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Shachi Shah
Ram Prasad *Editors*

Sustainable Bioeconomy

Pathways to Sustainable Development Goals

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Preface

Bioeconomy, an intersection between biological resources and economic activities, underpins a pathway to tackle global challenges and to achieve sustainable development goals. Bioeconomy involves the production and sustainable use of biological resources to further the growth of the sustainable economy through the generation of information, knowledge, bioproducts, ecosystem services and innovative processes. Biological resources are the bedrock of bioeconomy. It includes materials of biological origin, which have a potential role to play in the sustenance of the earth system. While traditionally bioeconomy strategies aimed at upscaling the production of biofuels and bioenergy and finding an alternative to fossil fuel-based energy source, recent developments in the field of biotechnology, synthetic biology and metabolic engineering have widened the scope of bioeconomy. Of late, waste valorization, production of biochemicals, phytochemicals, biopesticides, flavour compounds, etc. and transformation of bio-based materials including the building blocks and polymers into value-added products are an integral part of sustainable bioeconomy. In effect, the biological resources as a feedstock to biotechnological and microbiological processes generate a wide variety of ecosystem services and drive bioeconomy. Further, sustainability in bioeconomy is achieved through the application of principles of circularity. In essence, the sustainable bioeconomy is a paradigm shift from a fossil-fuel-based economy to a biological-based economy, which is driven by the virtues of sustainability, efficient utilization of resources and "circular economy" as well. As the sustainable bioeconomy hinges on the efficient utilization of biological resources and societal transformations, they exhibit the immense potential to achieve sustainable development goals. Sustainable bioeconomy has immense potential to achieve food and nutritional security (SDG 2), to promote human well-being (SDG 3), to ensure access to water (SDG 6), to ensure access to affordable and sustainable energy (SDG 7), to ensure sustainable living habitat (SDG 11), to ensure sustainable production and consumption (SDG 12) and to reduce greenhouse gas emissions (SDG 13). The book earnestly explores the facets of sustainable bioeconomy. The chapters focus on areas including but not limited to economics of the circular bioeconomy, social and economic contribution of the bioeconomic sector, production of bio-based products like biofuels, biochemicals and flavour and fragrance compounds, the sustainability of agricultural production system, use of biological resources like phytochemicals and biopesticides to improve agricultural bioeconomy, energy auditing, soil nutrient budgeting, low carbon future and the role of culture and moral responsibility in facilitating a sustainable bioeconomy. We are extremely honoured to receive chapters from leading scientists and professors with rich experience and expertise in the field of bioeconomy. The book targets scientists, researchers, academicians, graduates and doctoral students working on natural, biological and social sciences.

Our sincere gratitude goes to the contributors for their insights on sustainable bioeconomy. We sincerely thank Dr. Naren Aggarwal, Ms. Aakanksha Tyagi, Mr. Ashok Kumar and Ms. Kavitha Jayakumar of Springer Nature for their generous assistance, constant support and patience in finalizing this book.

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1 Exploring the Economics of the Circular Bioeconomy

Davide Viaggi

Abstract

The concept of circularity has become key for the bioeconomy. The objective of this chapter is to discuss the concept of the optimal level of circularity, how it can evolve over time and how it can be operationally used in decision-making about the bioeconomy. In the background of the current literature on circular bioeconomy, we first illustrate the concept of the optimal degree of circularity using a simple market equilibrium framework. Then we elaborate on how this can be connected to the reality of transition to a circular bioeconomy. From an economic point view, the identification of an optimal pathway towards a circular bioeconomy driven by cost of recycling and externalities is central to ensure economic efficiency. In practice, a series of information obstacles hinder the implementation (and even the quantification) of this pathway. Hence, articulated policy mixes are usually needed to promote transition towards a circular bioeconomy.

Keywords

Bioeconomy · Circular economy · Sustainable development goals · Circularity

1.1 Introduction

The bioeconomy has become one of the main issues in the world technological and social transitions. The bioeconomy, for its comprehensive view, touches a number of different societal objectives. An analysis of the 2018 EU Bioeconomy strategy confirms this point by finding that it is directly related to 12 out of 17 UN Sustainable

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Development Goals, in most of the cases with a synergistic effect (Ronzon and Sanjuán 2020).

Over time, the concept of bioeconomy has been growingly connected to that of circular economy as one of its key elements (Patermann and Aguilar 2017; Koukios et al. 2018). The circular economy concept relates to the idea that the economy should rely more on the reuse of resources that are already in the system and less on external raw materials. The connection with the bioeconomy is evident looking not only at the strategic and policy agenda, but also at the practical fact that a large number of technological solutions proposed for the bioeconomy actually target waste and by-products reuse, hence aiming to contribute to circularity (Ronzon and Sanjuán 2020).

Of the about 260 bioeconomy-related papers published in Scopus in the years 2018–2020, in the disciplines of economics, management and social sciences, about 40% also attach the issue of circularity to the bioeconomy. While it can be claimed that circularity is inherently an issue for the bioeconomy, in reality the bioeconomy does not imply circularity. The current literature highlights not only the variety and ambiguity of the circularity concept, but also the relevance of obstacles and hindering factors its realisation is finding (Jarre et al. 2020). In addition, from an economic point of view, it can be questioned that the higher possible level of circularity is an objective per se, without properly considering costs and benefits of achieving circularity.

In this context, the objective of this chapter is to discuss the concept of the optimal level of circularity, how it can evolve over time and how it can be operationally used in decision-making about the bioeconomy. The main contribution of the chapter rests on using simple economic analysis to frame the discussion of circularity in economic terms, an issue poorly addressed by the literature up to now. In the next section, we provide a representation of bioeconomy systems also emphasising circularity. In Sect. 1.3, we analyse the issue of the optimal rate of circularity. In Sect. 1.4, we discuss the limitations and research needs, followed by concluding remarks in the last section.

1.2 Circularity in Bioeconomy Systems

Several graphical representations of the bioeconomy are available in the literature, each highlighting different aspects (Wesseler and Von Braun 2017; OECD 2009). Figure 1.1 sketches the main components of the bioeconomy and their relationships, with a view on also making explicit the main circular components.

This representation of the bioeconomy emphasises biomass flows from ecosystems to consumers. Part of this biomass is destroyed in the process and part goes back to ecosystems, or to some of the previous steps of the process. Examples include food wastes used in non-food systems (e.g. bioenergy) and biomass feeding back agricultural soils.

There are different waste and by-products that can become usable as raw materials. First, wastes and by-products can be used as such, without any

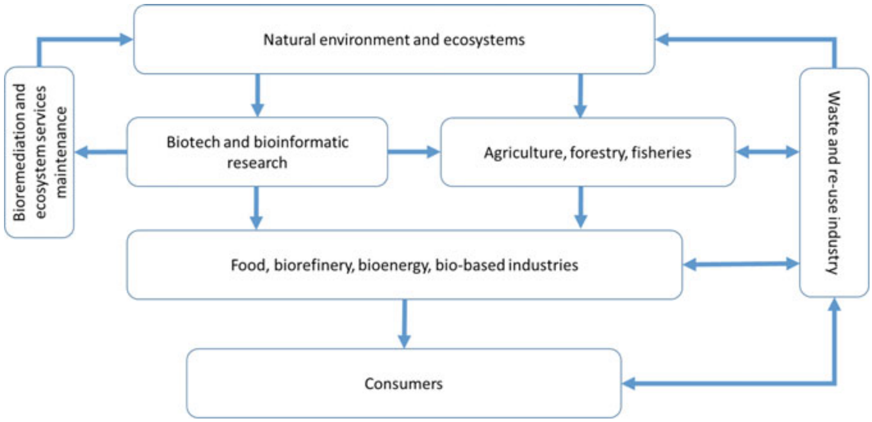

Fig. 1.1 A graphical representation of the bioeconomy (arrows represent the main flows of biomass). Source: Viaggi (2018)

transformation; this has been historically one of the main ways of closing cycles especially in the farming sector. Second, selected compounds of waste feedstock can be used after various processes of transformation/extraction, e.g., use of orange peel to produce compounds for beverages and snacks (Vergamini et al. 2015). Third, wastes and by-products can be used for bioenergy production; this is often not considered to be the best solution, as it causes the loss of valuable compounds. Finally, biowastes can be used in biorefinery processes that yield a variety of different output and end up with energy production (Venkata Mohan et al. 2016).

The amount of waste use at present is rather differentiated in different sectors due to various technological and organisational reasons (Egelyng et al. 2016). As an example, Kinnaman (2014) suggests an optimal recycling rate of 36% for municipal wastes in Japan.

In the bioeconomy, food is a key component of biomass production, so no surprise that food waste plays a very important role in the issue of circularity. This is also connected to ethically relevant issues, such as food security and affordability. In this respect, using food by-products and wastes in the food industry (i.e. to produce food) ensures a higher value addition.

Haas et al. (2015) provide an analysis of the degree of circularity of the global and the EU-27 economy. Their estimates for 2005 show that there is a global flow of roughly 4 Gt/year (gigatonnes per year) of recycled waste materials, i.e., less than 10% of the 62 Gt/year of processed materials and 41 Gt/year. of outputs produced worldwide. The bioeconomy accounts for a large share of processed material (19 Gt/year) but its degree of circularity is only 3% (7% in the EU-27). One of the reasons for this is that biomass is largely used for energy purposes (including food), so it is destroyed in the process of utilisation and is hence non-recyclable.

Circularity depends on the processes used to produce biomass. In particular, circularity of biomass-related industries requires circularity of input production and management processes. As an example, incresing circularlty in agricultur also implies closing the cycle of nutrients (nitrogen and phosphorous). Reducing waste from production and consumption, and changing consumption patterns towards solutions adapted to use less resources, can contribute to circularity (Viaggi 2015).

In general, as biomass is basically derived from solar energy fixation, if biomass is produced sustainably, it can be considered renewable and the emitted CO_2, as well as waste flows, can largely be reused into new primary biomass within ecological cycles (Jordan et al. 2007). However, while this applies at the global scale, systems may be rather far to be circular, even assuming input of solar energy, at the local scale. In addition, circularity in general refers to the anthropic system, hence excluding ecosystems and, in this respect, the minimisation of waste and the promotion of reuse is key to increasing the circularity of the bioeconomy (Cardoen et al. 2015).

Circularity is also becoming an issue in bioeconomy firm management. On the one hand, use of by-products is more and more a key strategic topic in promoting innovation and building competitiveness in key bioeconomy industries such as the food sector (Strøm-Andersen 2020). On the other hand, the industry organisational shift is pushing attention to the use of appropriate business models for the circular bioeconomy addressing in turn the topic of both new forms of business and mechanisms for value creation (D'Amato et al. 2020).

1.3 Optimal Rate of Circularity

Circularity in an economic perspective can be addressed under the lens of the optimal level of recycling/reuse (or more generally of circularity). The starting concept is that different circularity can be achieved using different technological and organisational solutions. These solutions have different effects/performances including financial/economic, environmental, institutional and social (da Cruz et al. 2014). It may be expected that these solutions are used starting from the cheapest ones, so that there is an issue concerning when to stop, i.e., what is the optimal degree of reuse. All of the dimensions above should hence be accounted for in discussing the optimal level of circularity.

Few examples are provided in the literature. Among them, Kinnaman (2014) and (Vollaro et al. 2016) study the issue of optimal recycling rate from the perspectives of, respectively, recycling in municipal waste management and phosphorous recovery from municipal wastewaters. Figure 1.2 illustrates the concept of the optimal level of recycling.

Figure 1.2 illustrates the market of a resource that can be obtained either through harvesting from natural sources (equivalent to extraction/mining) (supply function S) or from recycling. Suppose the recycling can be performed through a high cost technology represented by line RS_1. The cost of harvesting is assumed to be growing with increasing use, reflecting an increasing marginal cost of supply. On the opposite, in order to keep things simple, we initially assume that RS_1 is a horizontal line, i.e., with constant marginal cost. The technology based on RS_1 is profitable only if demand reaches a very high level (i.e. when RS_1 crosses S), but it is normally not

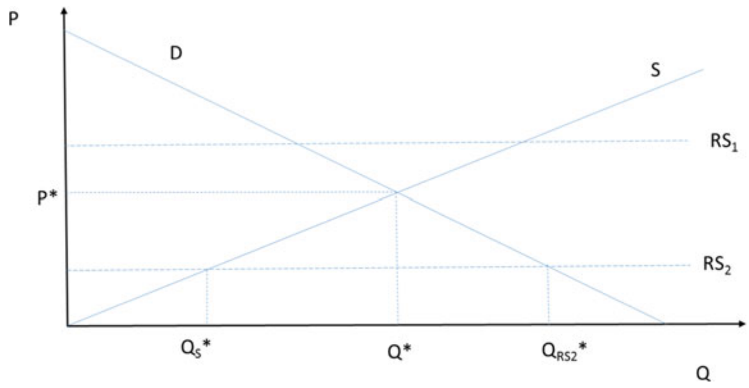

Fig. 1.2 Optimal level of recycling. Source: Viaggi (2018)

profitable and not used at all if, as in Fig. 1.2, the demand is lower and the market equilibrium is at P^*Q^*. In this case, the marginal cost of the resource is low and meets the demand at a price level lower than the cost of RS_1, causing the recycling technology to be out of the market.

RS_2 represents another recycling technology with rather different economic characteristics. In particular, RS_2 has a lower cost, lower also than P^*. As a consequence, some recycling is now of interest. However, the recycled product cannot be expected to completely substitute the harvested product. On the contrary, there will be an optimal level of distribution of the resource provision between harvested (Q_S^*) and recycled ($Q_{RS2}^* - Q_S^*$) resources. The optimal recycling level is found when the marginal social cost of recycling reaches the marginal social cost of supply by harvesting. A total substitution of harvested with recycled resource would only occur if the intercept of S is above RS_2, i.e., if the constant-cost recycling technology is below (less costly than) the least costs solutions for harvesting the good. If RS_2 is available, the outcome is a market using more product compared with the absence of a recycling technology. The source of the product comes partly from harvested and partly from recycled sources. Note that the harvested component (Q_S^*) is lower than the one under the initial market conditions (Q^*).

The shift from RS_1 to RS_2 may normally occur as an effect of technical change leading to a reduction of recycling costs and can be seen as a dynamic effect of innovation. Hence, as a result of the above, cost-reducing technical innovation will, other things equal, increase the use of the product altogether, but reduce the harvested component. The optimal level of recycling will be determined by the market and will be higher the lower the cost of the recycling technology. As an effect of the improved recycling technology, there is an overall welfare gain from the demand side. If the demand side reflects an industry, this would also imply higher profits and potential rebound effects, which may be a problem if industry development is also attached to negative environmental effects.

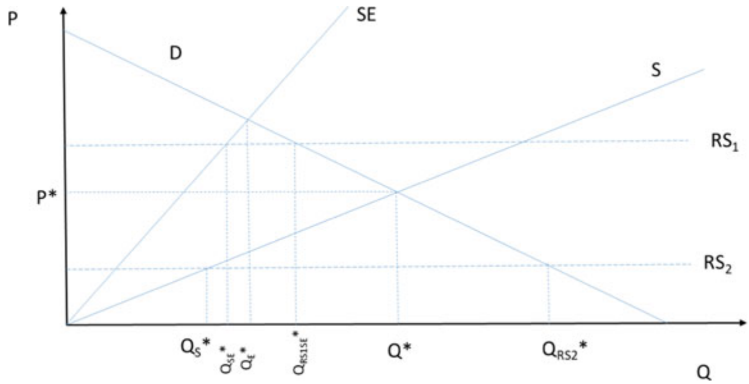

Fig. 1.3 Optimal level of recycling with externalities

Removing the assumption of horizontal supply of the recycled product does not change the outcome substantially. If the line had a positive slope, there would be two options. If it is always above S, the result will be similar to the case RS_1, i.e., the recycled technology is never profitable. If it crosses S, it will have an effect only if the crossing point is "south west" of P^*Q^*. The result, however, is then the same of the horizontal recycling cost assumed above.

Another option is possible, notably in the case of marginal cost increase because the natural resource has become scarcer, which reflects in a move upwards of the supply function S. The outcome, in this case may again be that the recycling technology becomes used, in a context of higher market prices and lower use of the resources altogether.

A similar situation can also occur due to the changes in demand. In particular, if demand of the good grows, the demand function will move upward, leading to a potential use of even RS_1 technology, when P^* becomes higher than RS_1. There will be an optimal level of recycling and the share of recycled vs. harvested will depend again on the level of prices. The overall situation will be the opposite of the previous hypotheses, as the use of the resource increases.

A problem is that of failures in the markets of recyclable materials. These may be due not only to environmental externalities, but also to imperfect and asymmetric information and technological and consumption externalities. Nicolli et al. (2012) review the nature of such failures and how they may affect markets for certain recyclable materials. They also discuss how these failures can be overcome by technological innovation and the role for policy measures in this innovation in the area of plastic packaging. Figure 1.3 depicts a situation in which the optimal level of recycling is affected by a negative externality attached to harvesting.

The social supply function is now represented by SE. If the externality is taken into account, the equilibrium would be in Q_E^*. In this case, even if only RS_1 was available, it would make sense to have some harvested (Q_{SE}^*) and some recycled good ($Q_{RS1SE}^* - Q_{SE}^*$) on the market. Clearly even more if ERS_2 was available.

However, as the difference between *S* and *SE* is due to an externality, this difference in value is not taken into account by the market that would still produce at P^*Q^*.

In this case, the problem is then how to reach the optimal level. Clearly, a tax on the harvested material would go in this direction actually moving from *S* to *SE* the actual supply curve. However, this would put a higher burden to consumers and have the limitations of any increase in taxes in terms of political consensus. On the other hand, this situation may also justify support to the alternative recycling technology.

A major issue in this case would be that, in the absence of market prices for the externality, it is much more difficult to identify the optimal level of circularity.

The analysis above is based on comparative statics, but can be used as a basis for some dynamic considerations. First, some level of path dependency may apply in terms of availability of materials to be recycled. In particular, the maximum amount of recycled feedstock cannot be higher than the amount used in the previous period (or in the same period); also the maximum efficiency of recycling technology should be taken into account in considering this type of restrictions. Second, as mentioned above, different costs levels may be interpreted as changes over time. It is usually expected that, as the stock of mined or the availability of harvested resources declines over time, while the stock of used products increases over time, the importance of recycling increases (Zilberman et al. 2013). However, pressure to moderate consumption increase can hinder the growth of production. Third and most important, research and innovation tend to decrease costs of recycling over time, but may affect also the costs of mining and harvesting.

It is important to note that bioeconomy resources may be grown or harvested, so that cultivation may replace recycling if more profitable. Also, the advances in technologies promoting reduction of biomass to elementary components, in particular platform chemicals, and their re-composition in new products open up to a wide range of substitutes (or of substituting sources of biomass). For this reason, recycling should be seen in the wider landscape of potential alternative technologies, rather than in isolation.

1.4 Discussion

While the above provides a sound conceptual background, its implementation in practical terms remains difficult for several reasons. The first and most important remains the complexity in accounting for actual costs of different technologies and how they shape the supply functions. Not only harvesting can come from different sources, but also reuse technology can follow different solutions and pathways.

Another key issue is logistic. This is usually more important for high volume low value goods. It is hence an issue for waste and other recycled material, similar but with different problems compared to primary production, taking also into account, e.g., legal constraints affecting wastes. Costs may depend on the way waste is collected and managed and hence depend on facility choices, network design and economies of scale. Costs may include fixed and variable costs per vehicle (transport), personnel cost, container or bag costs as well as emission costs estimated to be about 15% for urban wastes, as cited in Groot et al. (2014). Also in closing cycles of nutrients, distance and transport costs, and logistics issues at large are key (Akram et al. 2019).

The second main issue is that of externalities. While several methods have been developed over time to assess non-market goods and externalities, most of them are sufficiently reliable only when restricted to be used to assess average costs/benefits and usually much less robust when used to evaluate demand/supply functions, especially at the extremes. Needless to say, external costs may depend a lot on the ability to assess impact pathways and dose–response. This is rather a difficult task for the most relevant external effects attached to the bioeconomy technologies, such as the contribution to (combat) climate change.

The dynamic insights discussed above also hint at the fact that the optimal rate of recycling would change over time. This implies that it would be necessary to identify an optimal pathway of development of the recycled component. This, however, would be largely driven by expectations about future technology changes and related costs, as well as about demand.

Observing the current landscape, however, solutions to these policy dilemmas may come from a better ability of the system itself to adapt. Suitable business models are a key issue that requires proactive adaptation by the sector, but also policies ensuring a suitable environment. In connection to new business models, innovation remains a key topic, especially in the direction to solve cost issues and to address uncertainties in the emerging solutions.

1.5 Conclusion

While the bioeconomy concept largely relies on biomass flows that can to a good extent be connected to concepts of circular economy, such as waste valorisation and reuse, the bioeconomy is not inherently circular. Given the fact that biomass tends to degrade into energy, on the contrary, and that the primary sources of input for the bioeconomy is actually solar energy, the topic is rather that of the optimal (rather than the maximum) level of circularity. In other words, the question is to what extent it is really efficient and sustainable to close the cycles, also in relation to different geographical perspectives and levels.

The current literature still approaches this issue from a largely simplified perspective driven by recent policy evolution, rather pointing at promoting circularity. Attention should rather shift to a more focused and economics-based research in two complementary directions:

(a) Empirical economic analysis of “supply of circular solutions” and derived understanding of the optimal degree of circularity;
(b) Evidence-based analysis of socio-economic transition pathways and new business models.

Implementing point, (a) requires addressing a number of empirical issues due to the variety of solutions and to the fact that many of them are quickly evolving. On the same ground, and as shown directly by the graphical analysis, accounting for externalities may be key to understand the actual optimal level of circularity, which implies an improved ability to account for non-market values.

Understanding transition pathways is also an issue, not only for the technical dynamic issues, but also for the wider variety of aspects important for understanding and promoting transition, such as awareness building and hindering factors. The understanding of new business models and the study of options allowing their design and replication remain one of the most challenging emerging issues.

Policy has a key role in bringing private incentives close to social values. As discussed above, this can also be the case in order to foster a circular bioeconomy due to needs brought by innovation and externalities. Similar to most of the bioeconomy policy fields, the analysis above calls for actually a mix of policy actions (Ladu et al. 2020), which could include one or more of the following:

- internalising externalities through direct incentives or regulation, with a strong role of environmental and climate policies;
- providing incentives to technical innovation and cost reduction;
- providing incentives to innovation in organisational solutions and business models; and,
- allowing more value expression by consumers, through information and awareness rising.

Clearly, these policy areas require approaches much more qualitative with the respect to the general framework highlighted above. In particular, given the lack of ready-to-use economic information, participatory procedures and strategy would need to be widely used to substitute economic rationale in actual decision-making processes. However, there are also limitations of this approach. In perspective, with increasing empirical studies on the topic, it may be expected to achieve a more balanced use of different strategies in the direction of truly evidence-based policy making in the field of circular economy.

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The Role of Culture and Moral Responsibility in Facilitating a Sustainable Bioeconomy

2

Madhavi Venkatesan

Abstract

Economics influences and is influenced by culture; in turn, culture is both influenced by and influences the sustainability of the environment. Furthermore, to the extent that moral judgment encompasses human and non-human life, the environment and its sustainability are given significance within the economic system. At present, there is increasing discussion of the implementation of a bioeconomy within the present economic framework. This chapter discusses the role of culture and education in promoting a moral perspective of the human responsibility in establishing sustainable economic growth. The argument made is that a bioeconomy can promote sustainability only if consumption choices implicitly consider holistic impacts and are motivated by cultural values that are based in moral judgement. Otherwise, sustainable economic growth may be limited to the production process alone and fail to promote overall sustainability in economic outcomes.

Keywords

Sustainability · Economic Development · Bioeconomy · Culture · Consumption

2.1 Introduction

Bioeconomy has been defined as "the production, utilization and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes and services across all economic sectors aiming toward a sustainable economy" (Global Bioeconomy

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Summit 2018). As noted by the United Nations, Food and Agriculture Organization (2020), the drivers of bioeconomic development include three focus areas:

1. Societal aspirations and good governance for sustainable development and for improved health and well-being,
2. Needs and opportunities of valorization and protection of biological resources, including residues, in the traditional bioeconomy core-sectors linked to agriculture, forestry, fishery, water management food and bioenergy, and.
3. Scientific breakthroughs in biological, digital, and other technology fields, expanding the frontiers of innovation possibilities (FAO 2020).

While sustainability has no formal definition, the commonly accepted definition is that of the Brundtland Commission (1987), which notes, "sustainable development is not a fixed state of harmony, but rather a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs." Included in the Brundtland discussion is a recurring theme of moral decision-making that includes the welfare of all life.

> Major changes in policies will be needed to cope with the industrial world's current high levels of consumption, the increases in consumption needed to meet minimum standards in developing countries, and expected population growth. However, the case for the conservation of nature should not rest only with development goals. It is part of our moral obligation to other living beings and future generations (Brundtland Commission, 1987, p 51).

Interestingly, the Sustainable Development Goals (SDGs), due make a reference to the moral responsibility implicit in sustainability but appear to be aligned to an anthropocentric approach.

The Sustainable Development Goals (SDGs) are intended to be universal in the sense of embodying a universally shared common global vision of progress toward a safe, just, and sustainable space for all human beings to thrive on the planet. They reflect the moral principles that no-one and no country should be left behind, and that everyone and every country should be regarded as having a common responsibility for playing their part in delivering the global vision (Osborn et al. 2015).

What the FAO definition of bioeconomy has in common with the Brundtland Commission and the SDGs is the focus on sustainability and a fundamental need to adjust consumption and production behavior to account for a responsibility to the present and future. However, the difference in the perception and inclusiveness of sustainable development differs with respect to the explicit inclusion of non-human life, the intrinsic value of non-human life, as well as the moral obligation to protect non-human life (Fig. 2.1). Arguably, the FAO and the Brundtland Commission address non-human life, while the SDGs promote an anthropocentric perspective. The Brundtland Commission and the SDGs reference the moral responsibility inherent in establishing sustainable development.

