipment and Working

For ozone treatment in the food industry, ozone is either used in the gaseous phase or in the aqueous phase. The basic components of an ozone treatment system are namely: the gas (in the form of pure oxygen or air), ozone generator, power source, reactor, contactor, gas elimination (for surplus air) unit and ozone analyzer. For treatment of the food systems, basic types of contactors are used like the bubble diffuser chamber or the turbine-agitated reactors.

In the corona discharge type, the dry air or pure oxygen are used as the oxygen source to produce ozone. Usually zeolite towers are used for the production of pure oxygen by disabling the production of nitrogen compounds in the air, by acting as molecular screens.

During ozone treatment, the systems usually operate at low frequencies and high voltages of 50−60 Hz and greater than 20,000 V respectively. However, for higher effectiveness, the modern day advanced technologies require higher frequencies and low voltages of 1000−2000 Hz and 10,000 V respectively.

However, it is really essential to destroy the remaining ozone gas after treatment of the food systems for safety purposes.

11.3 Effect of Ozone Treatment on Microbial Decontamination

The ozone treatment shows its bactericidal action depending on the type of medium in which the bacterial cell is present. Ozone treatment can inactivate both the gram-positive and gram-negative bacteria. It can also destroy the vegetative cells and spores. However, it has been found that the bacterial spores are more resistant to ozone treatment than the vegetative cells (Kim et al. 1999).

Ozone is also known to have effect on the fungi. Yeasts are found to be more sensitive than the moulds to the ozone treatment.

Ozone treatment also affects the viruses and is able to inactivate the viral cells even at low concentrations of ozone in relatively short contact times.

12 Supercritical Fluid Extraction (SFE)

Supercritical Fluid Extraction (SFE) is an emerging non-thermal food processing technique that makes use of supercritical fluids for the processing and preservation of food systems. This is owing to the fact that the organic solvents that were earlier used were capable of causing solvent contamination in the food systems and were costly and had negative impacts on the environment as well (Temelli et al. 2012). SFE uses supercritical fluids, that is, a fluid that shows both the properties of a gas and a liquid. It exhibits the density of liquids and the diffusivity and viscosity of the gases. This phenomenon occurs when a fluid is either heated beyond its critical temperature or compressed below its critical pressure and attains a supercritical state (Brunner, 2005). Various substances can be used as supercritical fluids but the most common and widely used is CO_2. This is because it achieves a supercritical state at moderate temperature and pressure of 31.1 °C and 7.4 MPa respectively (Jadhav et al. 2021). SFE is being utilized in the food industry for the microbial decontamination of foods.

12.1 Principle

The basic principle of working of SFE can be attributed to the properties of the supercritical fluids as they show enhanced properties. Due to their quality of possessing both the attributes of liquid and gas, they can be used as a solvent for increased mass transfer rates.

The SFE technique works by reducing the pH of the microbial cell which causes their rupturing and bursting and leads to the death of the cell. Hence it reduces the microbial load of the food system (Spilimbergo and Bertucco 2003). Moreover, since SFE operates at low temperature, the functional and the nutritional properties of the food systems are preserved (Koubaa et al. 2018).

12.2 Equipment and Working

The basic parts of a SFE system are a pump, pressure cell, pressure maintenance system and a collection vessel. The pump is used for supplying the CO_2 to the system and the pressure cell is used to contain the sample. The sample is loaded into an extraction vessel and is pressure is applied on it by the means of the fluid by a pump. The material is transferred from the extraction vessel into a separator and the extracted material settles down. The fluid, that is $CO_{2,}$ can be regenerated.

12.3 *Effect of Supercritical Fluid Extraction on Microbial Decontamination:* Gaseous CO_2 Used in *SFE Has Anti-Microbial Effects on the Food Systems.*

13 Membrane Separation

Membrane separation technique is one of the novel food processing technologies that is used in the inactivation of microorganisms like bacteria and yeasts. The membrane separation techniques involve the utilization of semi-permeable membranes of specific pore sizes and aid in the removal of the microorganisms on the basis of their molecular size. Therefore this method is also sometimes referred to as cold pasteurization and sterilization. These membrane separation techniques are pressure-driven and can further be classified as microfiltarion, ultrafiltration, nanofiltration and reverse osmosis (RO). It preserves the natural organoleptic properties of the food systems and also protects the heat-sensitive compounds present in the food systems.

13.1 Principle

Generally, microfiltration is used for the separation of microorganisms from the food products. The microfiltration membrane pore size ranges from 20 to 0.1 μm^2.

13.2 Equipment and Working

When a food product, in the liquid form, is subjected into a membrane separation system, it gets separated into retentate (the fraction retained by the membrane) and permeate (the fraction that passes through the membrane). The microorganisms can either be in the retentate or in permeate or in both streams.

13.3 Effect of Membrane Separation on Microbial Decontamination

Membrane separation is found to be highly effect against the bacteria and spores in the dairy industry for the removal of the said microorganisms from skim milk. The microfiltration membrane separation can effectively remove the spore-forming bacteria from the milk samples.