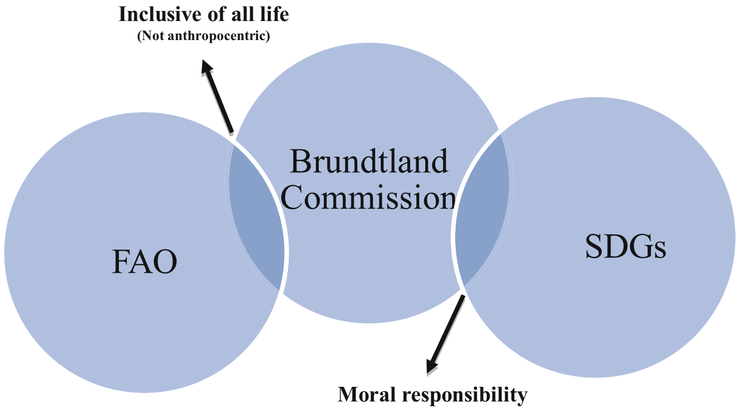

Fig. 2.1 Relationship between the FAO definition of bioeconomy and the Brundtland Commission and SDGs

However, implicit in the defining of bioeconomy is the measurement of economic growth, this is also true for the SDGs. Both focus on the continuation of a GDP-based economic growth model. Additionally, they do not explicitly address the short-comings of the model, which is based on resource utilization through either resource discovery or technological enhancement and efficiency of resource use. Further, neither discusses population growth and needed controls, which surface multiple times in the Brundtland Commission report (1987), "What is needed now is a new era of economic growth—growth that is forceful and at the same time socially and environmentally sustainable" (p. 7).

In this chapter, I propose that both a moral and inclusive perspective toward all life is needed to promote a sustainable bioeconomy. Furthermore, in order to facilitate a transition, a shift in cultural orientation is required, such that economic growth can be aligned to sustainability. Evaluations of bioeconomy often neglect this (Birch and Tyfield 2012; Fielding and Aung 2018). Without inclusion of consumer education related to the non-market costs and impacts or resource use, a shift toward bioeconomy may yield a change in production process with limited impact to outcome (Goven and Pavone 2015).

The discussion that follows begins with an evaluation of GDP and economic growth. The chapter continues by building an argument for addressing the relationship between economic growth and cultural values as the foundational step to promoting sustainable development that is both inclusive and morally based. The discussion concludes with the assertion that the attributes that enable sustainable resource utilization and social well-being, two of the three attributes which define the FAO definition of bioeconomy, are achievable through education that reconciles the relationship between economic outcomes and cultural values to promote sustainability. Promotion of production possibilities, the third attribute of the FAO bioeconomy is addressed as a future discussion item with a requisite inclusion of population growth.

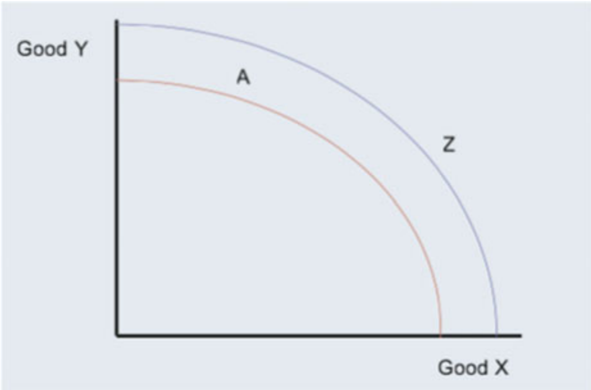

Fig. 2.2 Production possibility frontier. Source: Venkatesan (2017)

2.2 Consumption and Economic Growth

Cultural orientation toward consumption implicitly surfaces the perception of the human relationship with the environment as either one of symbiosis or dominion. In the case of the former, arguably stewardship would prevail. In the context of perceived dominion, the economic system would likely fail to assess intrinsic value of resources, as resource value would be dictated based on the value of the natural resource to the human system. Further and significant, the inclusion of time effects as they relate to the preservation and or regeneration of resources would determine if one period's stewardship or dominion impacted future access, availability, and viability of a resource.

Our present global society builds on an institutionalized western perspective of the environment as a resource for human use; this in turn is implicit to global economic systems and their focus on GDP. GDP is embedded within the prevailing neoclassical discussion of the production possibilities frontier (PPF)[1] and similarly, our policy interest in ensuring that we seek to maximize production subject to resource constraints at any given point in time. In the case of production, this conforms to policy, monetary, and fiscal that seeks to maintain or establish the economy at its peak in business cycle terms, which is equitable to the attainment of potential GDP.

The underlying and guiding assumption of production and consumption decisions is premised on neoclassical consumer theory, which defines individuals in an economy as having insatiable desires to consume. This assumption is reflected in the production possibilities frontier (PPF) where efficiency is defined as any production combination found on the PPF line (Fig. 2.2). On this line, the economy is maximizing production relative to resource constraints. Combinations of output along this can only be attained by allocating the resources in a way that maximizes

[1]This is referenced in the FAO definition of bioeconomy as item 3.

production relative to inputs (e.g., land, labor, and capital). To the extent that the allocation of resources at a given point in time considers intergenerational equity and threshold extraction rates consistent with the prevention of resource depletion, and enables repopulation for renewable resources, the trade-off decisions may or may not be consistent with sustainable resource utilization.

Furthermore, to the extent that a society is taught or maintains the social norm of stewardship and thus satiation of needs relative to that of wants, the efficient allocation of resources may not embody the maximum production. Instead an economy may not fully use observable resources given consideration of their availability from a long-term perspective.

In Fig. 2.2, the PPF line labeled Z represents the maximum production possible in an economy given resource availability at a given point in time; Z also corresponds to a society for which insatiable wants have been embedded into the culture. This society will be dependent on the identification of new resources and technology to enable an increase in future production and related consumption. Increased resource access and technological advancement are reflected in an outward shift of the PPF over time. For both societies, using a GDP definition of progress, the PPF would presumably be representative of the attainment of potential GDP. However, for the society depicted as operating on A, for which Z was also accessible, GDP would be lower as would be GDP growth rates over time. The focus on GDP omits the qualitative value the society derives from the preservation of resources for future periods and the related inter-temporal sustainability of consumption.

McCluney (2008) suggests that reduction in consumption is needed by developed countries to reduce the environmental burden and social justice implications of the present trajectory of consumption within those countries. He notes that there is a moral dilemma at present, given that developed countries have been able to grow and develop high standards of living by environmental exploitation but are now seeking to eliminate the same channels that enabled their development within the developing world. Addressing population pressures and finite growth prospects, he concludes with questions that surface the significant role of consumption: “Will the industrial world be willing to alter its own system to benefit the starving billions elsewhere? How much should the industrialized countries be willing to sacrifice for the sake of the underdeveloped world? Is it moral to conclude that we should not make such sacrifices, or is the very question born of a fallacious understanding of what it takes to live well (McCluney 2008)?”

2.3 Consumption and Sustainable Growth

In most western developed countries, consumption is a significant driver of GDP growth. To the extent that GDP is the standard metric of economic progress and economic progress is a focus due to the perception that progress equates with a higher standard of living, consumption has also become a targeted metric. From this perspective, nearly everything in an economy can be related to consumption, from maintaining full employment, to maintaining stable inflation and low interest rates, to the built-in obsolescence of the goods we purchase. Even the assumptions embedded in economics incorporate consumption: consumers are assumed to have insatiable wants.

Marketing and advertising have played a strong role in fostering consumption by creating marketed demand, which essentially is demand that arises as a result of marketing and advertising. However, the responsibility of consumption has not been fostered, developed, or perhaps even understood by consumers.

Consumers have become increasingly distanced from the production process of the goods they are consuming, and as a result, they are not cognizant about the impact that their consumption demand has on the degradation, exploitation, and depletion of planetary resources. Instead, what consumers are aware of is price. Fundamentally, consumers have focused on market price and have delegated the inclusion of value parameters, including environmental and social costs, to producers, but producers are incentivized to minimize cost and maximize return. Externalizing costs are beneficial to producer profit maximization. As a result, unfortunately, there is a failure in the incentive matching between consumers and producers. In most cases, due to the externalizing of costs and externalities, market prices do not reflect the true cost of a good. Individuals can purchase more resources because not all costs are captured in their production; in essence, reliance on market prices can enable unsustainable consumption (Venkatesan 2017).

From this perspective, consumption plays a significant role in the sustainability of the planet. Responsible consumption is requisite, and this can be promoted through education and the coalescing of the consumer base, where the common ground can be founded both on the self-interest assumed in economics and the trending cultural value of holistic assessment.

Consumption choices are based on demand and supply of a good and are identified with satisfying a need or a want. The impact of consumption decisions can be significant when there is asymmetry of information; fundamentally, there is a relationship between economic and environmental outcomes and consumption choices. Purchases affect labor and environmental resource use. However, most purchase decisions are made through a market mechanism, where the consumer is not explicitly made aware of the entire production process, prices are inclusive of only market costs of production, exclusive of the impact of externalities, and waste is not a factor in the consumption decision. This limitation in information transparency often creates a disconnect between the social and environmental justice sensitivities of a consumer and the realities of their consumption choice in enabling and maintaining the values that they espouse.

Consumption decisions can have a significant ripple effect throughout a single economy as well as the finite global resource base. Consider, for example, the life cycle of milk cartons. Polyethylene lined, printed paper milk cartons have been created for the transport and preservation of milk from the production to the consumption stage. However, the components of the carton were not developed with waste disposal in mind; rather, increasing distribution and sales was the rationale for the carton. As a result, largely related to the focused basis of its creation, the milk carton serves a consumption purpose without consideration of the impact to the environment and potential future human and animal health due to its non-biodegradable or re-usable composition. This illustration on a broader consumption scale provides a simplified perspective to evaluate the underlying values captured in consumption decisions. From this perspective, production for consumption may be expressed as a myopic activity, focused on near-term satiation of a need or want to the exclusion of the evaluation of the impact or ripple effect of the satiation.

Another example is the price of a t-shirt produced in an emerging market. The price will include the cost of the laborer who cut and sewed the shirt, but not the social cost resulting from the lack of a living wage (given the price differential from his payment for labor and the return to the producer who will sell the product at a US boutique) and the limited to non-existent safe working conditions. The price does not include the carbon footprint related to the ultimate transportation of the t-shirt to the store, or the waste cost related to the landfilling of a shirt that cannot biodegrade because it is not made of natural fibers. In net, the cost of the consumption of the t-shirt is only partially borne by the purchaser; other societies and the environment subsidize the price. The outcome, a price that is not reflective of the true cost of the resources used, allows a developed society to have more than needed, to satisfy wants, while unknowingly using more resources and creating environmental and social externalities. The developing country laborer subsidizes the consumption due to lack of labor market strength and in this manner, it becomes quite obvious the vicious cycle that exists between poverty and consumption. Poverty enables over-consumption through enabling the maintenance of low prices in developed countries. In the developing world, the pervasiveness of poverty limits self-funding for infrastructure, sanitation, and sustainable choices; this fosters a dependency trap that only promotes survival not a focus on quality of life.

Sustainable consumption requires that consumers base consumption decisions on the holistic impact of their consumption choices. The values embedded and communicated within demand and supply determine the manner in which a need is satisfied. Explicit awareness of present behavioral assumptions inclusive of the "unlimited wants" of consumers, the profit maximization motivations of producers to meet investor returns, and the understated resource depletion resulting from externalized or understated costs offer the potential to modify active and embedded behavior.

GDP is the global metric for economic progress. The metric is based on the market value of final goods and services sold within the geographic borders of a given country. The limitation of the calculation of GDP to market value in conjunction with firm profit maximization and consumer insatiability, two endogenized tenets of neoclassical economics, has resulted in externalities to the environment and societies. Externalities are observable in environmental degradation, and depletion of environmental resources as well as in exploitation of labor markets.

Given the strength of the consumer expenditures in developed countries' GDP, sustainability transformation to sustainable development may be catalyzed through education that promotes a shift in the cultural value of consumption to include a responsibility for the holistic impact of a given consumption choice. The result would potentially lead to internalization of externalized costs of production to ensure sustainable use of environmental resources. The outcome of conscious consumption would potentially be found in improved environmental and human welfare, such as working conditions and wages, most significantly in developing countries. Codification of the value shift embodied in sustainability transformation as described would be expected to result in regulation that establishes an ongoing framework for sustainable development, as consumer would be understanding of the need for regulation and be aligned with the intention of it.

2.4 Consumption, Economics, and Culture

Nearly everything we do either is influenced by economics or influences economic outcomes. This makes the study of economics unique relative to other disciplines. Economics is about daily life. It is the study of how individuals, firms, and the overall economy function every day in relation to wants, needs, resources, constraints, and perceived optimization. Underlying economics are *values* and our perception of the world in relation to ourselves. For example, is the environment a resource for our use or a needed asset for us to steward? In understanding the interconnection between human consumption and the ecosystem, awareness may augment the consumption/production relationship. As a result, the study of economics allows participants in the economy to make better decisions and derive greater benefit from their activities. However, the qualitative attributes of “better” and “greater” are not universal but are culturally determined.

Economics evaluates human behavior relative to wants, needs, and resource allocation within a natural environment. By definition, the parameters of the discipline include other life forms and physical resources needed to maintain both life and environmental regeneration. To the extent that a human culture incorporates non-human elements in decision-making, the economic system includes an understanding of the holistic inter-dependence of living and non-living elements of the planet.

Culture is a significant contributor to what is perceived as valuable and is the determining parameter in the designations that ultimately yield to resource allocation within a society (O’Hara 1995). Given that culture is a learned behavior, culture can either promote or diminish any given society’s understanding of the interconnectedness of human and planetary life, thereby determining the extent of the anthropocentric, or human-centered, perspective. The United Nations Educational, Scientific and Cultural Organization, UNESCO, defined culture as a significant component to attaining global sustainability:

> Culture shapes the way we see the world. It therefore has the capacity to bring about the change of attitudes needed to ensure peace and sustainable development which, we know, form the only possible way forward for life on planet Earth. Today, that goal is still a long way off. A global crisis faces humanity at the dawn of the twenty-first century, marked by increasing poverty in our symmetrical world, environmental degradation and shortsightedness in policy-making. Culture is a crucial key to solving this crisis (UNESCO 2000).

The inputs and outputs of economic systems are dependent on the culturally determined value structures of a society. To the extent that economics explains observable phenomenon and proposes optimal outcomes, the discipline can be not only responsible for the maintenance of an economic framework but can also be the catalyst for change. Economic outcomes in essence mimic the values of the participants in an economic system, as these evolve, so does the outcome of the economy.

Evaluating the historical cultural progression of human society can promote a stronger understanding of the economic relationship with resource allocation, both intra- and inter-society, and most importantly provide insights with respect to how perceptions of the world are shaped through cultural frameworks at a given point in time. The pace at which cultural attributes evolve may also provide a deeper understanding of why institutional and social frameworks may be inconsistent with the manifestation of contemporary challenges. Viewing economic thought or philosophy over time reveals the dynamic and cultural elements of society, as well as the basis of economic thought that remains in the principles literature in the present period.

2.5 Reconciling Economic Theory and Historical Context

The cultural attribution of value is a significant and arguably primary differentiator with respect to the variation in the perspective between societies of the quality of life for both human and non-human elements. Examples of surviving written works that provide a foundation or insight with respect to economic activities include Plato's *Republic* and Aristotle's *Politics*. The similarities in economic circumstances as described by the authors are consistent with the phenomenon observable today; however, the evaluation of human behavior as it applied to accumulation of wealth, stratification of society, and the role and impact of gratification were framed within an evaluation and discussion of moral philosophy and ethics, positioning Western economics up to the eighteenth century within the discipline of moral philosophy and politics. The evolution of the discipline continued through the modern era until the discipline formerly separated from moral and political philosophy through iteration as political economy to its present standalone context as economics. The observable mechanics of economic systems were the basis of discussion in conjunction with the human values, whether assumed as innate or culturally inspired. A connection between the qualitative and quantitative aspects of economic outcomes was articulated and addressed as an evolving and dynamic process. From this perspective, economics discussions offered both a *normative* and a *positive* perspective, where the former provided opinions and values related to optimization and the latter described observable activity. At the present time, economics in practice has shed the normative element of the discipline opting for a positive attribution as a means to enhance its standing as a science. In essence, the focus on optimization has been to the exclusion of explicit evaluation of prevailing values. Given the significance of embedded values in conscious decision-making, the lack of articulation of values may contribute to the implicit value of outcome-based decision-making that only considers the optimization of the outcome rather than the impact of the outcome to others and future consumption.

The foundation for current economic thought can be found in the writings of Adam Smith (1791), Jeremy Bentham (1879), David Ricardo (1911), and Karl Marx (1959) along with many others. However, though all of these authors provided insights related to the human behavior contemporary to their time, the context of their writings has often been neglected in lieu of an adoption of an absolute meaning of their opinions. In essence, allowing the commentaries of these authors to embody a universal significance independent of time has arguably enabled the transfer of the theoretical modeling of a society specific from one period to another, independent of any assessment of the temporal evolution of behavior and underlying values.

To a large extent, the economic principles in practice have maintained the theories espoused by the writers and contributors to economic thought contemporary to the Classical period. John Stuart Mill's (2016) *Principles of Political Economy* provided a summary of the contributions to economic thought by Adam Smith, David Ricardo, and other significant thought leaders of the nineteenth century and became a standard text used in the study of economics into the early twentieth century. However, of note is that the authors including Mill were relaying behaviors perceived in a society contemporary to their life and questioning aspects of the observed progress of the time including poverty, the role of money, and the potential impact of population growth. Their thoughts were debated, discussions and their frameworks were not adopted as immutable facts. Additionally, the issues discussed were similar to those of predecessor Western societies and as evidenced in the moral philosophical discourses of Plato and Aristotle, nearly two millennia earlier. The evaluation of the human condition within a given social and economic framework prompted economic commentators to be both positive evaluators from the perspective that positive signifies reporting on observable and factual phenomenon and normative participants, where normative requires an expression of value judgment.

In contrast with the foundations of the discipline, the present instruction of economics has eliminated the normative aspects of assessment, reducing economics to mathematical relationships that are addressed in absolute terms rather than in alignment with cultural attributions coincident with their development. Furthermore, the seeming lack of attention to values and behavior incorporated within economic assessment has distanced the tangibility of economics, limiting understanding of the explanatory potential of economics and the application of economics as both a cause and a remedy of unsustainable practices. As a result, at present there is a need to promote and foster an understanding of the role of values in economic outcomes and the sustainability of observed outcomes.

2.6 Values and the Tragedy of the Commons

Writing in 1968 to a highly respected scientific audience, Garrett Hardin presented a compelling formulation of what he coined as the "tragedy of the commons." In his assessment of the tragedy, population growth would lead to significant adverse impacts on common resources. He posed the population problem in stark terms. First, he examined the relationship of population to resources, and concluded population must be brought under control. He then evaluated the dynamics responsible for the increase in population size. From this analysis, he proposed solutions.

Hardin rejected the wild hope that improved food production technology will allow for an indefinite increase in population: "a finite world can support only a finite population" (Hardin, 1968). More specifically, we cannot hope to provide unlimited growth in *both* the material quality of life and population. Mathematically, both factors cannot be independently maximized; and biophysically, the calories available per person must eventually decrease as population increases. In his assessment, he invalidated the classical economic perspective of Jeremy Bentham, who espoused "the greatest good for the greatest number," and concluded, "the optimum population is, then, less than the maximum" (Bentham 1879).

Hardin asserted that a resource is a common good when many people have access to it. He reasoned that a self-interested *rational economic agent* would decide to increase his or her exploitation of the resource since he or she receives the full benefit of the increase, while spreading the costs among all users. The remorseless and tragic result of *each* person thinking this way, however, is ruin of the commons, and thus of everyone using it.

Hardin implicitly rejected the role of conscience or social self-policing of the commons. However, his perception of behavior is aligned with prevailing assumptions in economics related to self-interest embedded within both consumer and producer theory. As a result, individual optimization strategies prevail but produce outcomes that diverge from those predicted by Adam Smith. Smith in his assessment and promotion of individual self-interested behavior perceived such qualities as a mechanism that enhances overall public welfare.

2.7 The Role of Culture in Averting and Promoting Tragedy

Currently, interest in sustainability has promoted a reevaluation of the causality of observable environmental degradation, exploitation, and resource depletion. As a result, there has been an increasing interest in Indigenous societies specific to the balance between their development and the environment. However, the unfortunate reality is that much of the evaluation and attribution related to Indigenous societies falls within the realm of conjecture and anecdote. This is due in large part to the limited availability of records written in the pen of these people, as well as the countervailing bias of recorded observations written in the hand of the colonial settler. This is especially true in the United States, where the elimination and forced assimilation of the Indigenous limited and often prevented the intergenerational transmission of their culture. However, even with these data limitations there remain important insights and contributions associated with evaluating sustainability from the perspective of the Native American population, foremost is the role of culture.

2.7.1 Indigenous Relationship with the Commons

In spite of the light ecological footprints left by the numerous tribes inhabiting the North American continent, Indigenous populations were able to live and maintain their cultures within a thriving ecosystem. Though it is not possible to state that the Native inhabitants did not alter or augment their environment, their recorded cultural practices at the time of the Plymouth colony support the view that they lived in harmony with their ecological circumstances. This is most readily seen through the accounts of abundance of the commodities that the English colonizers observed and recorded, where the commodities were natural products that could be shipped to Europe and sold profitably to provide regular income for colonists. Of related interest is that the cost of these natural resources, as relayed in colonial documents, included only the expense of hunting, cultivating, harvesting, and extracting, as well as transport, there was no cost attributable for degradation or regeneration.

Native populations, in contrast to Europeans, appeared to live within purposely created resource constraints. European records indicated that in spite of the resources available, these societies stored insufficient amounts of food for the cold winter season, preferring to endure starvation for periods. This appeared irrational to the Europeans and was one of many lines of arguments used to justify the perception of the Indigenous population’s way of life was inferior. However, contrary to the Europeans interpretation, the practice of rationed fasting increased the hardiness of Natives and to their ability to literally weather the difficulties of the change in season. Additionally, consciously driven, limited food storage prior to the onset of winter appeared to constrain population growth, thereby limiting the longer-term human impact on natural resources and maintaining their accessibility to meet communal and ecosystem needs (Cronon 1983).

In short, the evidence is consistent with the view that Native populations used environmental resources sparingly despite their seeming abundance (Calloway 1997; Cronon 1983). This is easily seen in the descriptions of the wealth of resource availability in early explorer and colonial narratives. Differences regarding the cultural approach to the management of resources between the Indigenous and European populations are clear when one considers the resource depletion that took place, in the form of reductions in the availability of timber and animal resources within a few decades of European colonial settlement.

Specific to agricultural practices, Indigenous agricultural practices were not as intensive as the European planting and harvesting cycles. However, the mixed crop planting appeared to have benefits to both the soil and harvest. The seeming lack of attention to planting appeared to mimic the conscious ecological relationship between Indigenous communities and the New England ecological system. Native peoples rotated their settlements in relation to the seasons, maintaining a minimal impact to the ecosystem and limiting the burden that their settlements imposed on any species. In their migration, Indigenous peoples maximized their seasonal access to resources and minimized their efforts, while achieving greater ecosystem balance (Cronon 1983). The observation of Native practices only furthered colonial views related to the uncivilized nature of the Native population. Puritan accounts relayed a view that Natives were inefficient in their agricultural practices and the seeming lack of use of God given resources justified the taking of their land (Jennings 1975; Lopenzina 2006).

The maintenance of Indigenous peoples in New England extended over a multi-century period summing to millennia. Furthermore, at the time of colonial settlement, Indigenous communities were not recorded as being in a state of self-induced ecological peril. These observations compare to the significant environmental degradation, species elimination, and resource depletion observable in less than four centuries and arguably catalyzed by the culture of the usurping colonial settlers (Calloway 1997; Jennings 1975). The variation between the environmental legacies of the Indigenous relative to the colonists does promote a rationale for studying the impact of a society's cultural values on the environment.

2.7.2 Colonists Promotion of "Tragedy"

Colonial records of New England in the seventeenth century were not descriptive narratives related to the beauty or even objective assessment of the landscape. Instead the surviving descriptions are useful in providing insight into the market focus of colonial settlers. The colonial attitudes and appetite for what was coined as the "New World" equated to a "discovery" from the perspective that the resources found were thought of as accessible for the colonists' taking, the land for their ownership, and the Native people for whatever purposes the colonists so fit, including their elimination in the event they proved useless (Cronon 1983; Jennings 1975). Their views were legitimized by religion and a sense of moral superiority and indifference to whether their actions in the New World were contrary to those espoused in either. The initial justification of the settler's right to land that was already inhabited was provided through religion and in particular the book of Genesis, which said to give land to those who used their God given attribute of dominion over plants and animals and who followed God's pronouncement to multiply; neither if these characteristics were found to be in use by the Indigenous populations (Cronon 1983).

English settlers accustomed to scarcities of wood enthusiastically recorded that the New England landscape was filled with trees of sufficient number, to ensure a warmer winter than "the nobility of England could hope for." A century later in the 1700s, the same areas were observed and recorded by William Wood, "as being so clear that one may ride a hunting in most places of the land if he will venture himself for being lost." Another observer recorded that from a hill near Boston for thousands of acres not one tree could be seen (Cronon 1983). Like timber harvesting, the slaughter of animals for fur as a result of the European fur trade depleted large populations of beaver, deer, and bears. Other animals, especially wolves and cougars were exterminated as part of the colonial process of transforming wilderness to civilization. The loss of species impacted the entire ecosystem, in the case of beaver, the significant decline in population meant that dams and natural fisheries were no longer extant, this augmented river flow, fish spawning activities and impacted habitats, grazing, and ultimately increased erosion (Calloway 1997).

Returning to Hardin's assertion of the tragedy of the commons, it is clear that colonial cultural norms promoted the observed tragedy of the commons, in much the same manner as Indigenous cultural norms averted it. The enabling action for the sustainable use of resources appears to be embedded social norms; values impact behaviors that then establish economic outcomes.

2.8 Perception of Resource Value, Market Outcomes, and Price

Economics is the social science discipline that evaluates the relationship between human wants and the resources available to satisfy them. In identifying and explaining the relationship between wants and resources, economists use broad generalizations related to human behavior, arguably the most significant of which relates to wants (Fagg 1981).

Wants are based on the premise that individual economic agents, individuals interacting within the general economy, will always seek to have more of desirable goods and services. Desirable goods include both normal goods, which are goods that an individual will continue to purchase as their income increases and luxury goods, which are goods that are not needed but are wanted to support an external display or perception of status or wealth. Not all goods are desirable, for example, inferior goods represent a classification of goods and services that will be reduced or eliminated by consumers as their incomes increase.

The behavior of wanting more, sometimes referenced as unlimited wants, is a social value, consistent with consumerism, which is defined as the focused act of consuming goods and services to improve utility, the economic concept that defines the benefit of consumption. Insatiability is not representative of an intrinsic human characteristic but rather a learned behavior. This is an important point. If a behavior is learned, it can be unlearned and a new behavior can emerge, which in turn can produce a different economic outcome.