14 Findings on Microbial Decontamination by Non-Thermal Food Processing Techniques

All the techniques were profoundly studied and the effect of each technique on different microbial species was analysed and mentioned in the tables as HPP (Table 1); PFE (Table 2); Irradiation (Table 3); Pulse Light (Table 4); Ultrasound (Table 5); CPP (Table 6) Ozone Treatment (Table 7) and SFE (Table 8).

Table 1 Effect of High Pressure Processing (HPP) on Microbial Decontamination of the foods

Species	Pressure used (MPa)	Pressure holding time	Temp (°C)	Inactivation	Most commonly present in foods
Listeria monocytogenes	400–500	10 min	20–25	2.9 log10 CFU/g–5.1 log10 CFU/ml	Acidified foods, Ready to eat meats, Dairy Products
Staphylococcus aureus	300	50 min	25	8.0 log10 CFU/ml	Cooked meat, Poultry
Escherichia coli	350–550	2–10 min	12–25	1.28 log10 CFU/g–8.0 log10 CFU/ml	Beef, Milk, Vegetables
Salmonella	350–450	2–14 min	11–20	3.1 log10 CFU/g–5.94 log10 CFU/g	Meat and meat products
Bacillus cereus	600	20 min	80	7.53 log10 N0/N	Proteinaceous foods and starchy foods
Clostridium botulinum	827	10 min	55	1.8 log10 N0/N	Meats, milk products, vegetables
Clostridiumperfringens	600	12.5 min	65	2.54 log10 N0/N	Beef, Milk, Vegetables
Clostridiumsporogenes	900	5 min	100	~4.0 log10 CFU/ml	Milk
Hepaptitis A	500	300 s	–	–	–
Polio virus	600	60 min	–	–	–

Table 2 Effect of Pulsed Electric Field (PEF) on Microbial Decontamination of foods

Bacterial species	Number of pulses applied (n)	Electric field strength (kV/cm)
E. coli	5	14.0
L. brevis	5	12.1
P. fluorescens	5	11.5
S. cerevisiae	5	5.4

Table 3 Effect of Irradiation on Microbial decontamination of foods

Bacteria	D10 value (kGy)
Vegetative cells	
Bacillus cereus	0.17
Campylobacter jejuni	0.08–0.20
Clostridium perfringens	0.59–0.83
Escherichia coli (incl. O157:H7)	0.23–0.35
Lactobacillus spp.	0.3–0.9
Listeria monocytogenes	0.27–1.0
Staphylococcus aureus	0.26–0.6
Salmonella spp.	0.3–0.8
Bacterial spores	
Bacillus cereus	1.6
Clostridium sporogenes	1.5–2.2

Table 4 Effect of Pulsed Light on Microbial Decontamination of foods

Microorganism	Food product/ Food contact material	Number of pulses	Pulse energy (J/cm^2)	Pulse width (μs)	Log reduction (Log)
Penicillium expansum	Apple juice	40	32	300	3.76
Murine norovirus	Hard water, mineral water, turbid water, sewage treatment effluent	5	3.45	520	> 3.0
E. coli, *L. innocua,* *S. enteritidis,* *S. cerevisiae*	Orange juice (OJ), strawberry juice (SJ), apple juice (AJ)	20	71.6	360	0.3 – 0.8 for all strains (OJ and SJ) 2.1, 1.6, 2.4 1.0 respectively (AJ)
Lactobacillus brevis *Listeria monocytogenes*	Apple slices	3.0	1.75	50.0	3.0 2.7
Pseudomonas fluorescens *E. coli*	Cheese	–	–	360	3.74, 5.41, 3.37 respectively

Table 5 Effect of ultrasound technique on microbial decontamination of foods

Name of microorganism	Food product	Ultrasound conditions used	Reductions
Escherichia coli	UHT milk	20 kHz, 110 μm	At 60 °C: $D_{US} = 0.38$ min whereas $D_T = 1.28$ min
Lactobacillus acidophilus	Orange juice	20 kHz, 110 μm	At 60 °C: $D_{US} = 0.52$ min whereas $D_T = 0.79$ min
Listeria monocytogenes	Orange juice	20 kHz, 600W, 95.2 μm, 45 °C, 30 min	2.5 log cycles reduction
Saccharomyces cerevisiae	UHT milk	20 kHz, 124 μm, 26 °C, 2.5–10 min	2.10 log cycles after 10 min at 26 °C ($D_{US} = 4.3$ min)
Clostridium perfringens spores	Beef slurry	24 kHz, 210 μm, 0.33Wg − 1, 75 °C, 60 min	< 1.5 log reduction
Bacillus cereus spores	Beef slurry, rice porridge, cheese slurry and skim milk	24 kHz, 210 μm, 0.33Wg − 1, 75 °C, up to 20 min	After 1.5 min at 70 °C, 4.2, 4.1 and 3.2 log cycle reductions in beef slurry, rice porridge and cheese slurry, respectively, versus 0.7, 0.6 and 0.8 log cycles after heat-only treatment. In skim milk 3.5 log cycles after 10 min at 70 °C versus 0.75 after heat-only treatment
Salmonella enteritidis	Liquid whole egg	20 kHz, 117 μm, 200 kPa, 40 °C	$D_{US} = 0.76$ min