2.9 Competition and the Tragedy of the Commons

Market outcomes, price and quantity, are highly dependent on the information that consumers and suppliers have available. Informational asymmetry, where one party has more understanding or knowledge related to a good than another party, can create price and quantity outcomes that may not effectively consider scarcity. This results in market inefficiency, a situation where resource use is not efficiently allocated by the market. This is a significant issue and one that consumers are only beginning to understand. For example, abundance is a relative term but it is not inconsistent with scarcity; all resources are scarce. The perception of abundance without the recognition of inherent scarcity of resources can hasten resource depletion.

Resources are broadly defined as including all the inputs in the production of final goods and services that are ultimately tied to the satisfaction of a want. From this perspective, resources could include teak wood trees in the making of furniture, water in the production of soda, and cattle in the production of food. Typically, resources are classified into one of three groupings, which include natural resources, human resources, and capital resources. Trees, water, and cattle are all natural resources. Human labor or entrepreneurship defines human resources and capital resources consist of man-made objects that can be used to produce goods and services, such as factories and equipment. Regardless of the type of resource, all resources are finite and so by definition can be qualified as scarce (Venkatesan 2016; Czech 2000; Choi and Ng 2011).

Scarcity in economics essentially captures the relationship between wants and the access and availability of resources. For example, one could want a mango, see it hanging high on a tree but not have a ladder to reach it. The good in question is available but it is not accessible. Alternatively, one could stumble on a farmer's market selling mangos only to find that all the mangoes on display have been purchased. In this case, the mangos are accessible but they are not available. Both of these examples highlight the temporal or time sensitivity of scarcity. In the first example, one could borrow or purchase a ladder but this will take time and in the second scenario, one can drive or walk to another market, but again, additional time will be required to satisfy the want.

Looking at time in a slightly different manner, a community could require lumber for the construction of new municipal buildings. The lumber required will result in the deforestation of one hundred acres. In satisfying the want for lumber today, the community limits access and availability of lumber from the one hundred acres over the time period required for the forest to regenerate, creating time-based scarcity.

2.10 Market Distortions, Externalities, and Failure of Market Equilibrium

In a market system, access and availability establish a perceived scarcity embedded within the supply of a good. Ultimately, the supplier's willingness and ability to sell a specified amount of a good at a prevailing price are assumed to capture the costs of production of the good, implicitly including the scarcity of inputs. As a result, it is expected that the higher the degree of perceived scarcity of a resource, the higher its price and in the case of an input, the resulting price of the final good.

The production of goods by producers is based on a competitive framework. Additionally, the producer seeks to minimize costs and maximize revenue, to achieve maximum profitability. As a result of the focus on profitability, there is significant incentive for producers to externalize costs of production as a means of cost minimization. Externalizing costs can include pollution discharge, exploitation of regulatory differences between countries, overuse of natural resources, and limited waste disposal and reduction efficiencies. Though in the immediate period this may be beneficial to profitability, it may promote both short-lived unsustainable returns and longer-term environmental and social costs.

Consumers may not be aware of the implicit trade-offs being made as a result of the production of a good. This informational asymmetry can be attributable to many reasons, including a belief that regulatory agencies guarantee safety, to just simply a lack of diligence when assessing goods. For consumers, reliance on market efficiency without an understanding of the embedded incentives of producers can promote negative externalities. In effect, the pursuit of satisfying unlimited wants may include effectively delegating environmental and social stewardship to producers whose incentives may not include the evaluation of these parameters. The end result is most readily seen in natural resources, where under-pricing (Boran 2006) due to lack of inclusion of scarcity can lead to extinction or elimination of a resource's availability.

In a market driven economy, such as in the USA, the market is credited with efficiently determining the price of an item by implicitly incorporating the costs associated with production. When consumers or producers face low prices for consumption and input purchases, respectively, and the underlying belief is that the price being paid is fully reflective of the cost of the item being purchased, there is less of an incentive for efficient use and higher potential for waste. Price effectively becomes a measure of a resource's worth. When asymmetric or incomplete assessment of scarcity is prevalent, price may not properly indicate the cost of the resource being consumed.

In some areas of the world, forested land has been perceived as abundant and the resulting price for land has been limited to the perception of present period abundance. The net result of the perception has been excessive global deforestation, resulting in present period-pronounced scarcity in some regions. Decades will be required to promote regrowth of the same lands. Had prices considered the impact of forest harvesting, or the price of temporal scarcity, demand would have been lessened. Both consumption and production could have promoted efficient market pricing leading to sustainable resource use, all from this simple inclusion.

Demand and supply yield market outcomes that are assumed to represent an efficient allocation of resources. The price at which the quantity demanded equals the quantity supplied is therefore expected to embody the cost associated with the production and consumption of the good or service. However, production and consumption are not limited to the transactional nature of exchange of the final good at the determined market price. In the process of production and consumption, there are costs that are not factored that impact the well-being of the economy at large and these are referenced as externalities. In essence, externalities arise when an individual or firm engages in activities that influence the well-being of others and where no compensation is provided in exchange for the imposition.

Typically externalities are characterized as negative, signifying that the externality yields an adverse outcome. These externalities are referenced as being *negative* *externalities*. However, there is a potential that a positive outcome could be generated leading to a positive externality. In the discussion of externalities, it often assumed that market participants accept the externalities generated by their actions as acceptable due to their focus on immediate gratification of their needs. For the producer, this equates to externalizing the cost of disposal of waste products into waterways and the air where no cost is directly borne to adversely impact profits but qualitative costs are assessed that may impact the enjoyment and longevity of multiple life forms and generations of human life. For the consumer, the externality can be evaluated in the indifference to waste creation at the point of the consumption decision or even the externalities associated with the production of the good or service being purchased. In the case of the former, the cost of disposal of packaging material is typically marginal to zero, relatively negligible, but disposal creates a negative externality in the landfill, incinerator, or recycling plant that could have been avoided with a thoughtful exercise of demand.

At present, the type of internalizing of externalities that has occurred has been limited to quantifying the externality to an overt cost. However, to the extent that the costs may remain unassessed and the market mechanism is not cognizant and focused on the elimination of the externality-based cost, rather the minimization of overall costs, this process has yielded suboptimal outcomes. For example, assume that a firm produces ambient pollution as a result of incineration of waste. If a governmental regulatory body institutes a fee or cost for pollution, effectively charging the firm for the ability to pollute the air, the producer is able to delegate responsibility for environmental stewardship to the price of pollution. Additionally, depending on the price elasticity of demand for the service offered, the producer may be able to not only transfer the costs now associated with polluting activity to the consumer, but may also be able to maintain the pollution level. Assuming that the consumer is inelastic, in this example the negative externality related to internalizing the cost has not changed, instead only the responsibility of pollution has been transferred to a cost, revenue to the regulating body has been generated, and the consumer has suffered erosion in their overall disposable income and purchasing power.

The same type of scenario exists with a permit trading program, where in effect permits are issued for a specific amount of externality emission, allowing economic agents to trade and thereby optimize through again cost minimization. However, the cost minimization is founded on the presumption or delegation of the permit system to fostering socially optimal outcomes, again, relieving the economic agent engaged in the creation of the externality form being directly accountable for qualitative actions. Additionally, the trading of permits assumes that optimal financial outcomes equate to optimal environmental and social outcome due to the aggregated assessment of pollution. However, to the extent that pollution is not distributed evenly and certain locations may have a disproportionate concentration, the permit systems fails to generate a socially optimal outcome. This may be compounded by the impact of inelasticity, which may allow for the transfer of costs of implementation of the permit program to the economic agents the program was designed to protect.

Externalities are defined as a type of market failure based on the premise that optimal social outcomes result from individual economic agents acting in self-interest. However, if instead of being a market failure, externalities could be evaluated to assess and develop an optimizing strategy between individual interests and enhanced social outcomes, externalities could be internalized within the market model as a modification of preference. Perhaps externalities only indicate a lack of holistic awareness on the part of the consumer and producer or a cultural bias toward immediate gratification. These characteristics can be potentially modified through education. Optimal and universally acceptable strategies could then be adopted to promote sustainability.

The success of this internalization strategy relies on the development of the educated rational economic agent as a consumer. If consumers are aware of the responsibility inherent in their consumption and are aware of the environmental and social impact of production processes, consumer demand can create the coalescing framework to augment preference to exhibit demand for sustainably produced products. The augmentation in demand does not allow for the opportunity of delegation of responsibility of pollution capacity to a cost or alternatively, the incorporation within a cost minimization framework, as a result, the change in preference and subsequent modification in demand promotes the development of market outcomes that are environmentally and socially optimal from the position of what is supplied.

Resources such as air and water have no market price and are considered to be abundant. On the surface, these resources may appear to be unlimited; however, increased population pressures along with externalized costs related to production, such as pollution, have diminished the availability of both potable water and clean air. How could this have occurred?

The lack of price, a market model promoting the focus of profit maximization, and promotion and validation of unlimited wants are largely responsible. Consumers have effectively allowed supply to determine demand by not imposing restrictions on how goods can be produced. Producers have focused on short-term profitability in lieu of long-term strategic resource utilization. In the short-run, both consumers and producers have benefitted but the cost of consumption and profitability was externalized to other nations, the environment, and future generations. For example, in the seventeenth century, North American coastal waters were described and recorded as being rich in quantity and diversity of fish; the perception of abundance led over time to overfishing and presently many varieties are endangered or at the risk of extinction. The cost of fishing included the human and capital costs not the replenishment costs. This yielded an ability to maintain artificially low prices, greater yields for profitability (over fishing), and waste.

2.11 Market Prices, Values, and Common Goods

An understanding of the perception of scarcity and abundance provides a strong foundation to understanding supply, demand, and market outcomes as these concepts relate to resource allocation and sustainability. To the extent that consumers delegate responsibility for sustainable consumption to producers and producers are focused solely on profit maximization increased understanding of the responsibility inherent in consumption may provide a catalyst for increasing sustainable production, consumption, and development. As holistic evaluation of consumption is an assumed behavior of the rational economic agent, strengthening the understanding of the role of consumption may be significant in enabling the development of the rational economic agent.

Supply and demand reflect the amount that producers or suppliers of a good or service are willing and able to sell at a particular price and the amount that consumers of a good or service are willing and able to purchase at a particular price, respectively. Though on the surface the concepts of supply and demand appear simple the characteristics that determine the explicit *willingness and ability* can be complex. The complications can arise as a result of differences in the preferences, behaviors, cultural values, financial capacity, as well as resource access and availability to the production process as these relate to suppliers. For consumers or demand, the complications can also be attributed to preferences, behaviors, cultural values, financial capacity, and wealth perception, as well as the perception of value and price, along with access and availability, of other substitute and complementary goods. Where and how the supply and demand interact with each other define a market. A market is comprised of a group of producers (supply) and consumers (demand) for a specific good or service, who collectively, as part of their exchange process, determine the market price or equilibrium price of a good or service.

Price is the natural outcome of the supply and demand relationship. It is indicative of the value of a good based on a consumer's assessment of the costs and benefits of purchasing the good. As consumers become increasingly aware of the environmental and social costs of production, the prevailing price may be corrected either through regulatory imposition of the costs of externalities within the market mechanism or via consumers, who will opt to purchase goods not on price but related to holistic production costs.

It is important to note that the market relationship is dependent on information and understanding of the limits of duty of care. The outcome of the market relationship, price and quantity, can only reflect the embedded preferences and cultural values depicted in demand and supply. If the market outcome does not meet expectations, the market model is not to blame; rather the prevailing value structure may be the flaw.

Value in this context is related to how resources are valued from the perspective of the quality of care and maintenance we would be willing and able to provide to ensure the protection of the resource. The use of the word "value" is not directly based on market quantification but expresses the hierarchical importance that consumers and producers would attribute to a resource; examples may include the environment, human health, and animal welfare.

Every day consumers make decisions with the collective strength of aggregated individual demand. These decisions influence supply and demand going forward, including the ability of producers to develop new goods and services, as well as resources and technological advances to satisfy both existing demand and projected future demand. Demand is a powerful catalyst in the evolution of market outcomes. However, to a large extent the power of demand is limited both by the fragmentation of consumers due to limited opportunities for coalescing around specific interests and by the consumer understanding of the inherent power of aggregated consumption decisions. From this perspective, understanding how the market functions and the power of consumption in creating sustainable economic outcomes is one aspect of developing into a rational economic agent.

The values embedded and communicated within demand and supply determine the manner in which a need or want is attained. To the extent that there is no discussion of the values and behavioral factors assumed and reflected in demand and supply, arguably, implicit values, the values and the subsequent behaviors become endogenous to the economic system. From this perspective, explicit awareness of present behavioral assumptions inclusive of the "unlimited wants" of consumers, profit maximization motivations of producers, and the understated resource depletion resulting from externalized costs offer the potential to modify active and embedded behavior.

2.12 Conscious Consumption and the Social Norm of Sustainability

The explicit discussion of the embedded assumptions guiding the behavior of the decision-maker is typically not a part of the economic education process. As a result, to the extent that individual economic agents, producers or consumers of a good or service, are bounded by rationality that does not include addressing the impact of externalized or non-quantified costs, the economic discussion does not promote or position the assessment of alternative outcomes. Implicitly and endogenously, the economic discussion establishes and maintains consumption to production circular flow, focusing on the gratification of consumption and profit-taking from production, seemingly eliminating assessment of externalities and holistic dynamics.

Economics, in present practice, evaluates efficiency with respect to the use of resources to maximize production and consumption, not by the moral desirability of the physical methods and social institutions used to achieve this end. The factors that are included in an economic evaluation are limited to the tangible quantifiable costs and costs are overlooked where either a market or regulatory oversight has not provided a monetary justification (Shah 1999; Venkatesan, 2015). From this perspective, the impact of consumption decisions on the environment, economic disparity, or endangerment of other species is not an issue. The market mechanism disenfranchises the consumer from the welfare of those impacted by his/her consumption and promotes the perception that price alone is indicative of the true cost of a good. The possibility that consumption should be reduced because the act of consumption is not good for the soul, or is not what actually makes people happy, has no place within the economic value system (Nelson 1995). The underlying assumption is that consumers are driven to want more. As a result, economic modeling assumes that reduction in consumption in the current period is only addressed through the lens of an increase in consumption in a later period (Knoedler and Underwood 2003). That the assumption of insatiable want may be taught a learned behavior, reinforced through a market model is not even addressed in economics.

A general and seemingly applicable assumption is that consumers and producers maximize the benefit related to the opportunity accessible in their particular circumstance. The desire to reach an optimal outcome for a given point in time, as has been noted before, is subjective and specific to how these economic agents view the concept of maximization, which in turn is likely to be highly correlated with cultural values. For example, in Indigenous societies there is evidence that a balance between present and future periods along with that of the environmental system, as a whole, was included in decision-making and optimization (Nerburn 1999). In present consumerism fostered economies, the cultural values are less likely or unlikely to incorporate environmental and social justice parameters proactively. The focus of observable and marketed consumption is immediate gratification. However, as consumer awareness of both the impact of consumption and the power of consumption to modify and catalyze economic outcomes increases there is growing evidence of a shifting cultural paradigm to one of sustainability.

Markets do fail to produce environmental and socially optimal outcomes. Sometimes this is due to the myopic focus of market participants as in the case of lack of accounting for externalities and in other circumstances it can be attributable to the lack of excludability as in the case of common goods. To some extent, cultural values dictate the significance of the adversity related to the creation of externalities or abuse of common goods. The use of market models has been the regulatory mechanism to modify socially non-optimal outcomes, but through relying on the market mechanism rather than simultaneously including mechanics to promote cultural change, the majority of regulatory interventions to date have had limited to questionable success.

A constituency with an understanding of the holistic relationship between consumption and sustainability and having engagement in government are foundational elements in achieving and maintaining sustainability as a cultural norm. For long-term traction, sustainability is dependent upon holistic and routine evaluation of economic and societal frameworks. These frameworks need to be assessed and modified as part of an on-going continuous improvement process. Fundamentally, what may have been viewed as appropriate action at a point in time may no longer serve the same purpose due to changing environmental, social, and cultural parameters. However, the members of a society have to be both empowered and cognizant of the need for this type of evaluation in order for efficiency and ultimately sustainability to be a realized inter- and intra-generational attribute. From this perspective, the deployment of consumer education programs targeted at defining responsible demand and conscious consumption is a requisite foundation for sustainability (Junyent and Geli de Ciurana 2008).

2.13 Conclusion

The discussion in this chapter has focused on the role of culture in establishing economic outcomes and the relationship between the economic system and environmental sustainability and sustainable economic growth. In essence, argument has been made that the present consumption oriented economic system is veiled by the market, obscuring consumers from understanding their direct contribution to environmental degradation and social injustice. Furthermore, an economic growth model that measures growth based on consumption is misaligned with sustainability. In order to promote the inclusion of environmental assets and non-human life in the discussion of sustainability, consumers need to be made aware of the connection between prices, externalities, and consumption. Education to align consumer behavior with sustainability of outcomes is fundamental requisite to achieve a foundation where bioeconomy can promote sustainable economic development. Without an understanding of the impact of the consumer supply chain, the bioeconomy risks being a substitute for present production processes rather than a value-based paradigm shift that measures growth based on parameters independent of human and non-human life exploitation.

Given that bioeconomy is discussed as a substitute for present production processes and therefore relies on the development of new technologies to promote efficient use and sustainability of resources, there is a need to also address the sustainability of human population growth. Returning to the assertion that sustainability be holistic and inclusive of the welfare of non-human life, without discussion of human population control all non-human life will be controlled and maintained for the benefit of human life, ceasing in its own ability to have life value and evolve and further, eliminating the nature-based connection of the interconnectivity of life that silently provides for natural balance. Human population growth needs to be included as part of sustainability education and the role of reproduction needs to be evaluated in order to establish a sustainable bioeconomy.

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Social and Economic Contribution of the Bioeconomic Sector in Ecuador: A Methodological Approach

3

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Abstract

The national and international scientific community considers Ecuador's biodiversity to be a comparative—even competitive—advantage of a new development paradigm, which could pave the way for a future that is less dependent on non-renewable resources. Accordingly, the concept of bioeconomy has raised attention from different sectors, but its understanding and policy development to exploit its potential are still very limited. In the present work, we propose a methodological approach to assess the economic and social contribution of the bioeconomic sector in Ecuador. First, the theoretical and empirical foundations are delineated, based on conceptual aspects and similar previous case studies. Second, three available models (input–output model, general equilibrium model, and social accounting matrix) are evaluated in terms of comparability, applicability, external validity, and scalability. Based on a comparison of the models, the

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input–output matrix ranks best in terms of comparability and external validity. Aware that other countries in the region are also interested in implementing similar efforts, we have completed this exercise prioritizing the comparability (across and within countries) and external validity aspects. Thus, this work may aid in the elaboration of future evaluation approaches in other Latin American countries.

Keywords

Bioeconomy · Bioindustry · Input–Output model · Sustainable Development Goals · Latin America

3.1 Introduction

The Ecuadorian economy is highly vulnerable to external factors. The oil sector represents more than 40% of total exports and 20% of the public sector income (BCE 2018). Since the dollarization in 2000, the country has experienced an average growth rate of 3.7% but also negative growth (around −1.23%) in 2016, due to a fall in international oil prices and an earthquake in the northern coast of the country (BCE 2018). The dollarization of the Ecuadorian economy marks a turning point in the country's economic history, in which the loss of monetary policy, dependence on foreign currency, competitiveness, and other factors investigated by local authors (Acosta 2004; Correa 2004; Falconí 2004) are characteristics to consider when executing public policies. The national and international scientific community, bearing in mind that Ecuador is a megadiverse country, considers biodiversity as a comparative advantage (even competitive) of a new development paradigm that may contribute to the construction of a post-oil Ecuador (MAE 2016).

The bioeconomy has the potential to coherently address the complex challenge of generating from agricultural production, new sustainable sources of economic and social growth that contribute to the achievement of most Sustainable Development Goals (SDGs). In fact, promoting the bioeconomy and its subsectors in Ecuador allows the country to avail itself of a strategic resource that has been neglected so far, biodiversity and its genetic wealth. Despite the local interest awakened by the bioeconomy (Ortega-Pacheco et al. 2018), its understanding and the development of policies that could exploit its potential continue in an incipient stage.

In this context, the increasing exhaustion of natural stocks and volatility in prices of raw material (e.g. oil prices) raises the need to promote public policies towards a socio-economic transition that guarantees the environmental, social, and economic sustainability of the country, particularly the rural sector. This context provides an opportunity for the bioeconomy. In the same vein, the fall in prices of raw materials has an impact on agriculture, generating a crisis of alternatives for the rural sector and an opportunity for biodiversity-based production schemes that reduce vulnerability to external shocks. Indeed, the National Biodiversity Strategy (NBS) 2015–2030 has been designed to give way to the industrialization of biodiversity based on bioknowledge (MAE 2016). It is a structure to protect biodiversity and catalyse a sustainable transition of the Ecuadorian economy. The bioeconomy is compatible with this approach to Ecuador's development.

One of the main problems in the analysis of alternative development models are the opportunity costs between the relative GDP participation of the sector, labour migration, deforestation, loss of biodiversity, and the expansion of industrial and service sectors. Any configuration of the bioeconomy must then consider the complex interdependencies between these variables and the dependence of national incomes on extractive economies. Falconí and Vallejo (2012) argue that the key determinants that promote socio-ecological transitions in Andean countries such as Ecuador are economic efficiency, income redistribution, and physical sustainability. As extractive economies exert environmental pressure and deepen inequalities, their prospects for economic growth are limited by the carrying capacity of the ecosystem. Taking these factors into consideration, we have conducted this assessment of the bioeconomic sector's contribution to the Ecuadorian GDP.

The following section introduces the concept of bioeconomy and how it is understood by the most relevant organizations. In Sect. 3.3, the Ecuadorian economic structure is presented in terms of GDP components and bioeconomic shares within the economic subsectors. Section 3.4 presents the different models available for the assessment of the contribution of the bioeconomy. Section 3.5 compares the models considering the criteria mentioned above. Section 3.6 presents the estimates of the bioeconomy to the Ecuadorian economy, and Sect. 3.7 introduces five sectors in which the bioeconomy has exceptional potential to contribute. Section 3.8 offers final take-away ideas and suggests future research avenues.

3.2 Conceptual Framework

The present section aims to explore different definitions of bioeconomy to parameterize the identified methodology but not to critically compare the different theoretical proposals that are available nor to implement a normative analysis (Vivien et al. 2019). Relevant to the operational definition of bioeconomy is facilitating its applicability in other examples, within a time frame that permits the evaluation of its evolution. In other words, the concept of bioeconomy should be compatible with the incorporation of items and sub-items of a national system within the methodology to assess bioeconomy, as well as with the differentiation between the possible scenarios for the implementation of bioeconomy in a context of productive development.

About these possible scenarios, it is important to consider that bioeconomy requires the utilization of more resources, processes, and biological principles, only possible if there is a utilization of new knowledge, technology and information, and the availability of capacities that are related to its use. Accordingly, it has been identified that, in the short-run, a technological hybridization would be observed, whereby traditional technologies and new biotechnologies interact to pave the way for more efficient and environmental friendly production models (i.e. increase efficiency in the agricultural sector) (IICA 2019). In the long-run, progress in the biological sciences and information technologies will bring about better varieties and new uses for biomass. The element that underlies the analysis of the possible scenarios is the increase and focalization of investments in innovation and development (I & D) and the commercial scaling of biodiscoveries, as well as the formation of scientific and technological capacities, strategies to develop industrial clusters, support programs, and equitable distribution schemes of the added value that has been generated. Of particular interest is the possibility that these development bioeconomy scenarios promote social inclusion by means of the increase of opportunities in rural areas.

The Economic Commission for Latin America and the Caribbean (CEPAL, by its Spanish acronym) defines bioeconomy as (Rodríguez et al. 2017):

(a) an economy based on the consumption and production of goods and services derived from the direct use and sustainable transformation of biological resources, including biogenic waste generated in the transformation, production, and consumption processes,
(b) taking advantage of the knowledge of biological processes and principles, and,
(c) technologies applicable to the knowledge and transformation of biological resources and to the emulation of biological processes and principles.

Other authors and FAO sources (Bracco et al. 2018) consider that bioeconomy includes:

(a) use of renewable biomass and efficient bioprocesses to achieve a sustainable production,
(b) use of converging technologies, including biotechnology, and,
(c) integration between applications such as agriculture, health, and industry.

Likewise, there is an increasing interest in the literature in defining bioeconomy as technological solutions or other artificial solutions intended to complement or substitute non-renewable resources with alternatives with biological base (D’Amato et al. 2019). These solutions are based on:

(a) the idea of applying principles and biological processes in all economic sectors,
(b) the replacement of fossil-based raw materials with biologically based resources and principles in the economy (Dietz et al. 2018).

Thus, some authors conceptualize bioeconomy as the industrial transition towards the sustainable use of aquatic and terrestrial resources through the generation of intermediate and final products that involve the displacement of the use of products derived from fossil-based raw materials (Golden and Handfield 2014). Note that within these approaches, primary biobased products, such as those generated by agriculture or livestock, are not considered, but only the transformation of these products by means of an intensive use of knowledge. Therefore, combining these last approaches, the bioeconomy does not only refer to an industrial sector but also to the set of economic activities related to the invention, development, production, and use of products and processes based on biological resources within the national economy (OECD 2009). That is, a productive transformation that is both biologically based (Trigo et al. 2013) and circular (Giampietro 2019) as the ground for a socio-ecological transition (de Schutter et al. 2019; Ortega-Pacheco et al. 2018).

In summary, a definition could be posited: "The production and use of biological resources, biological processes and principles to provide intermediate and final goods and services in a sustainable manner in all economic sectors through the intensive use of knowledge that displaces the use of products derived from fossil fuel".

From this discussion, it is evident the need for a concept of bioeconomy that contributes to the comparability, applicability, external validity, and scalability of the applied methodology. Indeed, this concept should allow the incorporation of the different groups of sectors and subsectors that each country considers to be "bioeconomy". Similarly, it should allow to interpret the role over time of actions such as the provision of biomass resources, economic specialization, and investments in research and development (R + D) in a context that ensures an effective governance framework for a "sustainable bioeconomy" (El-Chichakli et al. 2016; IICA 2019).

3.3 Sectors in the Ecuadorian Bioeconomy

3.3.1 The Ecuadorian Economic Structure

Before detailing the methodology used to identify the sectors that compose the bioeconomy in Ecuador, it is worth describing the composition of the country's economy. Considering the traditional classification of three economic sectors, the Ecuadorian GDP is distributed as follows: primary 22%, secondary 24%, and tertiary 54% (BCE 2018). Considering a more disaggregated categorization, Fig. 3.1 displays the GDP contribution shares of the most relevant subsectors. Note that the contribution share of the manufacturing industry is equivalent to that of the Oil and Mines subsector. In other words, the wealth generation of the country's industrial apparatus is similar to the contribution of a single natural resource. Such a characteristic is relevant when determining the contribution of the bioeconomy and the planning of scenarios for a productive transition.

A priori, an assumption is that the bioeconomy participates more predominantly in the primary and secondary sectors. Despite the fact that the GDP contributions from these two are similar, the way their contributions come about is not. Note that the participation of subsectors in the primary sector (green bars in Fig. 3.1) is mostly composed of the Agriculture and Oil subsectors, whereas participation in the secondary sector (orange bars in Fig. 3.1) is less concentrated. The tertiary or service

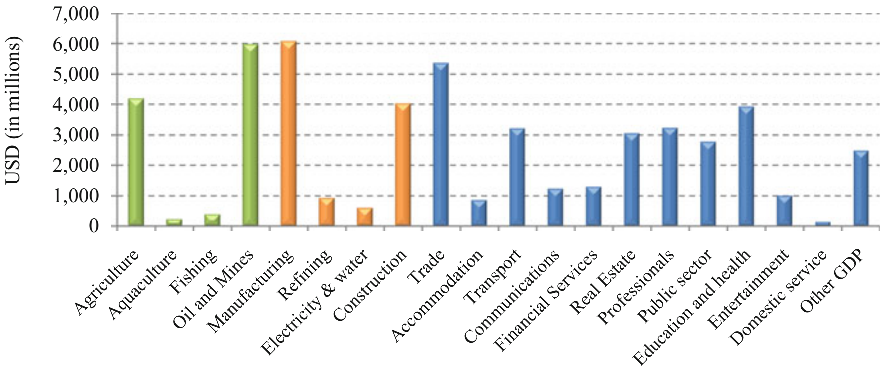

Fig. 3.1 Disaggregation of GDP by economic sectors. Green bars denote subsectors of the primary sector, orange bars denote subsectors of the secondary sector, and blue bars denote subsectors of the tertiary sector. Source: Central Bank of Ecuador (BCE) (2018)

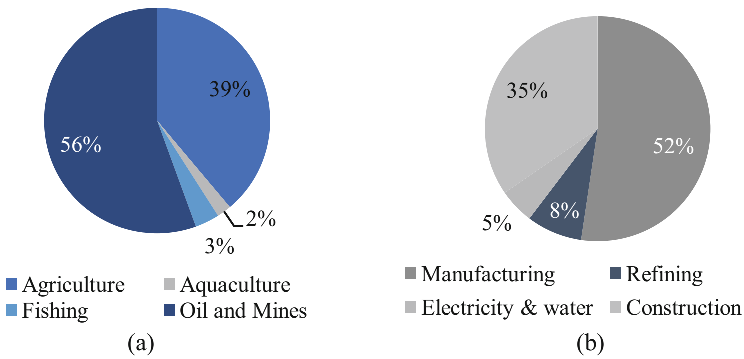

Fig. 3.2 Disaggregated share of GDP in (**a**) primary and (**b**) secondary sectors. Source: Central Bank of Ecuador (BCE) (2018)

sector contributes to the GDP the most, as shown by the numerous blue bars in Fig. 3.1; however, its bioeconomy-related contribution is expected to be low.[1]

Based on the concept of resource-industry supply chains, Fig. 3.2 displays the participation of the main primary (Fig. 3.2a) and secondary (Fig. 3.2b) subsectors. The agricultural sector has a 39% share of the total primary sector, whereas the primary resources coming from non-traditional sources, such as aquatic spaces, have minimal participation due to the specific weight of oil extraction (56%). In the secondary sector, oil refining has a relatively low participation (8%), whereas the

[1]Considering the conceptual framework described in the next section, assessing the role of the bioeconomy in the traditional tertiary sector is less straight-forward than in the primary and secondary sectors. Mainly for this reason, we will not address this sector.

manufacturing subsector has the highest participation (52%). Note also, the significant contribution of the construction subsector (35%).

3.3.2 Selection of Bioeconomy Subsectors

The methodology used to measure the contribution of bioeconomic activities to a country's GDP is based on the proposal of the Buenos Aires Grain Exchange or BCBA by its Spanish acronym (Trigo et al. 2015). This methodology proposes the creation of a satellite account within the system of national accounts (SNA) that is specific to the bioeconomy. Based on this account, the gross value added corresponding to the bioeconomy is calculated.

The dimensioning of this satellite account is done by using shares of the contribution to the bioeconomy within each productive sector of the SNA. The definition of these shares is done only by consulting experts, which can render a high degree of uncertainty and also limit the reproducibility of the calculation. Another aspect adopted from the methodology proposed by the BCBA is the consideration that all biomass is a bioproduct, not only those produced through the use of genetic engineering. This consideration is also supported by the definition of bioeconomy selected for this study.

Considering that the methodology proposed by the Buenos Aires Grain Exchange (Trigo et al. 2015) has advantages and limitations, for the development of a new methodology, some steps of the base methodology are adopted while other steps are modified in an attempt to improve them. Thus, in the new methodology for measuring the contribution of the bioeconomy, the use of the SNA as the economic database of a country's production is maintained. The use of the SNA guarantees the applicability of the methodology in countries where it is updated, since its construction is based on standards set by various international and regional organizations (Trigo et al. 2015). For countries where national accounts are not public or are outdated, the methodology presented here will be applicable only after the construction of an equivalent economic database.

The SNA additionally allows considering the linkages of raw materials and products between the different productive sectors, for example, the processing of palm oil uses the palm fruit production, a primary subsector, as its basis. In this way, the bioeconomic part of the primary production of the fruit of the palm is transferred directly to the production of the oil by means of the share of bioeconomic contribution of the fruit production.

Additionally, the creation of a satellite account within the SNA is not included as part of the methodology of this study due to restrictions on the availability of information, as well as the low level of disaggregation in the national accounts. This particularity makes it difficult to estimate specific parameters for the productive sectors, due to the high aggregation in the sectors of the economy. Nevertheless, this activity could be carried out based on estimates of productive parameters to determine the contribution of the bioeconomy for each aggregated sector (Table 3.1).

Table 3.1 Economic sectors considered to be part of the bioeconomy in Ecuador

Economic sector	Fraction of contribution to the bioeconomy
Primary sector	
Banana, coffee, and cocoa farming	0.67[1]
Cereal cultivation	0.41[2]
Growing flowers	0.62[3]
Cultivation of tubers, vegetables, melons, and fruits	0.68[4]
Oil and industrial crops	0.53[5]
Crop support activities	0.09[a]
Raising of livestock, other animals; animal products; and support activities	0.95[6]
Forestry, logging, and related activities	0.98[7]
Aquaculture and shrimp fishing	0.89[8]
Fishing (except shrimp)	0.87[9]
Aquaculture (except shrimp)	0.87[9]
Secondary sector	
Meat processing and preservation	0.77[6]
Shrimp processing and preservation	0.89[8]
Processing of fish and other processed aquatic products	0.71[9]
Conservation of aquatic species	1.00
Processing of oils and fats of vegetable and animal origin	0.43[5]
Dairy product processing	0.95[10]
Production of milling products	0.39[11]
Production of bakery products	0.83[12]
Manufacture of noodles and other farinaceous products	0.85[b]
Sugar processing and refining	0.85[b]
Processing of cocoa, chocolate, and confectionery	0.85[b]
Prepared animal food processing	0.85[b]
Coffee processing	0.85[b]
Processing of various other food products	0.85[b]
Production of alcoholic beverages	0.85[13]
Production of non-alcoholic beverages	0.41[c]
Manufacture of tobacco products	0.85[b]
Manufacture of threads, yarns, fabrics, and clothing	0.68[d]
Manufacture of leather, leather products, and footwear	0.85[b]
Production of wood and wood products	0.96[e]
Paper manufacturing and paper products	0.95[14]
Manufacture of rubber products	0.85[b]
Furniture manufacturing	0.88[8]
Generation, collection, and distribution of electrical energy	0.02[f]

[a]Fraction of organic fertilizers, herbicides and pesticides used in Ecuador (INEC)
[b]Economic sectors of low contribution. Their contribution to the bioeconomy was not analysed in detail and only assumed with an average value derived from the other economic sectors
[c]Soft drinks are not considered within the bioeconomy considering their contribution to the per capita consumption of non-alcoholic beverages (Valverde Obando 2018)

(continued)

Table 3.1 (continued)

[d]Number obtained from the total number of garment manufacturing enterprises that use cotton and wool as their raw materials (Ordoñez 2015)
[e]Value was assumed as an intermediate between wood production and paper production
[f]Fraction of the energy produced from the combustion of biogas and biomass with respect to the total energy produced in the country (INEC)
[1]Guevara Ramia (2015); [2]Baca (2016); [3]Chiluisa Fogacho (2002); [4]Instituto Nacional Autónomo de Investigaciones Agropecuarias (2002); [5]Mosquera Montoya et al. (2016); [6]Jaramillo Orozco et al. (2017); [7]Organización de los Estados Americanos (1977); [8]Lalangui Balcázar et al. (2018); [9]Ochoa Vivanco (2015); [10]Córdova Valverde and Valverde Peralta (2015); [11]MSME-Development Institute (2011); [12]Muenala Colimba (2018); [13]Guadalupe García and Sánchez Estevez (2014); [14]Chiluiza Benítez (2009)

The main modification made to the methodology proposed by the BCBA lies in the definition of the SNA productive sectors' bioeconomic contribution shares. In this study, the calculation of these shares is not only based on the consultation with experts, but also seeks to define the part of the production costs of the representative products of each sector of the SNA that are based on the bioeconomy.

Within the production costs, variable costs and fixed costs are considered. The differentiation of the bioeconomic part of the variable costs is simple, because raw materials and inputs from bioeconomic activities are considered and those from non-bioeconomic activities are excluded. For example, in banana production, the bioeconomic part of variable production costs is the acquisition of young trees and agricultural inputs of biological origin. If, for example, this activity uses biofuels for transport, energy production or machine operation, the costs related to the purchase of biofuels would be included in the bioeconomic part of the production costs. On the contrary, if the fuels are of fossil origin such as gasoline or natural gas, these costs are excluded from the bioeconomic part. Similarly, the costs of pesticides and fertilizers of non-biological (mineral) origin are not included in the bioeconomic part of the production costs. If these were of biological origin, they would indeed be added to the bioeconomic part.

Electricity is an additional important item to consider in the contribution to the bioeconomy. In the proposed methodology, the bioeconomic part of electricity costs would depend on the bioeconomic part of the local electricity grid. Biological sources for electricity production are biomass and biofuels. Although wind, solar, water, and geothermal energy have a smaller carbon footprint than energy derived from the combustion of fossil fuels, they are not of biological origin, which is why they are excluded from the bioeconomic part of the local electricity grid.

Within the fixed costs, however, are items related to labour, maintenance of machinery and civil construction, payment of taxes and the monthly payment of economic investments made for civil construction, acquisition of machinery, processing equipment, tools, land, and vehicles, among others. Since the economic activity could not take place without this part of the production expenses, the fixed costs are assumed to be totally bioeconomic.

The inclusion of 100% of fixed costs in the bioeconomy, however, has consequences for the measurement of the contribution of the bioeconomy. For example, if excess machinery is purchased for an activity, the share would incorrectly suggest that this purchase favoured the bioeconomic part of the productive activity. On the contrary, if only variable costs are taken into account for the calculation of the index, the purchase or lease of land is excluded from the bioeconomic part, which would not be very accurate either since the use of land is necessary for the economic activity. The advice of experts could be used for the resolution of this type of conflicts in the methodology.

In the specific case of Ecuador, the economic activities considered are included in the SNA classification of the Central Bank of Ecuador. These economic activities belong to the primary and secondary sectors. Table 3.1 lists all the sectors considered as part of the bioeconomy in Ecuador. In addition, the right column includes the bioeconomic contribution shares calculated for each productive subsector.

In the primary sector, the costs excluded from bioeconomic accounting are mainly those derived from the use of fertilizers and pesticides of non-biological origin and from the use of fossil fuels used for transportation and the execution of other reported mechanical tasks. In the secondary sector, costs related to the purchase of raw materials and inputs of non-biological origin, non-biological packaging materials, and fossil fuels used in transport are excluded. The item of expenditure on electricity used during industrial processing was assumed to be non-bioeconomic in its entirety because energy produced in Ecuador from biogas and biomass accounts for less than 1% of total production.

Considering the primary subsectors, the bioeconomic contribution shares determined in this study are lower than in the case of Argentina (Trigo et al. 2015), where the bioeconomic fraction of these sectors is 100%. Although in the secondary productive sector, the BCBA study uses varied value indices, in general the shares determined in this study are lower than those of the Argentine case.

Finally, it should be noted that the sources on which the calculation of contribution (to the bioeconomy) shares was based were mostly technical-economic studies; we gave preference to those developed in Ecuador. Additionally, emphasis was placed on using studies that contain real production data, that is, reported by operating companies. However, it should be stressed that this calculation is not without uncertainty. A sensitivity analysis is recommended to verify which rates should receive additional attention and to reduce such uncertainty.

3.4 Available Models to Determine the Contribution of the Bioeconomy in Ecuador

Considering the different alternatives to address the contribution in the economy, a macro-economic perspective is proposed to quantify the contribution share of the bioeconomy in Ecuador. François Quesnay is one of the first references for evaluations of flows of goods and services in the productive apparatus of a society in order to understand the interactions of its actors. In his model *Tableau* *économique*, he established the bases of the economic theory of the physiocrats. Chronologically, it is also worth acknowledging the contributions of Leon Walras' theory of general equilibrium (Walras 1874), Wilfred Pareto's study of private property tenure and, at the same time, the contributions of Kenneth Arrow and Gerard Debreu on the balance between supply and aggregate demand for each good or service of a specific set of prices (Arrow and Debreu 1954; Pareto 1906).

A study carried out by the FAO (Bracco et al. 2018) estimated the contribution of the bioeconomy in various countries. It concluded that the most appropriate approaches are descriptive macro-economic models with a top-down structure that allow for the evaluation of interactions between different actors in the economy. Such models include the input–output model, the general equilibrium model, and the social accounting matrix. Therefore, this study focuses on and carries out a literary review of the analysis of these types of models.

3.4.1 Input–Output Model (IOM)

The input–output model (IOM) was proposed by Nobel laureate economist Wassily Leontief. It consists of a system of linear equations that quantifies the interdependencies between the different sectors in an economic system, which are then compiled into a set of matrices to evaluate the behaviour of all actors in the face of external variations. Hence, the matrix representing the productive structure is also called Leontief's matrix (L).

The input–output model is based on existing transactions in all economic sectors, information that may generally be obtained from the countries' official economic policy agencies. In the model, the quantity of goods and/or services demanded by sector j of sector i output, measured in monetary terms for a given period, is the result of a z_{ij} flow of goods and services across sectors. Thus, the production of sector i, denoted as x_i, is demanded by all intermediate sectors and final consumers (y_i) such as households, government, fixed capital formation, and net exports.

$$x_i = z_{i1} + \dots + z_{ij} + \dots + z_{in} + y_i = \sum_{j=1}^{n} z_{ij} + y_i \tag{3.1}$$

where n represents the total number of sectors in the economy. In the case of Ecuador there are 71 economic sectors. By arranging the matrix, the economy's total production (X) can be defined in terms of all the intermediate consumption (Z_i) plus all final consumption (Y), as shown in Eq. (3.2).

$$X = Z_i + Y \tag{3.2}$$

In the IOM structure, a basic premise is that the demand/production ratio between sectors is fixed, i.e., the amount of inputs that sector j requires to carry out its production does not vary (Miller and Blair 2009). This ratio, referred to as a sector's technical coefficient, is presented in Eq. (3.3).

$$a_{ij} = \frac{z_{ij}}{x_{ij}} \tag{3.3}$$

According to the structure of the IOM, these coefficients (a_{ij}) are fixed because they represent the technological capacity of the society. They only vary if there are significant technological changes that modify the productive structure of the society. Thus, the matrix of technological coefficients (A) can be defined. Through a series of algebraic operations from Eq. (3.2), the following expression can be obtained:

$$X = (I - A)^{-1} \cdot Y \tag{3.4}$$

In Eq. (3.4), the element $(I - A)^{-1}$ is known as the Leontief inverse matrix (L). The structure of this equation will be used to determine the impact of the technological change in Ecuador on the national economy, considering the impacts per se due to the change in the refining structure, known as direct effects, and the impacts along the productive chains, known as induced effects.

Following the national accounts provided by the Central Bank of Ecuador, the model's reference year is 2015, generating an input–output matrix of 71 sectors (Z_I). Based on the theory shown, we obtain the respective technical coefficients (a_{ijI}) and consequently an initial matrix of technical coefficients (A_I), considering Ecuador's current refining capacity.

The literature review about the application of this model to the Ecuadorian economy includes estimates of the transport sector demand (CEPAL 2017), analysis of the impact of variations in the agricultural sector (Banderas and Hidalgo 2013), identification of key sectors in the national economy (Fernández 2009), estimates of the contribution of the construction sector to national GDP (Yagual Velástegui et al. 2018), and estimates of input–output matrices for the provinces of Guayas (Palma Luna and Vega Ramírez 2016) and Carchi (Fundación Alianza Estratégica 2015).

3.4.2 General Equilibrium Model

The general equilibrium model (GEM) is based on the theory of general equilibrium proposed by Walras. It is worth noting that the complexity of the model due to the significant number of equations, number of variables and iterations between them, made it difficult to enhance its development for several years. However, due to advancements in computer and high-speed processors, the development of models based on this theory was possible.

The theory of general equilibrium stems from the premise of the existence of an equilibrium between the different actors in the market. As such, this type of model seeks to explain the behaviour and interactions of the actors when faced with alterations to the condition of equilibrium, using mathematical equations for the supply (producers) and demand (consumers) of products or services according to the realities of each society.

Table 3.2 Supply and demand equations (GEM)

Demand—consumers	Supply—producers
$Max\ U = \beta \cdot x_i^{\alpha_i} \cdot x_j^{\alpha_j}$	$Min\ C = P_K \cdot K + P_L \cdot L$
Subject to: $P_i \cdot X_i + P_j \cdot X_j = M$	Subject to: $Q = t \cdot K^{\propto_K} \cdot L^{\propto_L}$
Optimal allocations: $X_i = \frac{\propto_i \cdot M}{P_i}$; $X_j = \frac{\propto_j \cdot M}{P_j}$	Optimal allocations: $K = \frac{1}{t} \cdot Q \cdot \left(\frac{P_L}{P_K}\right)^{\propto_L}$; $L = \frac{1}{t} \cdot Q \cdot \left(\frac{P_K}{P_L}\right)^{\propto_K}$

Table 3.3 GEM external sector equations

Imports	Exports
$X = A(\gamma_A \cdot M^{\rho_A} + (1 - \gamma_A) \cdot Xdd^{\rho_A})^{1/\rho_A}$	$Xd = T(\gamma_T \cdot E^{\rho_T} + (1 - \gamma_T) \cdot Xdd^{\rho_T})^{1/\rho_A}$

This type of model combines the assumption that all markets are in perfect equilibrium with realistic data derived from social accounting matrices (SAMs) to represent the initial reference points in equilibrium, after a political intervention. Equilibrium is guaranteed by price adjustments that cannot be influenced by internal agents, such as households, firms, and government. Since they are sensitive to price variation, consequently, they act as decision makers trying to maximize their welfare (in the case of consumers) or profits (in the case of producers) under certain constraints and quantity adjustments (Table 3.2).

The above is linked to a dispute between the actors over the factors of production: labour (L) and capital (K); the labour factor refers to the remuneration received by the company's workers as a result of their labour activities, while the capital factor is reflected in the remuneration of the capital produced by an investment. Consequently, workers' wages (P_L) and capital interest (P_K) are the main elements of analysis for the labour and capital factor, respectively.

Similarly, considering that society interacts with other economies, i.e., external sector. The GEMs express through mathematical functions that reflect actors' behaviour before the import and export of local and foreign products (Table 3.3), where the equations are sensitive to variations of the rates (γ_A, γ_T) and parameters (ρ_A, ρ_T) that reflect the internal productive and consumption structure of the society both for imports (M) and exports (E).

It is also frequent to refer to this type of models by the name of computable or applied general equilibrium models. This nomenclature refers to simulations made by computer systems that combine the concept of equilibrium with realistic economic data of the society, to solve numerically the levels of supply, demand, and prices that support the equilibrium in a set of markets. Therefore, the GEM is useful for the evaluations of energy policies, as in the case of the bioeconomy and particularly for policies that imply transitions in the productive and consumption structure of a country.

With respect to its application in Ecuadorian reality, there are no specific studies that use the GEM for evaluations to assess the impact of the bioeconomy in the country; however, in 2005 the Ecuadorian Model of Applied General Equilibrium

(MEEGA by its Spanish acronym) was developed, which includes households, government, the external sector, and industry based on the 2001 SAM. This model was designed to raise the level of discussion about the impact of economic policies in the country. Its main application evaluated the possible effects on the Ecuadorian economy of the Free Trade Agreement with the USA (Pérez and Acosta 2005).

Based on the structure of the MEEGA model, in 2007 the Model of Tributary Applied General Equilibrium Model for Ecuador (MEGAT by its Spanish acronym) was developed in order to conduct a comprehensive analysis of tax policies, taking into account the evasion of the value added tax (VAT) and income tax (IRC) (Ramirez 2007). In 2010 the model for evaluating exogenous shocks, economic and social protection (MACEPES) was developed. Based on this model, studies were conducted for seven Latin American countries, including Ecuador (Cicowiez 2012; Cicowiez and Sánchez 2010). More recently, Castro et al. (2018) developed a General Equilibrium Model for Ecuador to asses the socio economic impacts due to refinery matrix change.

3.4.3 Social Accounting Matrix

The social accounting matrix (SAM) is defined as the matrix representation of the circular flow of income of a socio-economic system in a given period (BCE 2017a). It has three main objectives: "(1) to organize the economic and social information of a country in a given period; (2) to provide a synoptic view of the flows of receipts and payments in an economic system; and (3) to form a statistical basis to build models of the economic system to simulate the socioeconomic impact of policies" (Giovanni Bellu 2012).

It is a complete and disaggregated data system that is one of the fundamental elements in economic modelling and descriptive socio-economic analysis. It is complete and disaggregated because, due to its construction process, it is established under the "Top-Down" methodology, where each element at the macro level represents a transaction within the same economic system involving different agents such as households, firms, government, and the rest of the world; and the micro level explains the disaggregation of different transactions, providing an analytical and mathematical description to obtain the macro SAM (BCE 2017b). This matrix is used for economic modelling, as it is the numerical basis for calibrating different economic models, such as general equilibrium models (Ramajo et al. 1998), and for socio-economic analysis, as it is a tool for analyzing and applying policies and planning, since it covers the economic and social structure of an entire country.

The SAM is built under the guidelines established by the United Nations System of National Accounts. It has a square matrix representation whose structure is fed by the transactions of different accounts, organized in row (income) and column (expenditure), or in its representation i and j, which represent the interconnections between the different economic agents (BCE 2017b). The accounts involved in the SAM are goods and services (origin and destination of final goods), production activities, factors of production, economic agents, capital account, and the external or so-called rest of the world account (Ramajo et al. 1998).

3.5 Comparative Analysis of the Models

Considering the criteria of comparability, applicability, external validity, and scalability, this section compares the available models to assess the bioeconomy's contribution to the Ecuadorian GDP. The first consists of the structure of a model that allows for the comparison of scenarios and policy implementation alternatives, in order to obtain a broader response to the implications of the bioeconomy. With respect to applicability, the following are considered: criteria of information availability, reality of the productive structure, and availability of natural and economic resources. In other words, the model should prioritize the validity of the results, considering the existing limitations in its development.

In terms of external validity and scalability, there is a need to structure a model whose results can be generalized to different populations, whether at a local or regional level, and whose methodology can be replicated in different economies or with characteristics similar to those of Ecuador. In this context, it should be noted that the System of National Accounts and the Social Accounting Matrix are standardized information in several countries, which allows for external validation of the results obtained. The scalability is related to the technical and process engineering aspects. An analysis in this regard will conclude up to what levels the system could be expanded or adapted, while maintaining or increasing the growth levels.

In addition, apart from the main criteria, the authors argue there is a need to include a criterion of easiness by users or readers of the present study. In other words, it is important that electronic tools are available for users to, by means of the methodological sheets, evaluate different scenarios or alternative analyses to those presented in this study.

Without a doubt, the use of the social accounting matrix has been historically and widely disseminated in several economies, as it is a tool that effectively reflects the socio-economic characteristics of countries. However, this study will refer to the locally developed SAM model, which is based on Ecuador's system of national accounts. The use of this model would imply a high applicability since it considers all conditions of the Ecuadorian system. As a counterpoint, it would be of low comparability and external validity because it is restricted to the country's characteristics, and not necessarily to local or regional characteristics. As a consequence of the contemporaneity of the model, it is probable that there are few studies or applications based on it, implying a medium scalability, since it has few references to the economic-technological relations with the aspects of process engineering.

On the other hand, IOM and GEM models would have better scalability, based on previous experiences and applications presented earlier, as is the case with the development of IOM for specific provinces. The previous studies contributed to the development of economic-technological parameters that would allow the extrapolation and evaluation of the conditions of the bioeconomy. Considering the higher level of mathematical complexity and specific information involved in the

Table 3.4 Selection criteria—available models

Model	Comparability	Applicability	External validity	Scalability
IOM	High	Medium	High	High
GEM	Medium	Medium	Medium	High
SAM	Low	High	Low	Medium

development of a GEM, the applicability criterion would be restricted to the availability of information.

Without a doubt, one of the strengths of the GEM is the responses of actors in the economy to possible price variations, a characteristic that is difficult to evaluate in the IOM. However, its comparability and external validity would be limited to the availability of economic information from other firms under the same conditions. On the other hand, the IOM, by not considering this type of conditions, allows structuring versatile models that can be validated and compared with characteristics of other firms.

Regarding ease of implementation by the user or reader of the report, the IOM and the SAM score favourably. The former can be structured in a spreadsheet using a standard operating system, while the latter could be run by the simulators available from official sources. In contrast, the development of a GEM would involve the use of more complex computer tools, due to the greater number of variables and equations.