Table 6 Effect of Cold Plasma Processing (CPP) on Microbial Decontamination of the foods

Microorganism	Substrate	Exposure Time	Log reduction
E. coli *S. stanley*	Apples	3 min	Up to 3.7
A. parasiticus; Penicillium	Grains and cereals	15 min	3
A. *flavus*	Pepper powder	20 min	2.5

Table 7 Effect of ozone treatment on microbial decontamination of foods

Microorganism	Inactivation (log10)	Treatment time (min)	Concentration (mg/litre)	Temp (°C)	Medium	Reactor type
Escherichia coli	4.0	1.67	0.23–0.26	24	O3 demand-free water	Continuous flow
Staphylococcus aureus	2.0	0.25	–	25	Phosphate buffer	Batch (bubbling)
Bacillus cereus	2.0	5	0.12	28	O3 demand-free water	–
B. cereus (spores)	2.0	5	2.29	28	O3 demand-free water	–
Salmonella typhimurium	4.3	1.67	0.23–0.26	24	O3 demand-free water	Continuous flow
Candida parapsilosis	2.7	1.67	0.23–0.26	24	O3 demand-free water	Continuous flow
C. tropicalis	2.0	0.30–0.08	0.02–1.0	20	O3 demand-free water	Continuous flow
Bacteriophage f2	> 4.3	0.16	0.41	20	Water	–
Poliovirus type 1 (Mahoney)	1.0	0.53	0.51	20	Water	–

Table 8 Effect of Supercritical Fluid Extraction (SFE) on Microbial Decontamination of foods

Microorganism	Fluid	Pressure (bar)	Temp. (∘C)	Time (mins)	Reduction factor– log10 N/N0
Bacillus stearothermophilus(endospores)	CO_2	75–207	60	120	1.0
Clostridium sporogenes (spores)	CO_2	54	70	120	0.8–7.8
Saccharomyces cerevisiae	CO_2	40–150	40	–	Inactivation Kinetics

15 Conclusion

There has been a noticeable increase in the transition from thermal to non-thermal food processing techniques as awareness of the advantages of non-thermal food processing techniques on the nutritional content and functional potential of the food systems has grown. The term "non-thermal food processing techniques" refers to those methods that do not use heat to treat or preserve food. This review study's main goal is to shed light on food processing methods that use thermal and non-thermal methods, types of distinct non-thermal food processing technologies, and the levels of microbial deactivation attained by each method. As a result, the study concentrates on the many non-thermal food processing techniques that are now used in the food business. Therefore, non-thermal food processing techniques aid in the elimination of certain pathogenic and food spoilage bacteria as well as have a general impact on microbial decontamination, ensuring the safety of the food.

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Trans Fats in Street Foods-Sources, Health Risks and Alternative Sustainable Strategies

Shalini Sehgal, Shubhadeep Roy, and Nikhil Mishra

Abstract Indian culture is inextricably linked to the consumption of street cuisine. Majority of popular Indian street foods are fried in oil. It is a known fact that the vendors frequently reuse the cooking oil in order to make more profit. The reheating of oils multiple times for frying and cooking purposes leads to a variety of chemical reactions that impact the structural integrity of the oil leading to deterioration in its quality. Some known reactions include oxidative destruction of lipids, formation of reactive oxygen species, and the depletion of natural oxidants. The reuse of fats and oils not only affects their quality but the consumption of food made with them, has serious health implications such as inflammation and hypertension. The negative effects range from the simple oxidative damage to complex ones which includes decline in cellular antioxidant defense mechanism. In this chapter, the role that fats and oils play in a balanced diet as well as their initial significance is highlighted. The numerous chemical processes involved in repeated frying as well as the negative health effects of the heat induced byproducts are discussed. The global and Indian context for regulating these harmful end products is also included.

Keywords Used cooking oil (UCO) · Trans fatty acid · Deep fat frying · RUCO · Oil oxidation · Fat degradation

1 Introduction

A healthy diet supports normal growth, development, and aging, aids in maintaining a healthy weight, lowers the risk of chronic disease, and improves general health and well-being. It also promotes healthy pregnancy outcomes. Fatty acids are the building blocks of fat, one of the macronutrients. Triglycerides, which are chemical substances made of three fatty acids joined by a glycerol molecule, are the main constituents of fats and oils. Based on their chemical makeup, fatty acids can be classed as saturated

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or unsaturated. Monounsaturated and polyunsaturated fatty acids are examples of unsaturated fatty acids. We require a sufficient quantity of fat in our meals to help our systems properly absorb the fat-soluble vitamins A, D, E, and K. Fats are a good source of energy.