Therefore, considering the criteria set out in Table 3.4, this study proposes to use an input–output model (IOM) as a basis. By providing methodological sheets, the model will allow replication for other economic or social conditions, of similar economies or conditions of extrapolation. Without a doubt, the IOM has its limitations and restrictions, but its extensive use and the development of similar studies make it possible to guarantee its versatility and assertiveness.

3.6 Contribution to the Ecuadorian Bioeconomy

Considering the criteria previously defined in Table 3.4, we now proceed to quantify the contribution of the bioeconomy. We consider three aspects of interest that will allow its comparison to other economic sectors, as well as with other realities or societies. Such comparisons are relevant in the decision making, planning, and definition of strategies to extend the participation of the bioeconomy, i.e., future scenarios.

- Labour and salary.
- Production and consumption.
- Growth and taxes.

Additionally, the contribution of the bioeconomy in these three aspects is quantified in segments in order to evaluate the interaction of results according to

Table 3.5 Subsectors of the bioeconomy

Segment	Economic sector	Vector reference (*k*)
Bioagriculture	Primary	1
Animal bioindustry	Secondary	2
Crop bioindustriy	Secondary	3
Bioindustry—Manufacture	Secondary	4
Bioenergy	Secondary	5

classification in the traditional economy as: primary or secondary. It is important to note that these segments are structured according to the methodology of means to take advantage of the bioeconomy, proposed by the Inter-American Institute for Cooperation on Agriculture (IICA by its Spanish acronym) (IICA 2019).

Hence, the bioagriculture segment is linked to traditional agricultural activities that produce goods and services derived from the direct use and sustainable transformation of biological resources. These are classified as primary economic activities, which are highly employment-generating but less capital-intensive. Within this segment, the main focus is on the use of resource biodiversity through innovation and the development of domestic markets, as well as sustainable intensification through agricultural practices that raise production levels while maintaining or improving environmental performance (Table 3.5).

With respect to the secondary economic sector or industrial sector, which are highly demanding in terms of capital, a segmentation is proposed based on the origin of the raw materials used in the industrial processes, which can be of plant or animal origin. The aim is for these segments to develop biotechnological applications to raise the level of technological development in traditional production processes. Another path identified is the increase of efficiency in the value chains, mainly in the use of wastes and residues for the use or creation of by-products.

Additionally, considering the energy consumption forecasts in the transportation sector, as well as the potential use of second-generation biofuels, a segment designated as bioenergy is proposed; there is a high potential for the use of biomass from the agricultural sector for energy generation. The production of biorefineries would be a replacement alternative for fossil fuels, mainly for the production of ethanol for passenger transport consumption.

In order to determine the contribution of the bioeconomy to the aspects of interest, we propose specific quantifiable indicators that are available in the system of national accounts, as well as in the country's IPM. Consequently, Table 3.6 presents an estimation of the participation in each of the indicators under the concept of bioeconomy. Within the methodological structure, each indicator is defined as a variable to be calculated, according to an established nomenclature.

The methodology proposes to estimate how many jobs (Emp.) are related to the bioeconomy in the Ecuadorian productive structure, as well as the corresponding total wage bill. Along the same lines, it is of interest to determine how much of the total production and current intermediate consumption is related to the bioeconomy and, consequently, estimate how much the bioeconomy contributes to the generation

Table 3.6 Variables used to estimate the contribution of the bioeconomy

Aspect	Indicators	Nomenclature
Labour and salary	Jobs generated Total wage bill	Emp. Sal
Production and consumption	Total production Intermediate consumption	TP IC
Growth and taxes	Gross value added Taxes on production	GVA Tax

of wealth (GVA) and taxes to the central government (Tax). Shortly, the aim is to carry out a comprehensive analysis of the contribution of the bioeconomy in multiple aspects so as to nourish the debate on this topic, and not only to focus its analysis on a specific indicator.

The calculation for each indicator is determined by the double sum presented below in Eq. (3.5a), which considers the five segments of the bioeconomy (Table 3.5), as well as the contribution factors from Table 3.1. Equations 3.5b and 3.5c are equivalent representations of Eq. 3.5a. The bioeconomic segments are denoted by the k subindex and the economic sectors by the ij subindexes. Therefore, the ijk coordinates represent an economic sector within the segments of the bioeconomy. This method quantifies the contribution of the segments first, in order to quantify the contribution of the bioeconomy as a whole by means of a general summation. For example, the generation of employment is calculated for the bioagriculture, animal bioindustry, crop bioindustry, manufacturing bioindustry, and bioenergy sectors, where the total sum would imply the generation of employment in Ecuador related to the bioeconomy.

$$\text{Indicator} = \sum_{k=1}^{5} \sum_{i=1}^{n} \sum_{j=1} \text{Variable}_{ijk} \times \text{Factor}_{ijk} \tag{3.5a}$$

$$\begin{aligned}\text{Indicator} = &\overbrace{\begin{pmatrix} v_{ij1} \\ \vdots \\ v_{nn1} \end{pmatrix}^T \begin{pmatrix} F_{ij1} \\ \vdots \\ F_{nn1} \end{pmatrix}}^{\text{Bioagriculture}} + \overbrace{\begin{pmatrix} v_{ij2} \\ \vdots \\ v_{nn2} \end{pmatrix}^T \begin{pmatrix} F_{i2} \\ \vdots \\ F_{n2} \end{pmatrix}}^{\text{Animal Bioindustry}} + \overbrace{\begin{pmatrix} v_{ij3} \\ \vdots \\ v_{nn3} \end{pmatrix}^T \begin{pmatrix} F_{ij3} \\ \vdots \\ F_{nn3} \end{pmatrix}}^{\text{Crop Bioindustry}} + \\ &\overbrace{\begin{pmatrix} v_{ij4} \\ \vdots \\ v_{nn4} \end{pmatrix}^T \begin{pmatrix} F_{ij4} \\ \vdots \\ F_{nn4} \end{pmatrix}}^{\text{Biomanufacture}} + \overbrace{\begin{pmatrix} v_{ij5} \\ \vdots \\ v_{nn5} \end{pmatrix}^T \begin{pmatrix} F_{ij5} \\ \vdots \\ F_{nn5} \end{pmatrix}}^{\text{Bioenergy}}\end{aligned} \tag{3.5b}$$

$$\text{Indicator} = \boldsymbol{V}_1 \bullet \boldsymbol{F}_1 + \boldsymbol{V}_2 \bullet \boldsymbol{F}_2 + \boldsymbol{V}_3 \bullet \boldsymbol{F}_3 + \boldsymbol{V}_4 \bullet \boldsymbol{F}_4 + \boldsymbol{V}_5 \bullet \boldsymbol{F}_5 \tag{3.5c}$$

3.6.1 Labour and Salary

As mentioned earlier, the labour and salary aspects allow us to quantify how many workers are related to the bioeconomic processes, as well as the remuneration involved in this type of activities. Such an analysis allows researchers to assess the quality of work and to propose possible alternatives for the improvement of these activities. In 2017, according to statistics from the Central Bank of Ecuador, 7.5 million jobs were generated in the country's productive sectors, of which 46% corresponded to the services sector, as shown in Fig. 3.3a. This fact is not surprising as the largest job-generating productive sector in the country. Meanwhile, the bioeconomy contributed with 20% of the jobs generated in the same year, a value equivalent to 1.53 million workers.

It should also be noted that the generation of jobs in the bioeconomy is higher than the generation of jobs in the traditional manufacturing industry (5%), the construction sector (8%), and energy generation and transport (8%); a situation that unfolds in an economy with low levels of industrialization and high export of primary products. It should be noted that the greatest concentration of jobs generated by the bioeconomy would be in the bioagriculture segment (76%), while the other segments in the bioeconomy (bioindustries, biomanufacture, and bioenergy) would represent a 24% share. Thus, there is a high potential for employment generation in the last two sectors.

Labour compensation allows us to evaluate the quality of employment. In this regard, the services sector represents the main share in workers' remuneration, as displayed in Fig. 3.3b. In addition, note that the public sector, which generates only

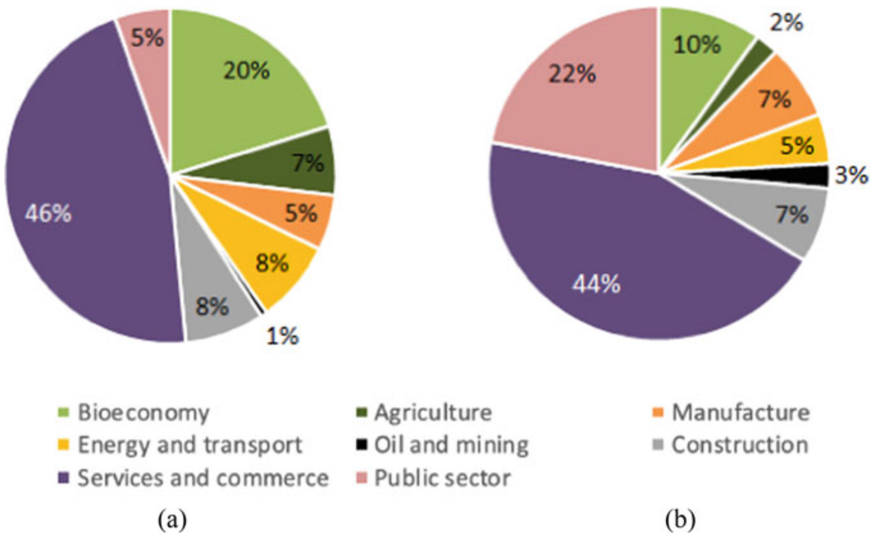

Fig. 3.3 Contribution to employment generation (**a**) and labour compensation (**b**). Source: Central Bank of Ecuador (BCE) (2017a, b)

5% of jobs, has a significant share of workers' total wage bill (22%). In fact, a public sector worker would have an average monthly salary of US$1746 in 2017, approximately 4.6 times the monthly minimum wage in that year. The opposite situation occurs with jobs related to the bioeconomy, which represent a share of only 10% of the workers' remuneration (Fig. 3.3b). On average, a worker in this sector receives US$207 per month, which is less than the monthly minimum wage and less than the minimum cost of living. This situation reflects the existence of inadequate work conditions and high labour informality in the sector, as it is mostly primary.

3.6.2 Production and Consumption

The consumption of intermediate products in 2017 reached a total of US$73,836 million, linked to a production of US$170,919 million, while the difference was destined to final consumption. Consequently, Fig. 3.4a shows that there is an almost equal participation between the bioeconomy (23%), service sector (26%), and the traditional manufacturing industry (19%) in the intermediate consumption of goods and services, implying a significant participation of the bioeconomy. More than 90% of the intermediate consumption of the bioeconomy is linked to the secondary sector (crop and animal-related bioindustry) and the rest to primary products (bioagriculture). The higher added value of processed products compared to agricultural products explains this situation.

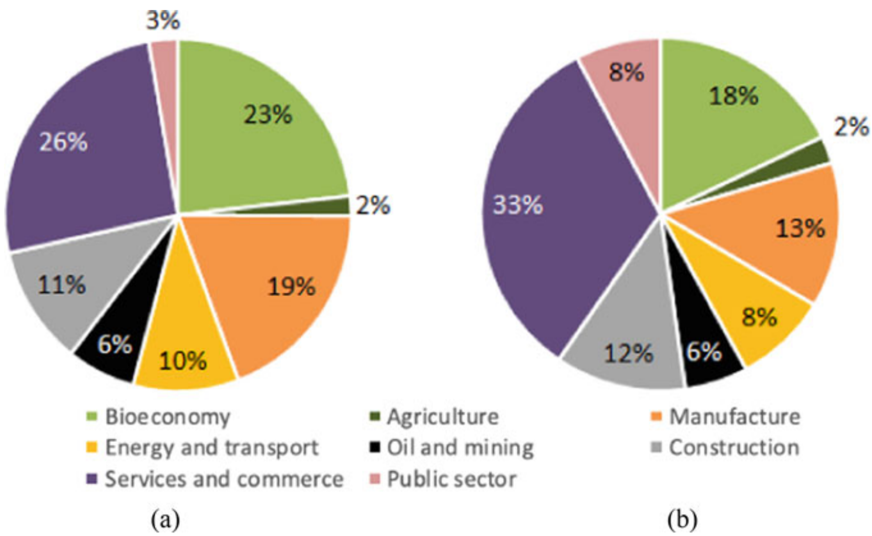

Fig. 3.4 Contribution to intermediate consumption (values at consumer price) (**a**) and total production (**b**) Source: Central Bank of Ecuador (BCE) (2017a, b)

Regarding total production, the services sector has contributed the most (US $55,922 million) followed by the bioeconomy (US$30,452 million); the latter is even larger than the manufacturing and construction sectors, as displayed in Fig. 3.4b. Consequently, the bioeconomy has room for growth in the production of goods and services. Once the labour and production aspects are exposed, we will expand the contribution of the bioeconomy in the generation of gross added value in society, i.e., the generation of wealth, as well as its contribution in taxes for the Ecuadorian state.

3.6.3 Growth and Taxes

Conceptually, the added value is composed of the sum of capital and labour remunerations. In 2017, the Ecuador generated US$97,082 million in gross added value contributions, considering all sectors in the economy. As may be expected, Fig. 3.5a shows that the services sector was the main contributor (38%), followed by the bioeconomy (14%). Of the US$13.279 billion in added value linked to the bioeconomy, it is worth noting that there is an equitable participation between the primary (bioagriculture) and secondary sectors (mostly crop and animal-related bioindustry and biomanufacture). Since there is low remuneration for the labour factor in the primary sector of the bioeconomy, this large contribution to the gross value added would be explained by a higher return to the capital factor in this same sector.

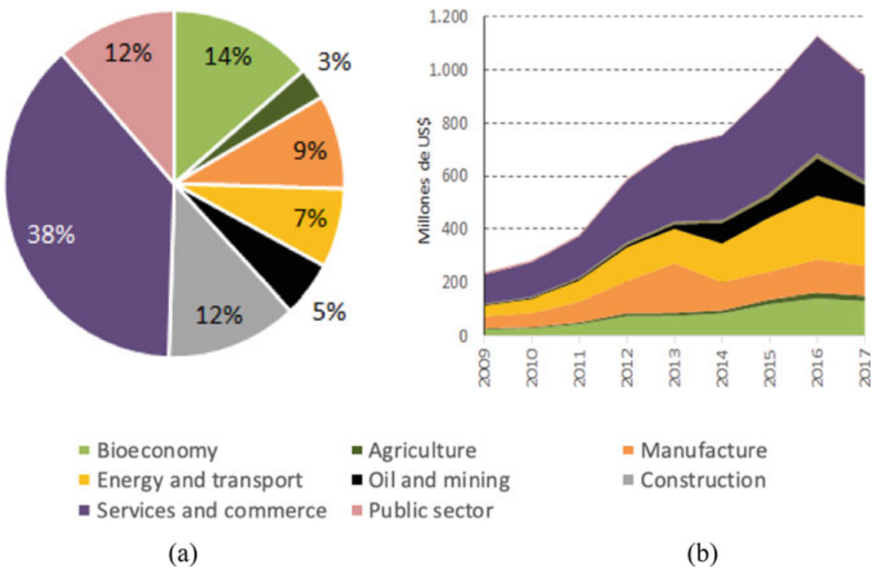

Fig. 3.5 Contribution to gross added value (**a**) and taxes on production (**b**) Source: Central Bank of Ecuador (BCE) (2017a, b)

Note in Fig. 3.5b that the services sector, the sector with highest production and consumption levels, is consequently the sector that contributes to taxes the most. Note also that, since 2013, the oil and mining sector significantly increased their tax generation, reaching a participation of 8% in 2017, compared to 1.4% in 2009. The sectors related to the bioeconomy have maintained a rather stable participation in the generation of taxes, with an average participation of 12.22%. In 2017, the bioeconomy generated US$132 million in taxes, which is more than the contribution of the industrial manufacturing sector but less than that of energy and transport. Thus, there seem to be opportunities to increase the participation of bioenergy at the expense of traditional energy sources that are mainly consumed in the transportation sector.

3.7 Insights for Assessing the Contribution of the Bioeconomy in Ecuador in a Future Scenario

To identify feasible possibilities of expansion of the bioeconomy, this section presents settings in the Ecuadorian context that offer a large potential for its development, considering it an opportunity for productive transition, given an unfavorable oil production horizon and significant fossil fuel energy consumption (Espinoza et al. 2019; Verdezoto et al. 2019). These settings are an estimation of the potential for improvement of agricultural and livestock activities in terms of yield per area of arable land used; estimation of the potential for the use of fertilizers, herbicides, and pesticides of biological origin; estimation of an industrial and energy development based on biomass; an estimation of the economic potential of the expansion of biological wastewater treatment; and configuration of the IOM to evaluate the future contribution of the bioeconomy. The methodologies to be used for each of the above items are described below.

3.7.1 Potential for the Improvement of Agricultural and Livestock Activities in Terms of Yield per Area of Arable Land Used

This contribution is calculated by estimating production yields per hectare of the main agricultural and livestock products. For this purpose, the environmental statistics available on INEC's "VDatos" platform[2] could be used. The results would be compared with yield data reported in countries of the region and other continents with similar climatic and biodiversity conditions. The calculation strategy shall seek not only to increase current crop and livestock production but also to improve land use that reduces the expansion of the agricultural frontier and the consequent degradation of native ecosystems.

[2]Available at: https://www.ecuadorencifras.gob.ec/vdatos/

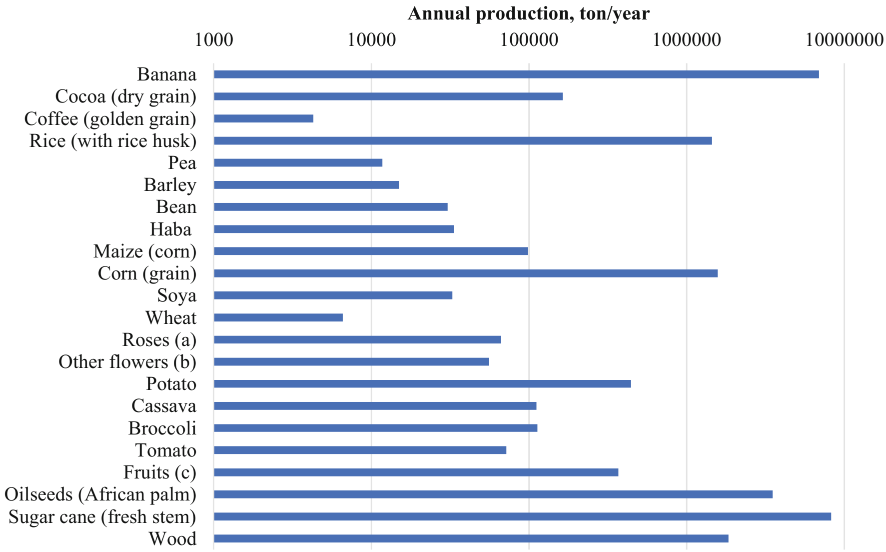

Fig. 3.6 Potential sources of biomass in Ecuador today. (*a*) It is assumed that the rose together with the stem weighs 25 g. (*b*) The reported number of stems produced is assumed to be the same weight as a rose stem. (*c*) Mango, passion fruit, orange, and tree tomato

3.7.2 Potential for the Use of Organic Fertilizers, Herbicides, and Pesticides

Until 2016, 9% of total fertilizers, herbicides, and pesticides used in Ecuador were of organic origin. Taking this percentage as a basis, it is important to review the impact of the expansion of the production of organic inputs for agriculture and the displacement of products of chemical origin and fossil materials. The limitations of organic products in terms of waste generation and product yields per hectare should be taken into account.

3.7.3 Estimating Biomass-Based Manufacturing and Energy Development

Considering that one of the main raw materials of the bioeconomy is biomass, Fig. 3.6 shows the mass weight of the primary economic sectors in Ecuador. Most of the data on the mass size of bioeconomic productive activities in Table 3.1 were obtained from the INEC (2014) and from INEC environmental statistics.

The production of bananas, rice, corn grains, African palm, sugarcane, and wood is the main primary productive activity that can become abundant sources of biomass. Among the secondary economic activities, shrimp, coffee, cocoa, and sugarcane processing are considered potential sources of biomass due to their

Table 3.7 Biomass available from waste in Ecuador

Available biomass	Ton/a (/1000)	Waste in kg/product in kg
Primary sector		
Rice straw	210.0	1.45[1]
Rice crust	289.7	0.07[1]
Banana stalk	1032.1	0.13[2]
Maize stubble	463.1	2.94[3]
Unspecified lignocellulosic waste	3642.9	2.44[4]
Secondary sector		
Shrimp shells	222.6[a]	0.44[5]
Cane bagasse	3301.0	0.40[6]
Coffee processing residues		
Barks	0.2	0.12[b 7]
Pulp	0.6	0.29[b 7]
Silver skin	0.1	0.05[b 7]
Spent grain	1.0	0.54[b]
Cocoa processing residues		
Bark	11.5	0.07[8]
Wasted grain	10.9	0.066[8]
Mucilage	11.4	0.07[9]
Noneconomic sector		
Municipal waste[c]	2607.1	0.717 (INEC)

[a]Shrimp export volume was obtained from the National Chamber of Aquaculture of Ecuador (http://www.cna-ecuador.com/estadisticas/)
[b]Calculation made considering that fresh grain (INEC data) has 55% humidity (Blinová et al. 2017)
[c]Cardboard, paper, organic waste, and wood were taken into account
[1]Moraes et al. (2014); [2]Pazmiño-Hernandez et al. (2017); [3]Muñoz-Tlahuiz et al. (2013); [4]Rodrigues Lima et al. (2005); [5]Khan et al. (2014); [6]Tyagi et al. (2019); [7]Blinová et al. (2017); [8]Akinnuli et al. (2014); [9]Balladares et al. (2016)

production volumes and relative geographic concentration. Table 3.7 presents the estimation of the amount of biomass available as waste.

The wastes considered as potential sources of biomass are 10% of all lignocellulosic material (plants, leaves, and roots) left after a harvest of transitional crops, i.e., cereals, tubers, and vegetables. Normally this material is left in the fields for soil nutrition (Lal, 2009), so its use is proposed at 10% only. This percentage could vary considering the possible expansion of the use of organic fertilizers whose contribution in trace minerals is significant. The items determined by this calculation are straw, stubble, and unspecified lignocellulosic wastes that bind all the other minor products listed in Fig. 3.4. The economic potential of using these lignocellulosic materials for the production of a range of products such as nutritional supplements, edible fungi, chemicals, fibres, biomaterials for construction and biomedical applications, polyphenols, bioactive substances, energy production, among others, will be studied (Cheali et al. 2015; IICA 2019; Lal 2009).

The secondary production sector can provide biomass in the form of waste from the processing of sugarcane, shrimp, coffee, and cocoa. Sugarcane bagasse has received attention as a raw material in the production of ethanol and other high value-added products such as xylitol, enzymes, organic acids, microbial protein, hydrocarbons, and furfural, among others (Nisticò 2017; Restrepo-Serna et al. 2018). Since bagasse is currently used as fuel by Ecuadorian sugar mills, the use of its ashes in the formulation of cements could also be considered due to its high silica content.

Residues from shrimp processing are considered to be important sources of calcium carbonate and chitin. Chitin is a long-chain sugar that can be used for the production of pharmaceuticals derived from chitosan and glucosamine, valuable monomers for the biopolymer industry (Oddoye et al. 2013). Coffee husks can be used as a source of bioactive substances, in the production of biogas and bioabsorbents for the removal of cyanide, heavy metals, dyes, lead, and fluorine in water treatment. Coffee pulp also has significant amounts of tannins, polyphenols, and caffeine. Silver skin is a potential source of antioxidants and can be used in functional food formulations (Blinová et al. 2017). From the residues of cocoa processing, mucilage is considered a raw material for the production of beverages, pectin, and as a source of sugars for fermentation. The shell, on the other hand, can be used for energy production and its ashes in the manufacture of soil fertilizers or soaps because of their high potassium and potassium soda content (Balladares et al. 2016; Kaviedez Hernández and Loyola 2014).

The proposal to use these wastes is based on the relative geographical concentration and high volumes of processing, such that their large-scale industrialization will not be limited by supply chain costs.

3.7.4 Estimation of the Economic Potential of Water Treatment Expansion

Water pollution has major effects not only on public health but also on a range of economic activities that depend on clean water. Public health is affected on two fronts: by the direct consumption of contaminated water and by the consumption of food products that were exposed to contaminated water during their production. Economic activities that are limited by the existence of contaminated water sources are tourism, commercial fishing and aquatic animal farming, and recreational businesses, among others. The fact that modern water treatment plants use biologically active sludge as a technological basis means that this sector can be explored as part of the bioeconomy.

The assessment of the economic potential of the expansion of the wastewater treatment sector will be based on the sum of potential reductions in the economic impact on people's health, the expansion of tourism and recreation businesses related to water sources that are currently biologically contaminated, and the expansion of the commercial fishing industry using currently polluted freshwater sources.

This calculation should be based on the estimated flow of contaminated water sources in Ecuador. For this purpose, it is proposed to use the ratio between the monitoring points of the National Institute of Meteorology and Hydrology (INAMHI, by its Spanish acronym) where the concentration of fecal coliforms exceeds 1000 MPN/100 mL, and the total number of monitoring points. This limit is one of the criteria for defining suitable water for crop irrigation according to the Unified Text of Secondary Environmental Legislation (TULSMA, by its Spanish acronym). According to the most recent data available (2013), in 231 of 503 stations in total the concentration of fecal coliforms exceeded the limit, i.e., in 46% of the points. To put this percentage into perspective, it can be considered that according to Ecuador's National Water Secretariat (SENAGUA, by its Spanish acronym), 70% of water sources below 2800 m (above sea level) have a considerable level of pollution.

3.7.5 Structure of the Input–Output Model to Assess the Future Contribution of the Bioeconomy

For the structure of the alternative scenario, one in which the bioeconomy has a greater participation in the social and productive structure, we propose the use of the IOM with base year 2017. For this purpose, we rely on the criteria presented previously. Two alternatives have been identified to address the objective.