Fatty acids are a component of our cell membranes within the body, and fat also aids in the insulation and protection of our internal organs, helps to regulate our body temperature, and plays a role in a variety of bodily functions, including the development and growth of our brains and, consequently, the communication between different cell types. Bile acids, which aid in food digestion, and several of our hormones depend on cholesterol for production. Every gram of fat contains 9 cal (kcal), which is more than twice as many as the 4 kcal per gram of protein and carbohydrates that we consume. So, over time, a high-fat diet may result in weight increase.

Certain dietary fatty acids are particularly significant. These fatty acids cannot be created by the body through the synthesis of other fats because they are essential to biological structures, especially the various cell membranes. Due to its capacity to change into other necessary fatty acids, linoleic acid stands out as the most important of them. A key function is played by linoleic acid, which is classified as a polyunsaturated fatty acid and distinguished by its two double bonds. Additionally, it tends to lower blood cholesterol levels due to its role as a major carboxylic acid. Several seed oils, including corn, cottonseed, and sunflower oils, contain linoleic acid in various amounts (Marette et al. 1990).

2 Physio-Chemical Characteristics of Fats and Oil

At room temperature, fat is plastic or semi solid and oil is a liquid, this is the sole difference between fats and oils (Manley 2000). The importance of fats and oils commences from their functionality which is due to their chemical composition and structural aspects (Belton 2000).

2.1 Fatty Acid Composition

A fatty acid is a long chain, carboxylic acid, which generally contains an unbranched chain that has a methyl ($–CH_3$) and a carboxyl (–COOH) end. Specific fatty acid compositions of oils are expressed as a percentage of total fatty acids. According to, the functional properties of commercial fats are strongly allied to their fatty acid and triacylglycerol compositions (Man 1998). The characteristics of fats and oils, both in terms of their physical and chemical attributes, are determined by the composition of their fatty acids and their arrangement within the triacylglycerol (TAG) molecule. In these molecules, fats and oils exhibit a significant concentration of saturated fatty acids when their triacylglycerol (TAG) molecules possess a high melting point. Conversely, an increased proportion of unsaturated fatty acids leads to lower melting points.

2.2 Melting Profile

As they contain a variety of triacylglycerols (TAGs), fats and oils exhibit a melting profile rather than a clearly defined melting temperature. As a result of the different kinds of acids occupying its three locations, each triacylglycerol has a unique melting point. According to the mixture's composition, the mixtures that make up fats and oils have softening ranges that are wider or narrower. Some fats have a wide melting range (palm oil melts between 27 and 45 °C), while coconut oil melts between 23 and 26 °C (Wade 1988). The extent of this range depends on a number of variables, including the degree of hydrogenation, the make-up of the fatty acids, and how they are distributed within the triacylglycerol structure (Belitz et al. 2004). The fatty acids can be saturated or unsaturated (cis or trans conformation) and their chain lengths can vary. The melting point is lowered by unsaturated fatty acid content, short fatty acid chains, and cis configuration (Belton 2000). Saturated fatty acids have the highest melting points, followed by trans fatty acids and then cis fatty acids. The fatty acids palmitic, stearic, oleic, and linoleic are the most well-known (Wade 1988; Belton 2000).

2.3 Solid Fat Content (SFC)

Solid fat content (SFC), which is the proportion of fat that is solid at a given temperature, is a crucial factor that can affect the appearance, flavor release, melt rate, shelf life, and stability of food products that contain fat. SFC significantly affects how functionally effective and texturally appealing fats and products containing fats are (Lai and Lin 2006).

2.4 Polymorphism

The triglyceride molecules in fat can be arranged in several crystal forms, each of which has a unique melting point. The term polymorphism refers to this phenomenon. There are three mai n polymorphic types of fats and oils: alpha, beta prime, and beta. Despite the fact that each configuration displays unique crystalline structures, free energy levels, and other physical and chemical traits, their chemical composition is consistent. Smaller crystals have more surface area than larger ones, which increases their ability to hold significant amounts of liquid oil within the crystal matrix (Devi and Khatkar 2016).

3 Chemistry of Deep Fat Frying (DFF)

Due to its high-temperature operations and rapid heat transfer, frying is a useful cooking technique. Heat is transferred to the meal by way of the oil that surrounds it. By causing the heat destruction of microbes and enzymes and lowering the water activity at the food's surface, this process aids in food preservation (Oke et al. 2018). Food modifications involving starch gelatinization, protein denaturation, flavour, and color formation via the Maillard reaction result from oil-food interaction cooking and dehydrating the meal at high temperatures. The majority of volatile chemicals are vaporized by steam, while the remainder are either absorbed by fried meals or go through additional chemical processes. The oil's remaining non-volatile components alter the physical and chemical characteristics of oil and fried foods. Non-volatile chemicals have an impact on the quality, texture, and flavor stability of fried meals during storage.