The first consists in varying the technological-productive parameters in the primary and secondary sectors of the Ecuadorian economy, assuming that the implementation of the bioeconomy will bring about structural changes in society as depicted in Fig. 3.7a. It should be noted that this premise would imply significant investments by either the state or the private sector, in addition to the availability of

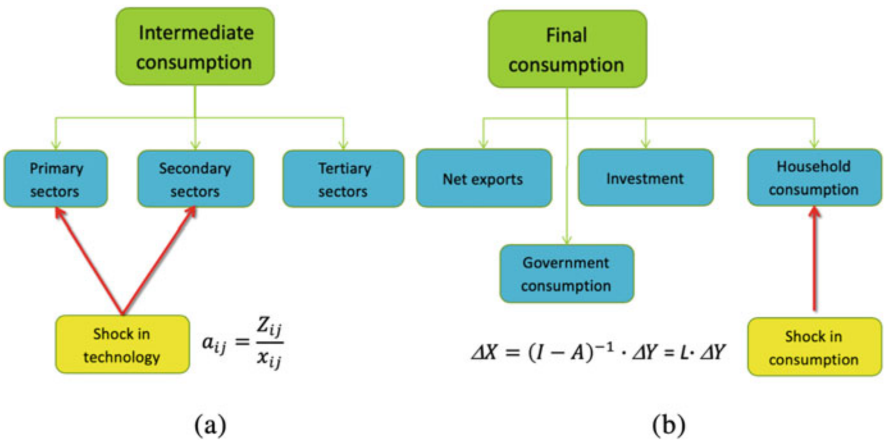

Fig. 3.7 Input–output model structure considering a shock in technology (**a**) and a shock in consumption (**b**)

raw materials, infrastructure, and qualified professionals in the prioritized areas. Undoubtedly, the above-mentioned aspects are difficult to access in the short term.

As a second alternative, variations in the final consumption of goods and services are proposed, focusing mainly on household consumption as shown in Fig. 3.7b. This premise consists in consumers preferring goods and services based on the bioeconomy, displacing the preferences for traditional goods of fossil origin or more polluting technologies. Notice that variations in final consumption do not consider variations in exports, reflecting the importance of oil exports, since the economy is still very sensitive to variations in this sector. It bares mentioning that variations of consumption would assume the existence of incentives to consumers, which can be channeled through tax incentives to sectors based on the bioeconomy or market regulation for traditional products, i.e., structured approaches in a public policy aiming for the development of the bioeconomy in the country.

3.8 Conclusion

The international scientific community acknowledges Ecuador's biodiversity as a competitive advantage whose potential is still not fully comprehended locally. Despite the institutional and academic local interest in the bioeconomy as a means for a transition of the productive matrix, the discussion is still lacking studies that quantify the sector or its potential. We hope that the present work nourishes the topic by assessing the current contribution of the bioeconomy sector to the Ecuadorian GDP. We evaluate the available methodologies for this exercise considering five criteria. Based on a comparison of the models, the input–output matrix ranks best in terms of comparability and external validity. The contribution of the bioeconomy sector in Ecuador was then calculated in terms of employment, total wage bill, consumption, production, gross added value, and taxes on production. In almost all aspects, except for total wage bill and taxes on production, the contribution share of the bioeconomy sector ranks second. The methodology proposed gives room for the measurement of the impacts of bioeconomic measures in developing economies.

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4 Biobutanol Production from Agricultural Biomass

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Abstract

Biobutanol, an alcoholic biofuel with 4-carbon atoms is one of the potential biofuels to replace petrol fuel. Biobutanol has higher density, higher energy content, and less corrosive as compared to bioethanol. Biobutanol also has similar characteristic as gasoline, therefore, it can be distributed in the current storage and pipeline system and used in a car's engine without any modifications. Biobutanol can be produced through fermentation process by commonly used microorganism, *Clostridium* sp. This species can consume both hexose and pentose sugars that can be derived from agricultural biomass. Agricultural biomass is considered as the most abundant material that can be continuously supplied as substrate for fermentation. This material is composed of cellulose and hemicellulose as polysaccharide building blocks made of sugar and protected by the lignin made of various types of phenolic components. The arrangement of these components in plant cell wall makes the plant material difficult to be degraded. Therefore, various technologies have been developed in order to utilize agricultural biomass as substrate for fermentation. In this chapter, how agricultural biomass is converted into biobutanol will be presented and discussed. The processes involved include preparation of the substrate and medium formulation, microorganism and inoculum preparation, fermentation operation, and the recovery process.

Keywords

Agricultural biomass · Biobutanol · ABE fermentation

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4.1 Introduction

Human population shows an increasing trend and it is projected to increase to 8.6 billion in 2030 (United Nations 2017). The increasing numbers of the human population had caused a high demand for energy especially for transportation and industrial activities. For more than two centuries after petroleum was found, now it supplies 90% of world energy (Chew and Bhatia 2008). Unfortunately, the petroleum is non-renewable resource and utilization of petroleum had caused the negative consequences to the environment including direct impact to the global warming due to the release of greenhouse gases. Besides, due to its unrenewable resource, the world also faces the insecure energy source due to the depletion of fossil fuels reserves (Adams et al. 2013). Therefore, the alternative energy is highlighted in these few decades, as scientific community is continuously reporting and exploring the possible alternative energy source to overcome this major problem.

"Biobutanol, a C4 compound, is construed as an alternative fuel of biological origin to gasoline due to its high energy density (29.2 MJ/L) and octane number of 87" (Shah and Venkatramanan 2019). Biobutanol is one of the promising alternative energy with the estimated fuel market around $247 billion by 2020 (Green 2011). As compared to other bioenergy, biobutanol has lower vapour pressure, less volatile and explosive, less hygroscopic, easily mixes with gasoline, and can be transported in existing pipeline (García et al. 2011). Apart from that, biobutanol can reduce hydrocarbon emissions by 95%; and oxides of nitrogen by 37% (Bellido et al. 2014). Interestingly biobutanol can be produced through acetone–butanol–ethanol (ABE) fermentation which has been produced for several decades after World War II. Recently, researchers are focusing on ABE fermentation using lignocellulosic biomass as substrate. The lignocellulosic biomass is cheap, abundant, and readily available that can be obtained from most agricultural and forestry industry. The utilization of lignocellulosic biomass will be feasible in the future as several studies reported positive aspects of using feedstocks such as whey permeate (Setlhaku et al. 2013), corn fibre (Guo et al. 2013), wood pulp (Lu et al. 2013), and other agricultural wastes for biobutanol production, besides reducing air pollution from burning of wastes.

4.2 Biobutanol

Biobutanol is an alcohol produced through acetone–butanol–ethanol (ABE) fermentation by *Clostridia* spp. The biobutanol properties depend on their four-carbon structure, either in linear or branched form. Biobutanol produced through fermentation is normally a straight-chained *n*-butanol, also known as 1-butanol, where the OH group attached to the terminal carbon (Mascal 2012). The other type of linear form of biobutanol is 2-butanol where the internal carbon is attached by hydroxyl group (−OH) (Fig. 4.1). Butanol with 4-carbon structure is more complex alcohol compared to methanol and ethanol that only has 1 and 2-carbon structure, respectively (Ranjan and Moholkar 2012).

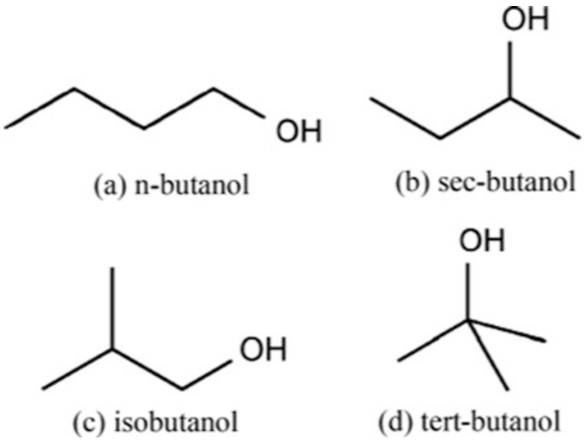

Fig. 4.1 Sturcture of butanol isomers

Butanol is a colourless and flammable four carbon chain alcohol. Besides being used as a fuel, butanol finds application as a solvent in detergent and cosmetic formulations and as a chemical intermediate. Butanol isomers have a different octane number, boiling point, and viscosity. All the butanol isomers can be generated from fossil fuels by applying the different methods; however, only *n*-butanol can be produced from biomass (Liu et al. 2013).

To date, the research on the substitution of fossil fuels are being undertaken very intensively. Recently, biobutanol have drawn attention of the most researchers' as it possess better properties as compared to other biofuels. Butanol has the capability to blend with gasoline very well. Apart from that, butanol can reduce hydrocarbon emissions by 95% and oxides of nitrogen by 37% (Bellido et al. 2014). Due to the properties such as high hydrophobicity, low vapour pressure, high energy density, and low heat of vaporization, biobutanol is regarded as a promising alternative fuel (Table 4.1). Biobutanol has higher energy content, less corrosive, and lower in flash point as compared to bioethanol (Prakash et al. 2016). These properties make biobutanol more suitable to be used in industry as there is no modifications needed for engines system. Furthermore, it can be a future option for blending with diesel since it contains more oxygen content compared with the biodiesel, leading to further reduction of soot (Cao et al. 2016).

4.3 Agricultural Biomass

Agricultural biomass is an organic matter derived from plant or animal that consists of stored energy obtained from the sunlight through the photosynthesis process. This energy is used to convert carbon dioxide and water into sugar and oxygen (Peterson and Hustrulid 1998). Furthermore, the stored energy contained carbon resource, which can be converted into many useful form of energy, for instance, heat and electrical energy which have made biomass as a renewable source for energy

Table 4.1 Properties of different types of fuel

Fuel	Octane number	Cetane number	Evaporation heat (MJ/kg)	Combustion energy (MJ/dm^3)	Flammability limits (%vol)	Saturation pressure (kPa) at 38 °C
Gasoline	80–99	0–10	0.36	32	0.6–0.8	31.01
Methanol	111	3	1.2	16	6–36.5	31.69
Ethanol	108	8	0.92	19.6	4.3–19	13.8
Butanol	96	25	0.43	29.2	1.4-11.2	2.27

Source: Liu et al. (2013)

production (Khan et al. 2015). Agricultural biomass includes food-based crops, nonfood-based crops, perennial grass, and animal waste.

Food-based crops provide food to mankind in a daily life. This type of crops produce either oil or simple sugar as a source (https://dnr.wi.gov/topic/ForestManagement/documents/WoodyBiomassToolkit.pdf). The food-based crops' biomass usually are rapeseed, sunflower, soybeans, corn, sugarcane, and sugar beets. The sugar that can be obtained from corn, sugar beets, and sugarcane are commonly fermented to produce bioethanol. Meanwhile, rapeseed, sunflower, and soybeans that have an oilseed usually are refined into biodiesel. However, bioenergy production from food-based crops or first generation feedstock has created a controversy and criticism due to its potential competition with food and animal feed (Dutta et al. 2014) This situation also resulted in a debate over the food versus fuel which subsequently diverted attention of the researcher over the world to find solution to this polemic.

Nonfood-based crops or second generation feedstock are non-edible for the human or animal consumption. The second generation feedstock includes lignocellulosic feedstock or waste materials from the food-based crops during the processing for food production (Cantrell et al. 2008; Havlik et al. 2011). The biomass includes wheat straw, barley, oil palm, oat straw, and nutshells. These waste materials or agricultural residue could cause a serious environmental problem due to the poor waste management. Therefore, utilization of this type of biomass into bioenergy can significantly reduce the environmental pollution and emission of greenhouse gases (Aditiya et al. 2016).

Perennial grass is the grass that has several years of life cycle and able to grow in diverge environments (https://dnr.wi.gov/topic/ForestManagement/documents/WoodyBiomassToolkit.pdf). They have been indicated as a leading feedstock for the bio-based economy for the production of variety of value-added products. This is due to their low demand on nutrient, wide-range of geographical growth, and high yield of net energy. There are various type of perennial grasses such as prairie cordgrass, switchgrass, and miscanthus. Since perennial grass is a lignocellulosic biomass, pretreatment is needed to break down the cellulose in order to use as a ferment for the biofuels productions (Sills and Gossett 2011). However, the research on breeding, agronomy, and postharvest logistics are needed to deliver the high quality of the products by maximizing the sources and efficiency of the bioconversion.

Animal waste in this context includes the manure produced from beef cattle, dairy cattle, hogs, and poultry. Manure generally can be categorized into three forms which are liquid, slurry, and solid (https://dnr.wi.gov/topic/ForestManagement/documents/WoodyBiomassToolkit.pdf). The solid manure can be burned to produce gas for energy production. Manure also can be converted into biogas, primarily methane by bacteria. This waste conversion into energy basically involves an anaerobic condition by using the anaerobic digesters (Amon et al. 2006).

4.3.1 Availability of Biomass

Recently, biomass has received an utmost interest and attention as an alternative energy source for the conventional fossil fuels due to the growing of exhaustion of fossil fuels and energy demand worldwide. As biomass has been widely seen as an effective substitute for the conventional fossil fuels, the assessment on the resource and its availability need to be performed (Sudha and Ravindranath 1999). This is to ensure the sustainability of present consumption patterns and feasibility on introducing the applications of a modern biomass fuel-based on a global level.

The global land area is about 13.2 billion ha and currently, about 12% of global area is under the cultivation of agricultural crops, 28% under forest, and 35% under grasslands and woodland ecosystems. Huge quantities of agricultural wastes are generated from the agricultural and forestry related activities. With the abundant bioenergy resources, it is crucial to implement the latest waste-to-energy technologies to tap the potential biomass resources (Zafar 2019). Asia is a key supplier of biomass feedstocks to markets such as Europe or the United States of America. Particularly, Southeast Asia with its huge biomass resources holds a strategic position in the global biomass energy atlas (Tun et al. 2019).

Rice and wheat are predominant crops in Southeast Asia (Carlos and Khang 2008). In Southeast Asia, Malaysia is blessed with the large palm oil cultivation. Malaysia is the world's leading exporter of palm oil. More than 19.9 million tonnes of palm oil has been exported in year 2017 (Nambiappan et al. 2018). However, huge waste were generated during the extraction of the palm oil from the palm fruit bunch. Out of palm oil processing yield, only 10% are finished products, while the remaining 90% are harvestable biomass waste in the form of palm kernel shells, empty fruit bunches, and mesocarp fibres. Production of oil palm is about 17.32 million tonnes per year which subsequently has generated up to 100 million tonnes of waste (MPOB 2017). Mostly, these biomass are left on the field to act as a soil amendment or organic fertilizer which plays a crucial role to ensure the sustainability of plantations and preserve soil fertility. However, due to the abundant of these waste, it could lead to the environmental pollution if not fully utilized.

Sago palm is also widely distributed and scattered in Southeast Asia specifically Malaysia, Indonesia, and Philippines. In the recent past, sago flour started to become one of the main agricultural export item (Karim et al. 2008). The export value of sago was reportedly increasing by 15–20% per year (Department of Agriculture Sarawak 2010). High production of sago products will significantly increase the amount of waste generated from this industry, which may lead to a large proportion of environmental issues.

4.3.2 Chemical Composition of Biomass

Starch-based biomass is made up of glycan, macromolecules of glucose and held together by α-1,4 and α-1,6 glycosidic bonds (Alias 2009). At the end of the polysaccharide chain, there is a presence of latent aldehyde group. It is important

Table 4.2 Various biomass with their constituents

Biomass	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
Sago pith residue	37.0	20.0	6.0	Linggang et al. (2013)
Oil palm fibre	40.0	39.0	21.0	Hassan et al. (2010)
Wheat straw	27.1	21.1	22.5	Adapa et al. (2011)
Sugarcane bagasse	41.6	25.1	20.3	Kim and Day (2011)

to degrade the chain of this carbohydrate polymer into sugar monomers via microbial action. Starch is made up of amylose and amylopectin polysaccharides that are assembled from glucose unit (Madihah et al. 2001). Their relative amount/ratio of amylose and amylopectin varies with biomass type and source of starch.

Amylose is made up of a long linear polymer consisting of more than a few thousands of glucose units through an α-1,4 glycosidic bond (de Souza and de Magalhaes 2010). Amylose contributes to the helical shape of starch polymer (Minteer 2011). Their content in starch is commonly between 14 and 27%. Amylose with roughly around 4000 to 340,000 in molecular weight has a hydrophobic inner surface that acts similarly to the cyclodextrins and able to withstand spiral molecules of water (Singhal et al. 2008). This is due to the substitution by aromatic molecules or hydrophobic lipid. Amylopectin appears like a root-like structure as it possesses α-1,4 linked linear chain consisting of 10–60 glucose units and α-1,6 linked side chains with 15–45 glucose units. Amylopectin consists of two chains, namely A-chain and B-chains. The A-chain is generally made of 13–23 residues while B-chain are composed of 235 residues (Bertoft et al. 2008). There are two fractions that exist in B-chain which are short and long chains.

Lignocellulosic-based biomass is a plant-based material and its component consists of three basic structures specifically cellulose, hemicellulose, and lignin (Balat et al. 2008; Ibrahim et al. 2017). This type of biomass includes wood and fibrous materials from agricultural wastes, organic sources, organic municipal wastes, and organic industrial wastes. Recently, this class of biomass have been abundantly produced by the agricultural industries, which has led to serious environmental problems. In order to overcome this problem, lignocellulosic biomass has been used as a substrate for biofuel production and to date, it has been recognized as one of the valuable source. In average, lignocellulosic biomass is composed of 38–50% of cellulose, 23–32% hemicellulose, and 15–25% of lignin (Abd-aziz 2002). The content between cellulose, hemicellulose, and lignin varies between one plant species to another dependent on age and soil (Table 4.2).

Cellulose is made up of long, linear homopolymers of β-1,4 linked D-glucose units and forms a crystalline amorphous structure. The rigid cellulose structure which requires harsh treatment to break down, is caused by the bonded hexoses by β-1,4 glycosidic bond in linear arrangement (Balat 2011; Saini et al. 2015). Cellulose can be found in the cell wall of plants, particularly in the stalks, stems, and in all the woody parts of plant body. The high tensile strength and solvent insoluble properties are provided by this structure (Sjöström and Westermark 1999). The build-up of plant cell wall is determined by the regular arrangement of microfibrils of cellulose (Chen et al. 2007). Hemicellulose that linked together with hydrogen bonds covers the adjacent spaces between the elementary fibrils (Ali et al. 2015; Saini et al. 2015).

Hemicellulose consists of different monosaccharide units compared to cellulose. Hemicellulose commonly possesses arabinose (five carbon sugar), xylans (five carbon sugar), and uronic acid, for instance, sugar acid (Jenol et al. 2014). They are heteropolymers consisting of linear and branched structure arrangement of pentoses, hexoses, and sugar acids (Peng et al. 2012). Amorphous morphology of hemicellulose made it partly soluble in water (Demirbas 2008). In terms of molecular weight, hemicellulose is lighter compared to cellulose and since it is composed of short lateral chain, it is easy to hydrolyse. Several components that act as inhibitors like furfurals and hydroxymethyl furfurals in the fermentation process might be produced during the degradation of hemicellulose. Hence, hemicellulose should be removed at least 50% in order to increase the degree of digestibility of cellulose.

Lignin is the most complex compound in lignocelluloses, which provides a structural support to the plant. Lignin tied the long molecular chains of sugars of cellulose and hemicellulose together to make sturdy and strong cell walls (Hüttermann et al. 2001). The tight association between lignin and different polysaccharides has conferred the mechanical strength to the cell wall. It also protects the cellulose and prevents the fibre to swell when reacting with water and acts as protective shield against microbial and enzymatic attacks. Therefore, the conversion of the cellulose into sugar is extremely slow. Lignin is bound to both cellulose and hemicellulose by the α-ether linkages, acetal bonds, phenyl glycosidic bonds, and ester bonds in the matrices (Ali et al. 2015).

There are many types of natural enzymes that can be utilized to depolymerize starch into glucose and maltose such as α-amylase and glucoamylase. Endoenzyme or α-amylase is used to hydrolyse α-1,4 glycosidic bond while exoenzyme or glucoamylase is used for hydrolysis of both α-1,4 glycosidic bond and α-1,6 glycosidic bonds. Each type of enzymes may give a different rate of hydrolysis. For example, rate of hydrolysis of α-1,4 glycosidic bond using glucoamylase is 20 times faster compared to hydrolysis of α-1,6 glycosidic bond. However, the rate of reaction are also affected by other factors like pH of solution, starch granules structure, temperature, and chemical composition of the starch itself (Murthy et al. 2011).

Commonly, the starch conversion is conducted at a first stage called liquefaction, where starch is hydrolysed by α-amylase to form a shorter chain of dextrin. The viscosity of starch will be reduced during this step. Then, in the second step, the maltodextrins are further hydrolysed by glucoamylase in order to release glucose together with a small amount of disaccharides or trisaccharides. In most practices, glucose produced then can be used as a feedstock in fermentation for biofuel productions and other applications (Husin et al. 2018).

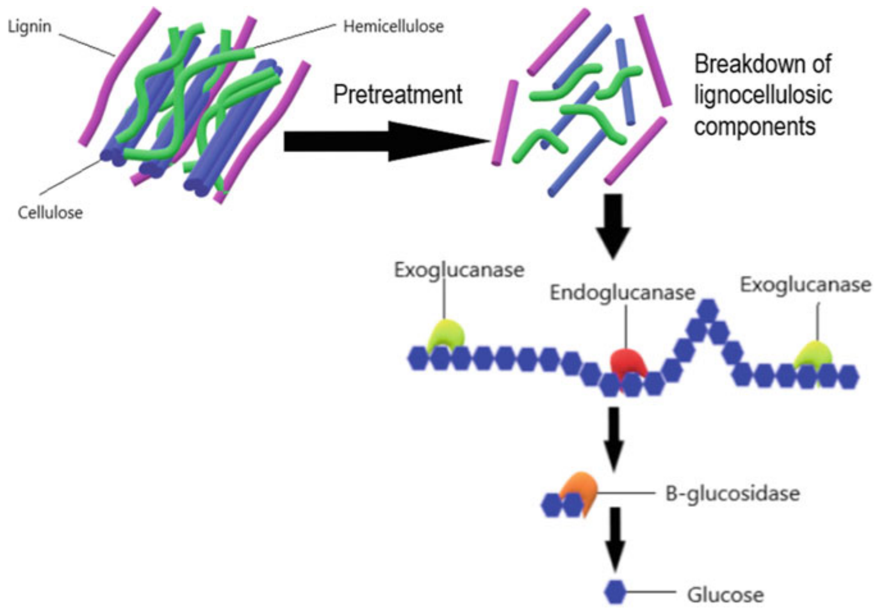

Fig. 4.2 Cellullose breakdown by cellulase enzyme

The lignocellulosic component degradation is usually performed by cellulase that is highly specific catalyst (Taherzadeh and Karimi 2007). There are three components that have been identified in cellulase which are endoglucanase, exoglucanase, and β-galactosidase (Fig. 4.2) (Linggang et al. 2013). Synergistic action among these three components is responsible to produce fermentable sugars from cellulose. From these three enzymes, at first, endoglucanase is responsible to attack β-1,4 bonds randomly within the cellulose chain in order to initiate the cellulose breakdown and make it accessible for the attack of second enzyme which is exoglucanase. Exoglucanase then attacks on units from the free chain ends and hydrolyses β-glycosidic bond and making cellobiose as the core product (Linggang et al. 2013). The degradation activities were further accomplished with the role of β-galactosidase that lessens the inhibitory effect of cellobiose on cellulase activity by breaking the cellobiose into glucose units.

4.4 Biobutanol Production from Agricultural Biomass

4.4.1 Substrate Preparation

Increase in the cost of feedstock is an important challenge in biobutanol production. So underutilized and cheap raw materials like lignocellulosic biomass have been intensively studied so as to use it as feedstock for biobutanol production. However, it is important to choose the right substrate, for instance, their structural arrangement and chemical composition as it plays an important role in product yield (Ibrahim et al. 2017). Therefore, high lignin content is not preferred as it will take a long time in pretreatment process.

In the first step, the substrate that has a high lignin content should undergo the pretreatment. The pretreatment methods vary with the biomass used for biobutanol production. The often used pretreatments include sulphuric acid pretreatment, alkaline peroxide pretreatment, steam explosion pretreatment, hydrothermal pretreatment, and organic acid pretreatment. These pretreatments are needed to degrade the structure of lignin that holds the cellulose and hemicellulose components. After the pretreatment, the substrate can be easily hydrolysed into fermentable sugar and subsequently into biobutanol. Pretreatment can be categorized into three types which are physical, chemical, and biological.

Physical pretreatment commonly is conducted for the woody biomass in order to reduce the woody size before chemical or biological processing. Woody biomass typically is very energy-intensive as high energy consumptions are needed for milling the wood chips into fibres and approximately 500 to 800 Wh/kg are used (Schell and Harwood 1994; Zhu et al. 2009, 2010a). Therefore, in order to reduce energy consumption and to ensure viable commercial cellulosic bioenergy production from woody biomass, post-chemical pretreatment size reduction approach has been proposed (Zhu et al. 2010b).

Chemical pretreatment includes alkali, dilute acid, oxidizing agents, and organic solvents. Chemical pretreatment has become the most promising method to remove the lignin and/or hemicelluloses of biomass and subsequently decrease the degree of polymerization and crystallinity of the cellulosic components (Behera et al. 2014). Furthermore, some chemicals used do not produce toxic residues for the downstream processes although those chemicals have a significant effect on the genuine structure of lignocellulosic biomass when the process has been carried out at room temperature and pressure (Mtui 2009). However, concentrated acid is not favourable as it is corrosive and not feasible for the economic pretreatment.

Biological pretreatment has provided more eco-friendly and economically viable strategy for enhancement of enzymatic saccharification rate as this pretreatment uses metabolite of a microorganism in nature for the biofuel production (Sindhu et al. 2016). Currently, pretreatment using rot fungi seems promising as it consumes less energy and contributes less damage to the environment (Chen et al. 2010). In addition, as the pretreatment is conducted at mild condition, the by-product produced during the pretreatment do not inhibit the subsequent hydrolysis.

4.4.2 Medium Formulation

An optimum medium composition is essential for a high biobutanol production especially carbon and nitrogen. It was reported that the amount of carbon source particularly sugar should not exceed more than 160 g/L. The cells growth is inhibited if more than 80 g/L of sugar is supplied and the cells cannot grow in medium containing more than 160 g/L of sugar (Monot et al. 1982). However, low sugars supply which is less than 40 g/L could produce more acids than solvents and inhibit the cells after 48 h of fermentation (Ibrahim et al. 2015).

P2 synthetic medium (P2-Medium) (Monot et al. 1982) is widely used as basic fermentation medium for *Clostridia*. P2 synthetic medium consists of vitamin, mineral and buffer, sugar. This medium is important for cell growth, and solvent formation. Cell growth is dependent on the presence of Mg, Fe, and K in the medium. It was reported that, excess of ammonium acetate supplementation caused acidic fermentation (Monot et al. 1982). Apart from P2 medium, buffer also plays significant role in modulating the transition between the conversions of acids into solvents in acetone–butanol–ethanol fermentation. Ibrahim et al. (2015) reported higher solvent concentration of 2.93 g/L in the ABE fermentation with buffer using Clostridia as compared to the fermentation without buffer.

4.4.3 Microorganism and Inoculum Preparation

The selection of microorganisms for biobutanol production is important. The organisms must tolerate toxicity in solvents and concentration of end products. Commonly, *Clostridium* sp. are used for the fermentation process. *Clostridium* sp. is a group of obligate, Gram-positive, and endospore-forming anaerobes. There are lots of strains that are commonly used for the fermentation which include ATCC (American Type Culture Collection), DSM (German Collection of Microorganisms. Or Deutsche Sammlung Von Mikroorganismen), NCIMB (National Collections of Industrial & Marine Bactria Ltd.), and NRRL (Midwest Area National Center for Agriculture Utilization Research, US Department of Agriculture). Though the strains are different, it still share the similar metabolic pathway and end products.

4.4.4 ABE Fermentation

ABE fermentation was first discovered by Louis Pasteur. He is the first person that found bacteria producing biobutanol in 1861. Interestingly in 1916, *Clostridium acetobutylicum* was first isolated by Chaim Weizmann. He is recognized as the father of ABE fermentation, and able to ferment sugars into acetone, butanol, and ethanol. *Clostridium* sp. was identified as the best organism for ABE fermentation. Commercial ABE fermentation plant was built in 1918, in Terra Haute, Indiana. This project supplied butanol for a primary component of paint lacquers (Ezeji et al. 2004). However, during the 1960s, the petrochemical butanol produced seem unbeatable as a competitor of biologically derived butanol. After decades of the energy crisis, interest on ABE fermentation was renewed. However, nowadays China is the only country currently running on ABE fermentation at industrial scale (Dong et al. 2012).

ABE fermentation continuously gaining interest among researchers to produced biobutanol with high yield and can tolerate with biobutanol toxicity. ABE fermentation is also feasible and could be a promising process for the second generation

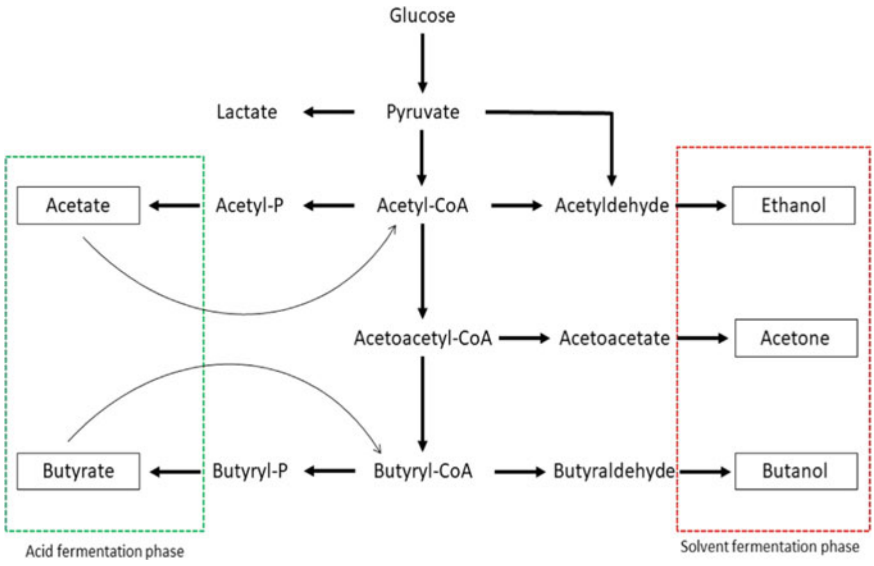

Fig. 4.3 Methabolic pathway of *Clostridium* spp. (Source: Lütke-Eversloh and Bahl 2011; Shinto et al. 2008)

biofuels that use lignocellulosic biomass substrate (Morone and Pandey 2014). Previously, the sources of carbon for ABE fermentation are sugarcane, corn, and cassava which has competing demands. Currently, researchers are interested to utilize agricultural lignocellulosic biomass as a substrate for the biofuel production including bioethanol and biobutanol.

ABE fermentation involves two important phases (Fig. 4.3). First phase is acidogenesis stage where acids (acetic acid, butyric acid) and gases (hydrogen, carbon dioxide) are formed usually during log phase of microbes. The next phase is solventogenesis, in which solvents are produced during stationary stages (Gheshlaghi et al. 2009). Acids then reassimilated for ABE production. In order to achieve high biobutanol production, the reassimilations of acids need to be successfully converted to solvents. The excess amount of acetic and butyric acid produced by *C. acetobutylicum* at its maximum growth rate causes the failure of transition from acidogenic to solventogenic phase (Schuster et al. 2001). Interestingly another study suggested that "acid crash" can be halted, by promoting the transition phase from acidogenesis to solventogenesis phase by adopting delayed yeast extract feeding (DYEF) (Li et al. 2012).

4.4.5 Recovery

The lower concentration of biobutanol in ABE fermentation is mainly because of inhibition of biobutanol towards the microbes, low biobutanol titer, sluggish fermentation. Integration of in situ recovery could help to increase the recovery of biobutanol from the fermentation process. Several in situ recovery techniques are suggested such as pervaporation (Li et al. 2014), gas stripping (Qureshi and Blaschek 2001), liquid–liquid extraction (Yen and Wang 2013), and adsorption (Luyben 2008). The low energy input and less capital investment for facilities could be another specialties of this techniques compared to other techniques (Xue et al. 2014). The best recovery technique in terms of high biobutanol recovery, cost-effectiveness, and capability to upscale into large scale processing is preferred. Besides in situ recovery enhances the overall fermentation process and is able to prolong the microbial growth and productivity. Separation of biobutanol from the production process should not remove other biobutanol precursor such as butyric acid, enzyme and others glucose, and media. Gas stripping has shown as a suitable candidate for the biobutanol recovery since only volatile compound was stripped out without interfering the fermentation process itself. In other words, the gas stripping is preferred as it selectively separates volatile substances and do not harm the cell,

Table 4.3 Comparison of biobutanol recovery techniques

Butanol recovery technique	Principle	Advantages	Limitations
Adsorption	Adherence of solvents to silicalite resin, clay, activated carbon, or other adsorptive materials	Easy to operate, low energy requirement	High adsorbent cost, low efficiency, low selectivity (will absorb any component), low adsorbent capacity (loading: ~0.1 g/g)
Gas stripping	Volatile solvents being stripped out by gases and then condensed	Easy to operate, no harm to the culture, no fouling	Require a high temperature or vacuum for sufficient volatility, low selectivity (separation factor: 6–20)
Liquid–liquid extraction	Using the solubility differences of solvents	High selectivity, efficient	Forming emulsion, toxic to the culture
Perstraction	Membrane-based extraction, separating the fermentation broth from the extractive solvents	High selectivity, low toxic to the culture compared to liquid–liquid extraction	Poor stability, membrane fouling, high cost
Pervaporation	Using membrane to selectively let the vaporous solvents pass through	High selectivity (separation factor: 5–100)	Membrane fouling, high cost

Source: Dhamole et al. (2012), Durre (1998), Gapes et al. (1996), Groot et al. (1992), and Qureshi et al. (2005)

and not strip out the nutrient. (Lu et al. 2012). The in situ recovery by gas stripping is integrated in fermentation system by removing the biobutanol and retaining the concentration of biobutanol under its maximum value in fermentation culture. The gas stripping is a promising technique due to its economic and operation simplicity. Besides, the study of gas stripping technique from small scale up to large scale can be carried out extensively. However the process to selectively recover biobutanol from ABE medium need to be carried out using two-stage gas stripping technique (Xue et al. 2013), which increased biobutanol production by two-fold. Further, the energy consumption for gas stripping process could be reduced by obtaining high recovery of biobutanol (Xue et al. 2013). Table 4.3 summarizes and compares the pros and cons of these alternative biobutanol recovery methods.

4.5 Conclusion

Agricultural biomass could provide a sustainable and economical way to produce biobutanol via biotechnology approach in order to overcome the limited fossil fuels reservoir that the world has been facing. However, the bioconversion of biomass into biofuels still faces many challenges that include limited yields of biobutanol due to the multiple by-products, the suitability of the biomass as feedstock, and cost of pretreatment. Therefore, research must be directed to decipher the fundamental processes of biobutanol production, enhance the productivity of metabolic pathway through genetic engineering of microorganisms, and reduce the cost of pretreatment of agricultural biomass.

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5 Valorization of Biowastes into Food, Fuels, and Chemicals: Towards Sustainable Environment, Economy, and Society

M. Iniya Kumar, S. Naveen, and A. Ramalakshmi

Abstract

The ever increasing global population, continuous dependence on fossil fuels for chemicals, fuels, feeds, and food substitutes, movement of population towards urban, and emergence of more urban cities, have created a shift towards more renewable technologies for sustainable development of environment, economy, and society. One of the renewable technologies which promotes sustainability is efficient waste management technologies. Existing waste management technologies such as open dumping, land filling, and incineration results in generation of more greenhouse gas emissions. The concept of circular economy against existing linear economy emphasizes, if the wastes are managed properly more resources can be extracted out if it, which not only contributes to sustainable economic development but also to environment and society in general. Wastes can be broadly classified into degradable (biowastes) and non-degradable waste, at present the per-capita generation of waste is 0.74 kg/day; as the population continues to rise the amount of wastes generated will double causing serious environmental, public, health, and socio-economic and political concerns. In order to be more sustainable, in the recent years global attention is focused towards valorization of biowastes into energy, food, feed, chemicals generation. This chapter deals with different types of wastes viz., biomass, food, industrial, animal, municipal solid wastes, their characteristics and scope for valorization into fuels, chemicals, and food.

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Keywords

Biowastes · Valorization · Fuels · Chemicals · Food · Circular economy · Environment · Sustainable development

5.1 Introduction

According to United Nations report, the global population will continue to rise in a steady state phase; it will reach 8.5 billion in 10 years from now and will be 9.7 billion in 30 years from now and around 80% of the mentioned population will live in cities (Wilson et al. 2016). As the population increases the demand for food, fuels, chemicals will increase simultaneously with consequent utilization of natural resource also increases tremendously. Besides these, the dependence of global population for their primary source of energy has not reduced significantly. The current balance of fossil fuels such as coal (3,789,934 ktoe), Natural Gas (3,106,799 ktoe), Nuclear (687,481 ktoe), and oil (4,449,499 ktoe) indicate its finite quantity and if the current rate of utilization continues, the remaining years for complete depletion of fossil fuels are 53 years for oil, 54 years for natural gas, and 110 years for coal (Ritchie and Roser 2020). The consumption rate far exceeds the production of fossil fuels. The transportation sector continued to be the highest consumer of total energy produced during 2017 (IEA 2019). This unprecedented utilization of fossil fuels has emitted more CO_2 adding to the global climate change (IEA 2019).

Besides these negative effects on the environment, the burgeoning population levels lead to generation of enormous quantity of wastes to the environment. Wastes are defined as unwanted and unsuitable materials or by-products. Depending on degradation nature, wastes can be classified into biodegradable and non-biodegradable. The most common and abundant waste of all, is Municipal Soil Waste (MSW). Worldwide, the total MSW generation for the year 2018 was 2.01 billion metric tonnes (Kaza et al. 2018). The USA was among the highest in terms of generation (267.8 million tonnes) followed by Europe (249 million tonnes) which was followed by China (215 million tonnes) during the year 2017 (Bhatia et al. 2018). It is predicted that by 2050, 3.40 billion metric tonnes of MSW alone would be generated (Kaza et al. 2018). Accumulation of waste seems to be on increasing trend, for instance, the most notorious plastic waste generation was over 8 million tonnes in the year 2017 and unfortunately most of them were dumped into sea (Xu et al. 2019). The most common methods of treatment of wastes are land fill, open dumping, and incineration with very less amount goes for recycling. Such management practices add more greenhouse gases (GHGs) to the environment, for example, 3% Methane was emitted by open dumping, land fill, and direct incineration of MSW in the year 2017 (Wilson et al. 2016).

Therefore, the world is confronted on one side with the explosion of population, the other side with increased waste generation due to increased consumption of fuels, chemical, food, and feed. Thus, the developed and developing countries think of

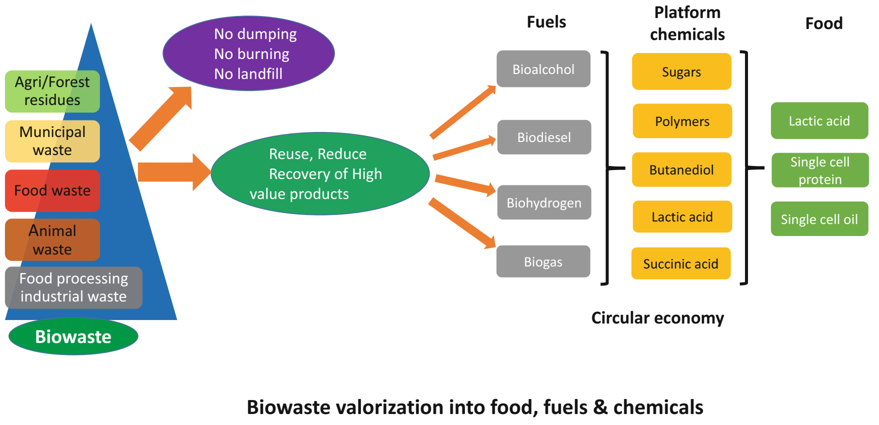

Fig. 5.1 Valorization of biowastes into fuels, chemicals, and food—an effort towards circular economy

management of waste in more sustainable way which would significantly contribute to economy, environment, and society. In the past decade, the concept of "circular economy" was introduced which describes maintaining the market value of the products, resources instead of disposing them as in the case of linear economy (Bos et al. 2017; Dahiya et al. 2018; Kaur et al. 2018; Maina et al. 2017; Vea et al. 2018). In other words the circular economy matches with green chemistry of bio-based product generation from wastes. Thus eliminating disposal of wastes, rather producing new products/recycling and reusing in more sustainable way. It is high time to develop new technologies to extract value added products from the biowastes. Hence, this chapter aims to review the biowastes valorization into chemicals, fuels, food, and feed additives. This chapter covers the various types of biowastes, ways to utilize them, products generated out of it, and their future scope (Fig. 5.1).

5.2 Biowastes

According to European Union definition, biodegradable garden and park waste, food and kitchen wastes, office waste, restaurant waste, whole sale waste, and food processing plant waste are included in the biowastes (Fava et al. 2015). However, increased evidence of literature suggest that agricultural wastes can be one of the main feedstock for the production of biofuel and chemicals. This chapter focusses on agricultural residues, food wastes, animal wastes, and industrial wastes for generation of chemicals, fuels, food as described in Fig. 5.2.

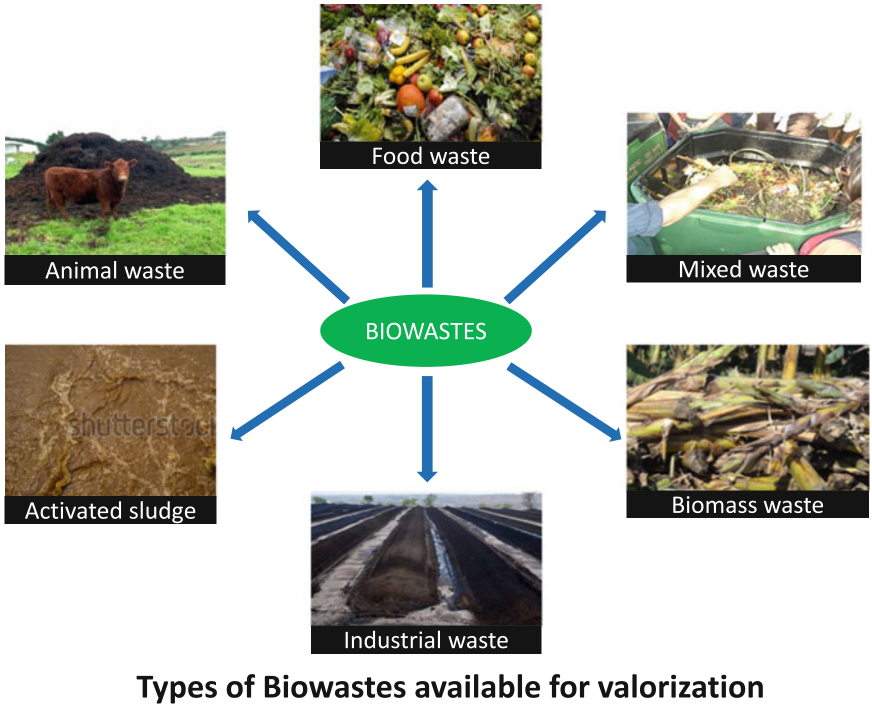

Fig. 5.2 Biowastes available for valorization

5.2.1 Valorization of Biomass into Fuels and High Value Added Products

Biomass constitutes largest resource of carbohydrates and lignin. Every year 2×10^{11} tonnes of biomass is generated worldwide (Appels and Dewil 2012). Among the biomass, the estimated global production of lignocellulosic biomass is about 181.5 billion tonnes per year (Narron et al. 2016). Due to increasing energy demand, environmental, geo-political factors of fossil fuels utilization, biomass as a renewable alternative was considered for production of different types of biofuels. Biomass can be divided into four types based on the origin.

- Biomass exclusively produced for fuel purposes. For example, sugar beet, corn, sugarcane, etc.
- Lignocellulosic biomass includes all agro-residues rich in carbohydrate for biofuel production.
- Organic fraction of municipal soil wastes rich in fuel properties
- Crop residues that include residues after harvest of crop (Fig. 5.3).

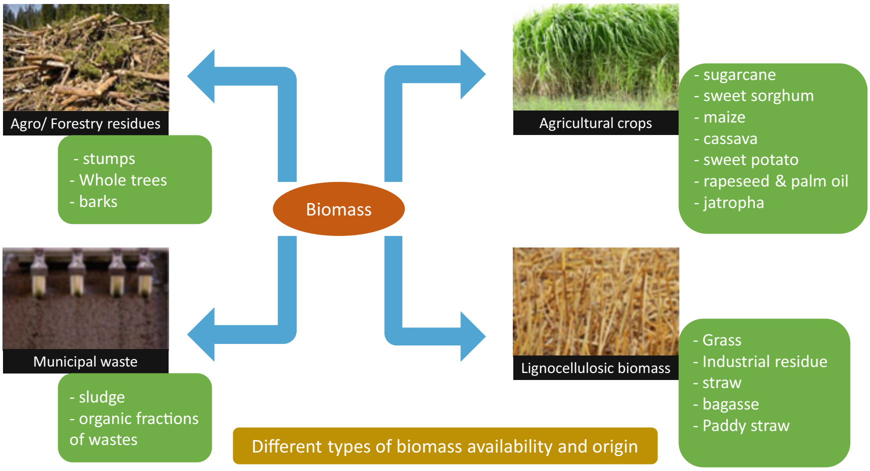

Fig. 5.3 Availability of biomass for valorization based on origin

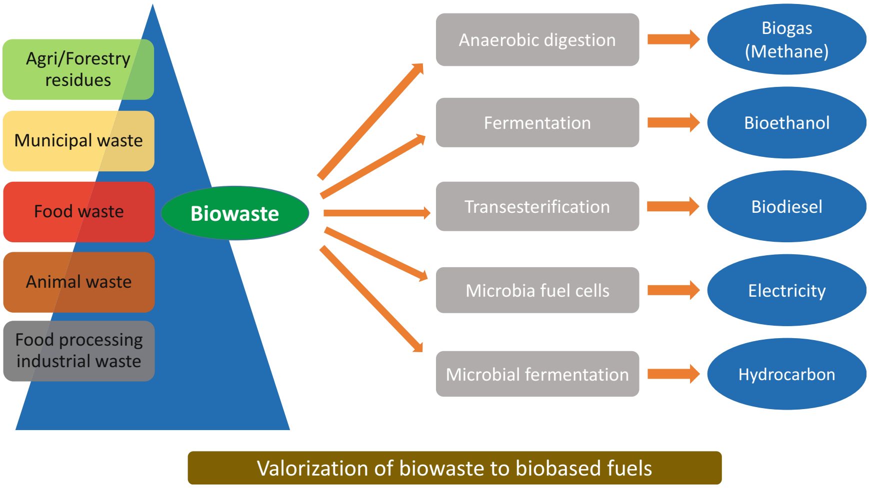

Fig. 5.4 Valorization of biomass into fuels

All of the different types of biomass can be used for generation of biofuels. The major pathways used for generation of biofuel from biomass is given in Fig. 5.4. For efficient conversion of biomass to biofuels initially it needs to undergo pretreatment to remove the recalcitrant molecule lignin and enable the sugars such as cellulose and hemicellulose to be fermented by microorganisms to produce biofuel (Narron et al. 2016).

5.2.1.1 Anaerobic Digestion of Biomass

The carbohydrates in the biomass using anaerobic digestion (AD) can be transformed into biogas which constitutes methane (60%) and CO_2 (40%). The AD technology, although known for many years, in recent times gained more attention. The home based AD has become more popular in developed and developing countries. In India, AD of biowastes has gained traction in different sectors namely as home based AD, community based AD, and large scale AD depending on the quantity and quality of waste generated in the region (Breitenmoser et al. 2019). Although AD generates energy out of biomass, this technology also generates digestate to be used as bio-fertilizers or soil enhancer. However, if the AD is to be completely operated throughout the sector from home to large scale units, it needs to accommodate more innovative ways such as co-digestion with other wastes, design and development of suitable reactor for individual sector, synergy between public, private, and industrial sectors (Bhatia et al. 2018).

5.2.1.2 Bioalcohol Production from Biomass

Among the different sectors of energy consumption worldwide, the major share (28%) goes to transportation sector which contributes to global warming. It is predicted that the global mobility will increase triple fold in the 2030; use of petroleum products will also likely to increase (Balan 2014; Fatih Demirbas et al. 2011). Many countries started producing biofuels from lignocellulosic biomass. Among the biomass, lignocellulosic biomass (LCB) is the most preferred option for generation of bioalcohol. The LCB contains 40–50% cellulose, 30–40% hemicellulose, and 20–30% lignin. Cellulose and hemicellulose are polysaccharides which mainly contain Beta 1, 4 linkages. Lignin the abundant aromatic polymer finely laced between cellulose and hemicellulose hindering many pretreatments and prevent accessible of hydrolytic enzymes (Manisha 2017). General bioalcohol production methods first remove lignin and depolymerize cellulose and hemicellulose into glucose and xylose units. After enzymatic hydrolysis, microorganisms convert the carbohydrates into bioalcohol. Lignin although not valorized is mostly burnt to generate electricity. However enormous value added products can also be generated from lignin (Narron et al. 2016).

5.2.1.3 Biodiesel Production from Biomass

Although bioalcohols were significantly produced, recently biodiesel production from biomass is gaining attention. Europe is the forerunner in biodiesel production worldwide. Biodiesel are lipids from oleaginous microorganisms. In nature, certain bacteria, fungi, yeast, and algae are capable of accumulating lipids in their biomass more than 70% of their dry weight under high carbon and low nitrogen conditions (Bhatia et al. 2018; Intasit et al. 2020). These lipids are similar to any vegetable oils in terms of their biodiesel properties. Use of microorganisms for lipid production although known for more than 100 years, due to its high cost they were not commercialized. Recently they are gaining momentum as the use of renewable biomass is available as a cheap source for biofuels. Biodiesel from oleaginous microorganisms has many advantages over plant oils, as they do not require huge land, time, labour, and no seasonal disturbances. Microbial biodiesel can be produced significantly under controlled conditions. Although several research efforts are still needed to commercialize this technology on larger scale. Biomass to biodiesel continues to be an important source of energy in the recent years (Dahiya et al. 2018).

5.2.1.4 Biohydrogen Production from Biomass

In the current wave of renewable energy generation out of wastes, anaerobic digestion, municipal solid waste, organic waste, agricultural waste, waste water, and sludge are considered as renewable source of biohydrogen production. Although the continuous production of biohydrogen has some disadvantages such as low H_2 yields, the technology can be improved by mixing photosynthetic microbes with anaerobes to degrade carbon rich and less toxic raw materials. Under anaerobic conditions, hydrogen production proceeds with photo fermentative as well as dark fermentation (Balan 2014). Biohydrogen production is an anerobic fermentation of organic substances. The most studied anaerobic bacteria *Clostridium butyricum* can serve as a candidate for biohydrogen production. The theoretical yields of hydrogen is 4 mol of H_2 per mole of glucose or 2 mol of H_2 per mole of acetate. In order to be competitive with other biofuels, the H_2 production should be enhanced by isolation and identification of novel microorganism with high titres, bioreactor designs, use of mixed culture, and more advanced phototrophic microorganism for higher yields (Venkata Mohan et al. 2016).

5.2.1.5 Bulk Chemicals from Biomass

As mentioned biomass constitutes a largest renewable resource for chemicals production. There has been renewed interest to produce fine chemicals and platform chemicals from biomass. Although the concept is promising, and high value added products can be generated, the industry must also think of producing bulk chemicals initially to sustain its production (Ahorsu et al. 2018; Appels and Dewil 2012; Balboa et al. 2015). The major limitation with fine chemicals is that they have very small market. On the other hand, chemicals such as surfactants, plastic monomers, lubricants, fibres, and industrial solvents serve as bulk chemicals with huge market potential. High value added fuels and chemicals currently replace 300 million gallons of petroleum per year. The market for high value chemicals is growing rapidly and will have a better future in contributing to economy of the nation (Biddy et al. 2016).

For the production of bulk and fine chemicals, focus must be paid to use the food processing waste. The residues left on the field although in enormous quantity, they may be preferred to be retained on the field, as they add more value to soil. On volume basis, rice husks and sugarcane bagasse are the two important processed residues from rice processing plant and sugar industry, respectively. These two high volume renewable sources are available for production of fuels and chemicals. Organic fraction of municipal solid waste is also another important source of biowastes that can be efficiently transformed into fuels and chemicals (Gallezot 2012).