The rate of heat transfer is impacted by the food's composition and its attributes associated with heat and mass transfer, which encompass thermal conductivity, thermal diffusivity, specific heat, and density. As the frying process unfolds, alterations occur in all these characteristics due to transformations in both the oil and the food, as outlined in (Table 1). Besides, there are other changes caused by interactions between food compounds (Bordin et al. 2013). The content of carbohydrates and protein in raw material, strongly interacts with lipids, especially with thermal and oxidative degradation products (Maillard reaction products, reticulated proteins), generating toxigenic and carcinogenic compounds. Additionally, the longer the oil is used, the greater the induction of adverse reactions. Extended exposure of oil to high temperatures and atmospheric air can generate highly oxidized, potentially toxic products (Sikorski Zdzislaw 2001; Bordin et al. 2013).

Table 1 Changes in food components induced by frying

Components	Changes during frying
Fat	Increased concentration and change in composition
Water	Significant loss
Reducing sugars	Maillard reaction
Starch	Gelatinization
Proteins	Alteration of the composition
Amino acids	Formation of heterocyclic flavoring substances
Flavoring substances	Formed by oxidative and maillard reaction
Vitamins	Increased concentration and change in composition
Minerals	Significant loss
Antioxidants	Maillard reaction

4 Physio-Chemical Changes in Oil during Deep-Fat Frying

Hydrolysis, oxidation, isomerization, and polymerization resulting in the production of free fatty acids, aldehyde, ketone, acid, lactone, hydrocarbon, diglyceride, and monoglyceride, cyclic and epoxy compounds, monomer, trans isomers, dimmer, oligomer are the chemical reactions during deep-fat frying as shown in (Table 2).

4.1 Hydrolysis of Oil

During the cooking process of frying, moisture changes into steam, which bubbles and vaporizes as the food cooks. Water, steam, and oxygen begin the chemical processes that take place in the frying oil and food. Triacylglycerols' ester bond is attacked by water, a weak nucleophile, leading in the formation of di- and monoacylglycerols, glycerol, and free fatty acids. As the number of frying increases, so does the concentration of free fatty acids in frying oil (Choe and Min 2007). Fry oil's health is determined by its free fatty acid content. Because short and unsaturated fatty acids are more soluble in water than long and saturated fatty acids, hydrolysis is more practical in oil with short and unsaturated fatty acids than in oil with long and saturated fatty acids. Short-chain fats and oils can easily access water from foods for hydrolysis. (Choe and Min 2007) (Fig. 1).

4.2 Oxidation of Oil

The mechanism of thermal oxidation is principally the same as autoxidation and it involves thermal oxidation involves the initiation, propagation, and termination of the reaction.

Table 2 showing the formation of new compound/s under the influence of heat

Type of change	Causative agent	New compound formed
Hydrolytic	Moisture	Free fatty acids Diacylglycerols Monoacylglycerols
Oxidative	Air	Oxidized monomers Oxidized dimers and polymers Volatile compounds (aldehyde, ketones, hydrocarbons) Sterol oxides
Thermal	Temperature	Dimers and non-polar polymers Cyclic monomers Trans isomers and position-isomers

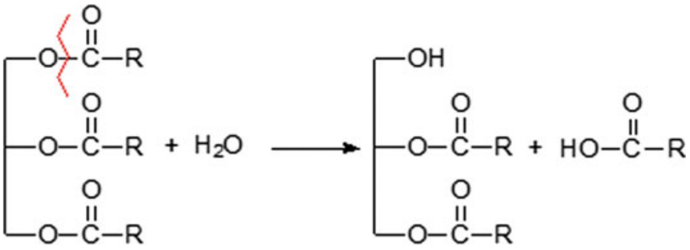

Fig. 1 Formation of fatty acids and diacylglycerols (Instituto de la Grasa (CSIC) (Carmen Dobarganes 2009)

The chemistry of lipid oxidation at high-temperature food processes, such as frying, is extremely complex because oxidative and thermal reactions occur simultaneously. Although all oxidation reactions are accelerated as temperature rises, the solubility of oxygen decreases dramatically. (Instituto de la Grasa (CSIC) and (Carmen Dobarganes 2009).

The oxidation mechanism consists of three phases: induction, propagation, and termination (Fig. 2).

The oxidative stability of oil/fat is influenced by degree of unsaturation of fatty acids. Generally, unsaturated oils oxidize more rapidly than less unsaturated ones.

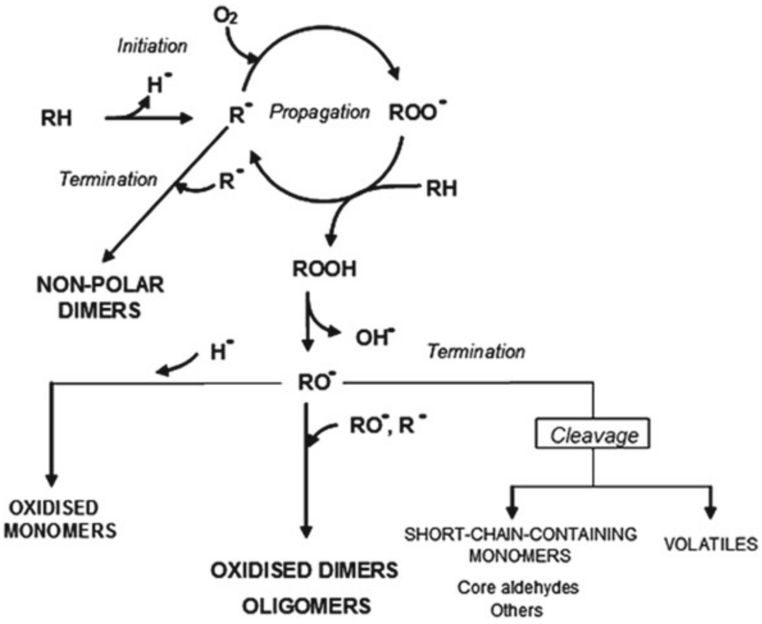

Fig. 2 Simplified scheme of thermal oxidation (Instituto de la Grasa (CSIC) (Carmen Dobarganes 2009)

Other components such as metals, free fatty acids, and mono− and diacylglycerols can negatively affect the frying stability of oil (Aladedunye and Roman 2013).

The oxidation of fats leads to a reduction in the nutritional quality of the food due to the breakdown of fat-soluble vitamins and the degradation of polyunsaturated acids (BTSA 2019). Auto-oxidation is an irreversible oxidation process. It is impossible to avoid it in its entirety, but it can be delayed by the addition of antioxidants.

4.3 Polymerization

During frying, polymerization occurs, resulting in a wide range of chemical reactions that result in the formation of compounds with high molecular weight and polarity. The Diels–Alder reaction produces polymers from free radicals or triglycerides. Cyclic fatty acids can form within a single fatty acid, dimeric fatty acids can form between two fatty acids, either within or between triglycerides, and polymers with high molecular weight can form a cross-link.

The formation of dimers and polymers is affected by the type of oil, frying temperature, and the number of frying. The primary breakdown products of frying oil consist mainly of non-volatile polar compounds, as well as triacylglycerol dimers and polymers. The number of cyclic compounds is relatively minor in comparison to the prevalence of non-volatile polar compounds, dimers and polymers (Frankel et al. 1984; Dobarganes et al. 2000; Sanchez-Muniz et al. 1993). Dimers and polymers are large molecules with molecular weights ranging from 692 to 1600 Daltons that are formed by the combination of −C–C−, −C–O–C−, and −C−O−O−C− bonds (Kim et al.1999). Cyclic polymers are produced within or between triacylglycerols by radical reactions and the Diels–Alder reaction. With the increase in the number of frying and frying temperature, the amounts of polymers also increase. Polymers that develop during deep-fat frying exhibit a high oxygen content. These oxidized polymer compounds expedite the oxidation process of the oil itself. Additionally, these polymers contribute to the acceleration of oil degradation, causing heightened oil viscosity, diminished heat transfer efficiency, foam generation during frying, and the emergence of undesirable colours in the food.

4.4 Isomerization: Formation of Trans Fatty Acids (TFA)

Many factors influence trans fatty acid formation, including partial hydrogenation, refining, baking, and frying (Ganguly and Grant 2015). These factors can cause a double bond to change from a cis to a trans position (geometric isomerization) or to move to a different position in the carbon chain (positional isomerization), and both types of isomerization can occur in the same molecule (Shabbir et al. 2015).

Different trans isomers can form depending on the factors influencing their formation. Trans fatty acids are geometrical isomers of monounsaturated and polyunsaturated fatty acids with non-conjugated interrupted by at least one (CH_2) group carbon–carbon double bonds in the trans configuration, including trans monomers, which are mainly stereoisomers of elaidic acid, and trans isomers of polyunsaturated fatty acids (trans dienes, trans trienes) with non-conjugated carbon–carbon double bonds, produced by hydrogenation of oils and fats (Martin et al. 2007).

5 Indian Street Foods and the Use of Fats and Oils

It has frequently been noticed that street food vendors, who play a significant part in our food chain, repurpose cooking oil and top it out with new oil. We have also heard that larger restaurants offer discarded cooking oil at a discount to smaller eateries and street vendors. India is classified as a developing nation since 30% of its people reside in cities and 70% live in rural areas. Fried food is frequently consumed in India in roadside eateries, market food stands, and restaurants. People's patterns of food consumption are influenced by their social position. For instance, low-income individuals in India eat only fried foods from roadside shops to survive. According to a poll, 48% of participants ate fried food 1–6 times each week (Chakraborty et al. 2009). Snacks make up 21% of all meals, with shallow and deep-fried dishes being the most popular categories (Chakraborty et al. 2009).

CAG (Citizen Consumer and Civic Action Group (CAG) undertook a study of street food vendors in Tamil Nadu. A survey, titled 'Reusing of cooking oil—A survey of street vendors'–focussed on street food vendors who prepare fried foods across Tamil Nadu viz. Nagapattinam, Madurai, Virudhunagar, Nilgiris, Erode, Salem, Thiruvanamalai, Karur, Dharmapuri, Dindigul, Cuddalore,Thiruvarur, Namakkal and Mayiladudurai. CAG surveyed 2333 street vendors.

Some highlights of the study are as follows:

- The study reveals that palm oil usage ranks highest with 76.2% and could be considered the commonly used oil for cooking purposes by the respondents of the survey. Apart from this, 12.5% of respondents use groundnut oil, followed by gingelly oil, vanaspati, and sunflower oil.
- About 4% of surveyed vendors admitted to buying reused oil from hotels, restaurants, and big snack shops mainly because of low prices.
- 64% of the street vendors said that they add fresh oil to the used oil. Of these, 30% of them said that they topped up the used oil with fresh oil once, while around 49% said that they do the same twice or more.
- Around 9% said that they reuse the same oil throughout, till it got exhausted.
- Around 55%of street vendors dispose of used oil. 24% of street vendors make use of the old oil for other cooking purposes such as using the oil for house use or as a fuel, to start fires for stoves.

Most of the respondents (around 90%) are not aware of the Repurposed Used Cooking Oil (RUCO) initiative of the Food Safety and Standards Authority of India. Very few of them (10.5%) avail the services of RUCO. Among the unaware population, the majority of the street vendors (95%) are ready to know and avail of the services offered under the RUCO scheme (CAG Report).

6 Health Effect of the Use of Deteriorated Frying Fats/Oil

Consumption of repeatedly heated cooking oil **(RHCO)** has been a regular practice without knowing the harmful effects of use. The heating of edible oils to their boiling points results in the formation of free radicals that cause oxidative stress and induce damage at the cellular and molecular levels. Peroxide value of heated oil, histopathological alterations, antioxidant enzyme levels, and blood biochemistry was determined in Wistar rats treated with the **RHCO**. RHCO revealed a higher peroxide value in comparison to oil that has been unheated or singly heated. Histopathological observation depicted significant damage in the jejunum, colon, and liver of animals that received oil heated repeatedly for three times. The altered antioxidant status reflects an adaptive response to oxidative stress. Alteration in the levels of these enzymes might be due to the formation of reactive oxygen species (ROS) through auto-oxidation or enzyme-catalysed oxidation of electrophilic components within RHCO. Analysis of blood samples revealed elevated levels of glucose, creatinine, and cholesterol with declined levels of protein and albumin in the repeatedly heated cooking oil group. Results of the present study confirm that the thermal oxidation of cooking oil generates free radicals and dietary consumption of such oil results in detrimental health effects (Perumalla and Rekhadevi 2016).

Production of free radicals and reduction of antioxidant and vitamin levels eventually lead to oxidative stress. Oxidative stress and endothelial dysfunction play pivotal roles in the genesis of cardiovascular diseases, which may be controlled by diet modification. Ingestion of repeatedly heated vegetable oil should be restricted due to the detrimental consequences on one's antioxidant defence network, leading to pathologies such as hypertension, diabetes, and vascular inflammation.

The human lipase enzyme facilitates the digestion, transportation, and processing of dietary lipids, including triglycerides, fats, and oils. It exclusively acts on molecules with the cis configuration, and it is unable to metabolize trans fatty acids (Perumalla and Rekhadevi 2016). Consumption of diets high in hydrogenated fat and/or trans fatty acids has been shown to hurt lipoprotein profiles concerning cardiovascular disease risk (Lopez-Gracia et al. 2005). Industrially-produced TFA is the predominant source of dietary TFA in many populations (Wanders et al. 2017).

Nonetheless, as the late twentieth century approached its conclusion, a substantial body of evidence had amassed from diverse studies, revealing the adverse metabolic consequences of trans fatty acids (TFA) and establishing a link between TFA consumption and Coronary Heart Disease (CHD) (Nishida and Uauy 2009; Mozaffarian et al. 2009).

7 Guidelines for Trans Fatty Acids—Global Scenario

Governments and public health bodies across different nations and regions have undertaken diverse initiatives to curtail trans fatty acid (TFA) consumption. The approach that has proven to be the most efficient and uniform in reducing TFA within the food supply involves the implementation of legislative or regulatory measures aimed at restricting or forbidding the production of industrially-derived trans fatty acids (Downs Shauna et al. 2013). Denmark emerged as a pioneer in the regulation of industrially-produced TFA, introducing legislation in 2003 that enforced a limit of 2% of total fat content from industrially-produced TFA in all foods available in the market. This encompassed imported goods and restaurant offerings as well. This decisive action led to a substantial reduction in the levels of industrially-produced trans fatty acids within their food supply (Leth et al. 2006).

Subsequent to Denmark's lead, comparable legislative or regulatory measures have been embraced by several European nations such as Austria, Hungary, Iceland, and Norway, as well as certain countries in the Americas, Asia, and even one African nation. In 2007, the Pan American Health Organization (PAHO) established a Task Force with the aim of achieving a Trans Fat-Free Americas, utilizing legislative approaches resembling the recommendations proposed by the Canadian Trans Fat Task Force Argentina adopted a series of policies aimed at decreasing industrially-produced trans fatty acids (TFAs). These initiatives included the compulsory labelling of TFAs in food in 2006 and a revision of the food code in 2014 that imposed a limitation of 2% of total fats for vegetable oils and margarine, and less than 5% of total fats in other foods, as industrially-produced TFAs (Rubinstein et al. 2015).

The REPLACE action package, introduced by the World Health Organization (WHO), functions as a comprehensive guide for countries to execute measures aimed at eradicating industrially-produced trans fatty acids (TFA). The following six strategic action areas are designed to facilitate the swift, comprehensive, and enduring removal of industrially-produced TFA from the food supply. These strategic action areas are not presented in a sequential order, but instead offer suggested actions to attain the objective of eliminating industrially-produced TFA.

- **R E**–REVIEW dietary sources of industrially-produced trans fats and the lands
- **P**–PROMOTE the replacement of industrially-produced trans fats with healthier fat
- **L**–LEGISLATE or enact regulatory actions to eliminate industrially-produced TFA
- **A**–Assess and monitor trans-fat content in the food supply and changes in trans-fat consumption in the population
- **C**–CREATE awareness of the negative health impact of TFA among policy-makers, producers, suppliers, and the public.
- **E**–ENFORCE compliance with policies and regulations.

In a recent notification, the FSSAI established the maximum allowable Total Polar Compounds (TPCs) for unused vegetable oils/fats at 15%. Furthermore, the authorities prohibit the use of used vegetable oil/fat with TPCs larger than 25% for frying. The FSSAI emphasizes that a "Triple E strategy" and a concerted effort are necessary for the proper application of used cooking oil regulations. The first element of the "Triple E Strategy" is "Education," which involves informing both consumers and the food industry about the negative effects of rotten "used cooking oil" on public health. The second "E" stands for "Enforcement," especially in major food processing facilities, eateries, and fast-food chains that frequently fry large quantities of food; the third "E" stands for creating an "Ecosystem" for collecting leftover cooking oil and manufacturing biodiesel.

By taking concerted measures, the FSSAI believes India may collect 220 crore litres of wasted cooking oil for the creation of biodiesel by 2022. While the amount of biodiesel made from recycled cooking oil is now quite tiny, India is developing a strong ecosystem for conversion and collecting that will soon reach a significant size. An order from the FSSAI requiring FBOs that use more than 50 L of cooking oil daily to maintain UCO disposal records has been issued. Repurpose leftover Cooking Oil (RUCO), a mechanism for collecting leftover cooking oil and turning it into biodiesel, was also introduced. Impact of RUCO is very helpful. RUCO will help bring:

- Health benefits by avoiding ill effects of UCO
- Employment generation and economic growth
- Infrastructural investment in Rural Areas
- Cleaner environment with reduced carbon footprint
- Reduction of import dependency (Palm Stearin).

RUCO will also help promote a shift towards a circular economy model with health, environmental and economic benefits (FSSAI RUCO report 2017).

8 Conclusion

We have covered a wide range of subjects in the discussion above, from the value of fats and oils to the negative health impacts associated with consuming degraded fat and oil, and everything in between. This review clarifies the processes and actions involved in high-temperature frying. Various legislative initiatives (such as compulsory and voluntary TFA labelling, reformulation, and national and local TFA restrictions) have been put into place during the past 10 years by countries with the goal of limiting the TFA content of food and lowering TFA intake in their populations. We have also talked about the numerous illnesses that can result from consuming TFA and used cooking oil. It becomes an enormous undertaking to keep track of everything that happens at every roadside shop and kiosk in a big country like India. However, this is insufficient justification to jeopardize consumer health. Therefore, innovative tactics are essential in substituting oil and fat because street merchants may not consider it an inexpensive decision and may try to exploit legal loopholes. The EEE strategy of the FSSAI is a positive step. From a different angle, one might advocate educating people about the health risks associated with fried and high-fat foods, but we must also take India's economic and social structure into consideration. In terms of cost, a sizable portion of the population considers fried food to be less expensive than an expensive meal. Indians have a social tradition of gathering over snacks, therefore it can be challenging to ignore the diversity of foods. India is a diverse nation, and this is true of its cuisine as well. Regulations must allow for consideration of street food from various regions via a variety of lenses and must not be objective but rather subjective. Implementing strategies is one of the key principles for achieving the accomplishment of controlling the quality of fats and oils. We have repeatedly observed regulations that were false for a variety of reasons. After a predetermined amount of time, the implementation plan and its outcomes need to be reviewed. Education and public awareness, in my opinion, should focus more on the dangers of consuming low-quality fats and oils and less on the long-term advantages of avoiding them because individuals are more motivated by their immediate impacts.

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