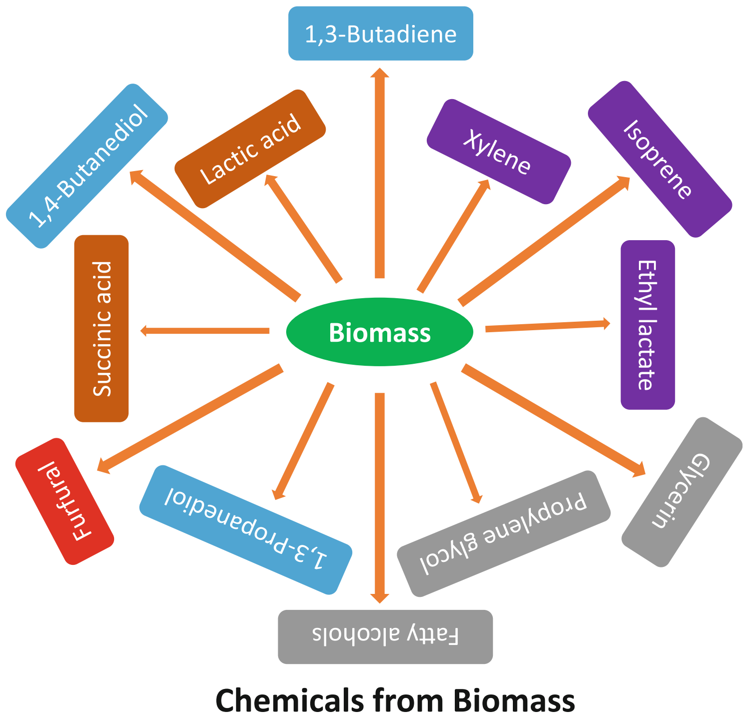

Fig. 5.5 Fine and platform chemicals production from biomass

Majority of industry focus on biofuels especially bioethanol from biomass. However, a high value compound ethylene is produced by dehydration of ethanol. Then ethylene could serve as platform chemical for production of multiple high value chemicals. Oxidized form of ethylene is ethylene oxide or ethylene glycol. The National Renewable Energy Laboratory (NREL) has released a list of bio-based chemicals with near-term market potential (Fig. 5.5) (Biddy et al. 2016). The chemicals mentioned in Fig. 5.5 can serve as building blocks for production of several other chemicals. Polybutadiene and styrene butadiene rubbers can be produced from 1,3-butadiene (BD). 1,4-butanediol (BDO) is a platform chemical from which polymers and solvents are synthesised. Surfactants are the products produced from fatty alcohols and are used as floor cleaners (Gallezot 2012; Rosales-Calderon and Arantes 2019). Furfural alcohol (FA) and product of furfural obtained via chemical condensation of hemicellulose are widely used in resin preparation. Glycerine, a well-known hygroscopic substance is used in variety of industries. Lactic acid, a fermented product of sugars by microorganisms can be used in many fine chemical transformations. 1,3-propanediol (PDO) has gained popularity in polymer industries and cosmetics industry. Similar to lactic acid, succinic acid has multiple product transformations with high market potential. Xylene, an important platform chemical serves as an integral part of polyethylene bottle manufacturing

Table 5.1 Industries involved in production of chemicals from biomass

S. no.	Company	Country	Product
1.	Braskem	Brazil	Polyethylene
2.	Genomatica	USA	1,4-Butanediol
3.	INVISTA	USA	2,3-Butanediol and butadiene
4.	LANZATECH	USA	2,3-Butanediol and butadiene
5.	International Furan Chemicals	Netherlands	Furfural
6.	Archer Daniels Midland	USA	Glycerol
7.	Amyris	USA	Bio-isoprene
8.	NatureWorks	USA	Lactic acid
9.	Cellulac	UK	Lactic acid

Source: Adapted from Biddy et al. (2016)

(Rosales-Calderon and Arantes 2019; Shahbazali 2013; Singhvi and Gokhale 2019) Several industries involved in production of fine and platform chemicals from biomass is described in (Table 5.1).

5.2.2 Valorization of Food Waste into Chemicals and Fuels

Management of food waste is another critical issue in both developed and developing nations. It is estimated that globally, about 30–40% of food is wasted during the supply chain (Dahiya et al. 2018). The trend in low income countries suggests that more food loss occurs at initial stages of supply chain due to improper infrastructure, lack of finance to maintain the supply chain. On the other hand, the food loss is found at the end of supply chain for high income nations. Together both high and low income nations contribute equally to food waste. It is estimated that about 1/3 of the world's food was lost or wasted per annum. It is not only the food that is wasted without consumption, but also loss of the resources that played a part in the food production. Further, food production also involves release of greenhouse gases emissions. Hence, food loss and waste is cause of concern. Global agenda on SDGs also focusses on this problem, as SDG 2 (Ending hunger) and SDG 12 (Responsible consumption and production) are connected to this problem. In fact the target 12.3 of the SDG "calls for halving per-capita global food waste at retail and consumer levels by 2030, as well as reducing food losses along the production and supply chains". Further, potential exists in the valorization of food waste into value added chemicals and fuels.

5.2.2.1 Existing Methods of Management of Food Wastes

Aerobic decomposition (compost production) and anaerobic digestion are currently followed worldwide to manage the food wastes. Both the technologies are operated in the mode of biodegradation of organic matter. Composting is aerobic degradation of food waste with the help of decomposing microorganisms to produce compost. Compost is excellent manure that adds nutrients to soil and enhances the water holding capacity of soil. Composting also has several limitations such as release of odour, NH_3, GHG, and leachate. While AD works well for biomass, waste water, sludge, industrial by-products, food waste to methane has several shortcomings. Due to high nutrient load in food waste, the methane yield gets reduced. Further, increased production of free fatty acids which are volatile in nature results in formation of foams. In some countries the digestate can be of excellent fertilizer to soil; however, it increases the nutrient content in soil. Hence, the demand for sustainable methods of valorization of food wastes are increasing from the past decade (Mirabella et al. 2014).

5.2.2.2 Fuels from Food Wastes

The rich nutrient content in food wastes makes them suitable feedstocks for generation of biofuels. In the past years enhanced research efforts have been oriented towards valorization of food waste into biofuels. Potential of food wastes in generating different biofuels are given in Fig. 5.6.

Anaerobic Fermentation

Anaerobic fermentation (AF) is the most popular method of food waste valorization towards generation of methane, volatile fatty acids, hydrogen, and other organic acids such as butyric acids, propionic, iso-butyric, valeric acids. However, the AF to be competitive over other platforms, use of mixed microbiome for utilization of different nutrients should be performed. Combining anerobic fermentation with bioelectrode systems to generate electricity from methane is one of the promising way of valorization. Anaerobic fermentation consumes all organic load for platform chemicals production and reduces the carbon foot print (Dahiya et al. 2018; Venkata Mohan et al. 2016).

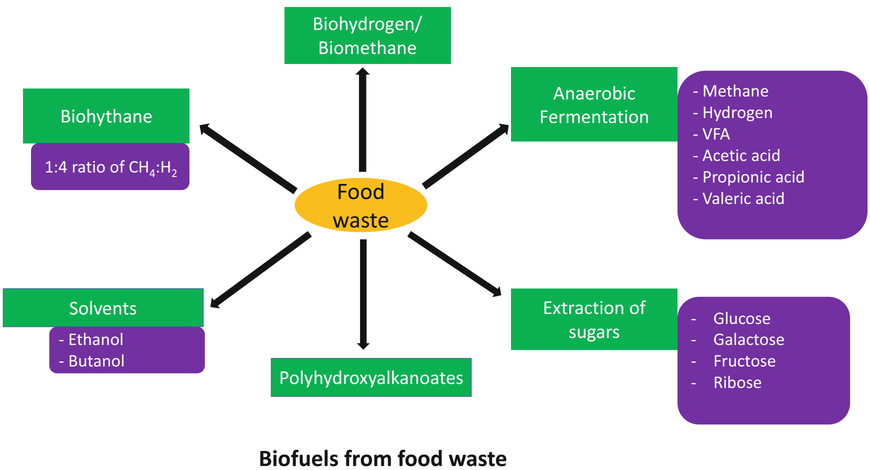

Fig. 5.6 Fuels production from food wastes

Extraction of Sugars from Food Wastes

Due to the rich organic content of food wastes, research has been directed at the possibilities of extraction of sugars from food wastes for production of fuels and chemicals. To extract sugars from food wastes, pretreatment step is necessary. Dilute acid pretreatment yields more sugars than other methods. Similarly, amylase enzyme digestion leads to production of glucose, fructose, galactose, and ribose. Such sugars can then be used to make platform chemicals, fuels, and food additives. It is worth noting that during any pretreatment either it be chemical, physical, or biological, product recovery should be maximum (Dahiya et al. 2018).

Biohydrogen

Highly degradable organic material content in food wastes makes it a potential candidate for biohydrogen production. Biological production of hydrogen involves photo-fermentation, biophotolysis, and anaerobic fermentation. Biohydrogen production using anaerobic fermentation is directly dependent on nature and property of microbial inoculum, type of treatment adopted, pH, inclusion of inducer, design of bioreactor, etc. In addition, integration of anaerobic fermentation with photo-fermentation to increase the yield is an additional option. Similarly fusing dark and photo-fermentation also increases the yield of hydrogen fermentation (Arancon et al. 2013; Maina et al. 2017; Mirabella et al. 2014).

Biomethane

The most preferred technology for energy generation from food wastes is methane production through anaerobic digestion. The major bottleneck while using food waste as a substrate is their rich nutrient content and foaming in the reactor. To overcome such shortcomings process should be optimized with better C/N ratio, newer reactor design, co-digestion with other wastes to improve methane yield (Bhatia et al. 2018; Jobard et al. 2017; Marin-Batista et al. 2019).

Biohythane

Biohythane is a combined fuel of methane and hydrogen prepared at 1:4 ratio to improve the calorific value of fuels. Such type of adding a small percentage of hydrogen with methane improves efficiency of methane fuels. Food wastes as a source of biohythane production has received attention and semi-pilot scale studies reveal that they are the good source for production of biohythane.

Volatile Fatty Acids

During the generation of H_2 production, a combination of short chain volatile fatty acids as co-products are generated under anaerobic fermentation. Currently these volatile fatty acids are produced from petroleum refinery and not benign to the environment. Hence volatile fatty acids generated from the anaerobic fermentation of food waste has got renewed interest. Production of volatile fatty acids has numerous advantages in textile, pharmaceutical, and food industries (Posmanik et al. 2017).

Bioethanol

Global demand for bioethanol has increased considerably. Currently biomass to biofuels route are most commercialized and many pilot and industrial plants are operated. Due to the increased demand, alternative feedstocks are explored simultaneously. It was observed that fermentation of food wastes at high solids content with a vacuum recovery system yielded higher amounts of bioethanol than the conventional fermentation (Huang et al. 2015). Thus food waste can also be a suitable substrate for bioethanol production as they do not require multi-step pretreatment processes for biofuel production.

Biodiesel Production

Biodiesel is a mixture of esterified fatty acid and is conventionally produced from non-edible and few edible oils, cooked oils, and fats from animal origin. However, their supply is very limited and cannot meet the increasing demand. There are microorganisms called oleaginous microorganisms that can accumulate lipid in their biomass. These oleaginous microorganisms have potential to convert food wastes into lipids. The lipids are trans-esterified with chloroform and methanol in the presence of KOH (potassium hydroxide) to form biodiesel.

5.2.2.3 Chemicals Production from Food Wastes

Food wastes are not only good candidates for biofuels production, owing to their nutrient content they are also good source for extraction and recovery of value added chemicals. An overview of chemicals generated from food waste is given in Fig. 5.7 (Dahiya et al. 2018; Mirabella et al. 2014). The three major wastes vegetable waste, dairy products, and meat industry wastes contribute to food wastes.

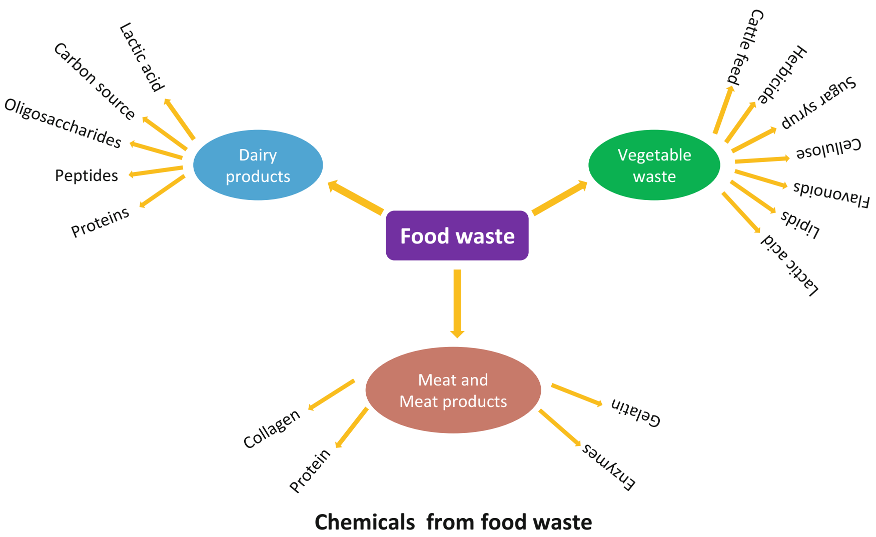

Fig. 5.7 Chemicals production form food wastes

Fruits and vegetables waste constitutes to be largest fraction of food wastes. It has significantly high solids, high COD and BOD, and it can be used for production of high value chemicals. During processing of vegetables and fruits viz., apple, potato, tomato, berries, olives, citrus, enormous amount of wastes has been generated. Their production potential has been reviewed by (Mirabella et al. 2014). Several food industry, pharmaceutical industry produces can be generated from fruit and vegetable wastes (Fig. 5.7). Biologically active phenols and pectins are extracted from apple pomace, citrus peel residues, and berries. Gelling and thickening agents are also obtained from fruit wastes.

Dairy industries generate enormous quantity of liquid wastes with different nutrient content. The liquid of dairy waste mainly contains proteins, salts, fatty substances, lactose, etc. Precipitation, filtration techniques were followed to purify the whey from different cheese whey. Such treated whey is a rich source of lactose which can be used for production of chemicals, especially industrial production of kefiran, an exopolysaccharide rich in glucose and galactose. Whey permeate was used as sanitizing agent to treat fruits and vegetables.

Global meat consumption has increased significantly due to increased demand for protein rich food. One of the causes of concern with respect to recovery of chemicals from meat and meat processing waste is health and hygiene issue. For instance, Bovine Spongiform Encephalopathy is found to be one of the most dangerous diseases that affect the value and consumer chain, calling for much attention during handling of meat wastes. Meat wastes are also a rich source of proteins, hence several extraction methods were tried to extract meat proteins from lungs and beef pork. Such proteins can be a flavour enhancer, nutritional additive, etc. (Arancon et al. 2013; Dahiya et al. 2018; Ibarruri and Hernandez 2019; Imbert 2017).

5.2.3 Industrial Wastes

During the processing of organic material into high value products, a significant quantity of wastewater is generated. In most cases they are not treated properly either land filled or directly disposed into water bodies causing environmental problems. Valorization strategies are followed for such industrial wastewater. Starch processing wastewater is one such waste composed of high quantities of starch from peelings of potato. Starch containing wastes also have significant amounts of total soluble nitrogen and total soluble phosphorous which can be recovered/removed by biological wastewater treatment (Muniraj et al. 2013). With regard to Olive mill waste (OMW), the wastewaters contain enormous amounts of organic load. In this case, biogas production can be a better option. The digestate after treatment with appropriate concentration of nutrients can be composted and used as soil amendment to enhance the organic carbon content. Further, the reclaimed wastewater can be a good source for irrigation of agriculture and horticultural crops (Fritsch et al. 2017).

5.3 Conclusion

Valorization of biowastes (agricultural, food, industrial wastes) is an important step towards sustainable economy, environment, and society. Valorization technologies and their adoption vary with type, composition, availability of biowastes, energy demand, economic and technological feasibility. However, there are challenges that need to be sorted, for instance, sorting different wastes, storing them, instability of microorganisms in the wastes, and high heterogeneity of by-products. The challenges warrant development of new and innovative technologies. Further, while the valorization of biowastes into value added products is a good option, many of the technologies available for valorization of biowastes are costly. Hence, concerted effort is required to reduce the cost of technology and upscale the economic returns.

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Sustainable Biorefinery Technologies for Agro-Residues: Challenges and Perspectives

6

Desikan Ramesh, Thangavelu Kiruthika, and Subburamu Karthikeyan

Abstract

Agro-residues are kind of the lignocellulosic biomass feedstocks used for both biofuel and biochemical production via a biorefinery approach. The renewable bio-products from these residues have the potential to replace the petroleum sources. Immediately after the harvest of the first crop, farmers have a short period for land preparation to raise the next consecutive crop. Due to lower prices, huge quantity, and poor logistics, farmers are forced to burning of residues at an open field. Existing disposal methods of agro-residues management such as in situ burning would create air pollution, and the biomass is burnt into ashes without utilizing their biofuel or biochemical potentials. The biorefinery would aim for minimum or zero waste generation and to produce biofuels and value-added biochemicals from agro-residues. The process selection for a biorefinery is entirely dependent on targeted end products. This chapter briefly discusses the valorization of cellulose, hemicellulose, and lignin of agro-residues for biofuels and biochemicals production. The barriers to the commercialization of biorefinery plants are also discussed.

Keywords

Biorefinery · Lignocellulosic wastes · Agro-residues · Biovalorization · Biochemicals · Biofuels

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6.1 Introduction

The energy products obtained from underground mines/reserves had shown significant contributions in the industrial era and occupied first place in terms of higher energy value as compared to other energy resources. Transportation, power generation, industry, and agriculture sectors are the primary consumers of fossil fuels. Furthermore, liquid and solid fuels derived from fossil fuels play a vital role in the transport sector. The fossil fuel reserves are shrinking rapidly due to an increase in demand worldwide, and the crude oil reserves will be depleted in the next 30 years (Bajpai 2020). Looking from another side, about 15–22% of the world's greenhouse gas (GHG) emissions come from fossil fuel-run vehicles, and it contributes one-fifth of global CO_2 emissions (Soimakallio and Koponen 2011; Chin et al. 2013; Kirtay 2011). The alarming rate of usage of these fuels in the present scenario showed a negative impact on the environment, which results in air pollution, climate change, and global warming. Renewable energy sources are one of the potential candidates to resolve the above-said problems. Among the renewable energy sources, biomass was used by mankind from the ancient period and especially for thermal energy and other purposes.

Biomass means biodegradable organic matter, which is produced by plants/animals/microorganisms. The present predominant usage of lignocellulosic biomass feedstocks is burning or treated as waste and less exposure for tapping other energy values. The biomass is one of the potential feedstocks to produce multiple bio-products via different biomass conversion technologies. Among the different biomass feedstocks, agro-residues have come under the lignocellulosic feedstocks category. Recent trends show that the crop production area increased with food demand for the growing population and results in increased crop residue generation. The available agriculture wastes subjected to poor utilization and management practices such as decomposing field itself or in situ burning results in significant environmental impacts (Tripathi et al. 2019). However, these residues have the potential to produce biofuels, biochemicals and bioenergy. For effective utilization and minimal waste generation, multiple bio-products production from agro-residues are proposed.

Biorefinery helps to generate a variety of products from these residues. There are several reasons for the agro-residues to be used as inputs in the biorefineries, such as their low price, massive production, and potential resource for multi-bioproducts. The goal in a biorefinery is to isolate all the added value from the biomass feedstock, resulting in little or no wastes generation. By producing multiple value-added products, a biorefinery offers huge potential. Biofuels, bioenergy, and biochemicals are commonly known bio-products from biomass materials and the biorefinery concept targets two or more of these bio-products through combined bio/thermochemical conversion processes. Biofuels are defined as fuel derived from the biomass substrates, which may be in the form of liquid, gaseous, or solid. These biofuels can be used as alternate to petro-fuels.

The constituents of agro-residues are converted into different platform chemicals via suitable technologies. For example, the cellulose can produce different chemicals viz., sorbitol, 5-HMF, glucaric acid, succinic acid, and lactic acid. Furthermore, furfural and xylitol can be produced using hemicellulose as a source, whereas levulinic and glutamic acids derived from both cellulose and hemicellulose of biomass (Ge et al. 2018). However, the process technologies used in the biorefineries are still under the research stage. This chapter delves about the broad outline of biorefineries and also discusses challenges faced in commercialization.

6.2 Potential and Availability of Agro-Residues

Generally, the agro-residues are mainly classified into primary residues and secondary residues. Primary residues are collected at the time of crop harvesting, whereas secondary residues are collected from the processing of agro-produce. The agro-residues are made of three major constituents such as cellulose, hemicellulose, and lignin. The composition of selected agro-residues is listed in Table 6.1. The biomass compositions vary with biomass species, environmental conditions, and even in the same variety grown in different seasons. The cellulose content of selected residues is in the range of 24–53%, and variation in the values is due to their biomass types and other factors. Lignin is another vital constituent of agro-residue, which offers more resistance for biological conversion. Generally, the percentage of lignin content in these residues ranges from 6 to 29, and lignin content can be used as the chemical platform to produce biochemicals.

The cultivation of crops is mostly region-specific, and a variety of crops is grown in different parts of the world. Generally, the quantity of agricultural residues generated per annum is directly linked with the residue to grain ratio of the individual crop. The details of the residue to grain ratio for most of the crops are already available in the literature. Therefore, we can use the individual crop yield data to predict their respective residue, and summing up the individual crop residue would give the total crop residue availability for a region or nation. The cereal and sugarcane crops are contributing a significant share in global residue production (Tripathi et al. 2019). Annual agro-residues produced in India is estimated as 500 million tonnes (Mt), which includes sugarcane (141 Mt), wheat (110 Mt), paddy (122 Mt), maize (71 Mt), millets (26 Mt), fibre crops (8 Mt), and pulses (28 Mt) (Saroj Devi et al. 2017).

6.3 Biorefinery Methods

The biorefinery is a platform used to produce biofuels, bioenergy, and biochemicals from single/multiple biomass feedstocks by applying a group of selected biomass conversion methods with their appropriate equipment/machinery. The group of selected biomass conversion methods used in the biorefineries could be operated by one by one in a sequential order. In the case of biorefinery, the raw material can be converted to main products in the first process, and their intermediate products further converted into secondary products through the second conversion process.

Table 6.1 The composition of selected agro-residues

S. no.	Agricultural residues	Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
1	Rice straw	25–44	20–34	10–26.4	Mussatto and Dragone (2016), Hassan et al. (2018), Paul and Dutta (2018), and Rangabhashiyam and Balasubramanian (2019)
2	Wheat straw	30–44.5	20–50	15–22.3	Cai et al. (2017), Dai et al. (2019), Paul and Dutta (2018), and Sharma et al. (2019)
3	Barley straw	30–48	21–38	6.3–26	Cai et al. (2017), Paul and Dutta (2018), Rangabhashiyam and Balasubramanian (2019), and Harindintwali et al. (2020)
4	Sorghum straw	26.93–35	24–32.57	10.16–21	Hernández-Beltrán et al. (2019), Cai et al. (2017), and Harindintwali et al. (2020)
5	Sugarcane bagasse	18.6–45	12.2–35	10.6–30	Mussatto and Dragone (2016), Paul and Dutta (2018), Rangabhashiyam and Balasubramanian (2019), Sadhukhan et al. (2019), and Srivastava et al. (2019)
6	Com cob	33.7–45	25–45	5–18.8	Cai et al. (2017), Dai et al. (2019), Paul and Dutta (2018), and Rangabhashiyam and Balasubramanian (2019)
7	Corn stover	29.6–43.9	19.1–32	14–21.8	Huang et al. (2016), Sadhukhan et al. (2019), Paul and Dutta (2018), and Harindintwali et al. (2020)
8	Rice husk	24–41.05	12–29.3	14.45–26	Hassan et al. (2018), Mussatto and Dragone (2016), Dai et al. (2019), and Sadhukhan et al. (2019)
9	Poplar	35–53.3	14.8–28.7	15.5–29.1	Kumar et al. (2020), Cai et al. (2017), and Rangabhashiyam and Balasubramanian (2019)
10	Switchgrass	26.8–45	21.9–31.4	12–28	Mussatto and Dragone (2016), Dai et al. (2019), Paul and Dutta (2018), Srivastava et al. (2019), and Sharma et al. (2019)

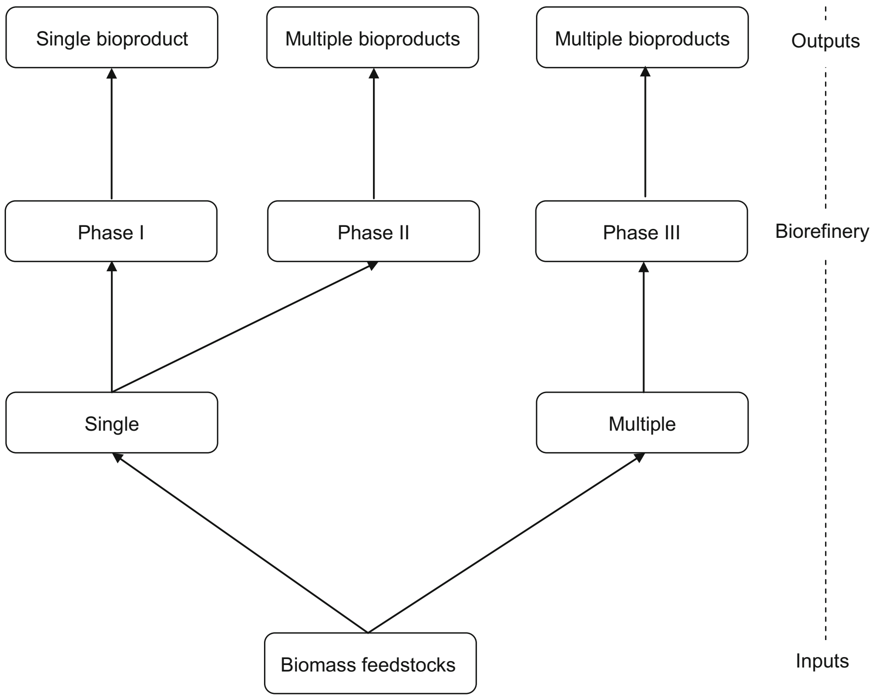

Fig. 6.1 Biorefinery concepts apply to biomass feedstocks (source: Kamm and Kamm 2004).

There will be minimum or less waste generated in the biorefineries. The biorefinery routes applicable for biomass feedstocks are shown as phase I, II, and III (Fig. 6.1) (Kamm and Kamm 2004). Furthermore, phase III biorefinery systems are divided into whole-crop biorefinery, green biorefinery, lignocellulosic biorefinery, and two-platform concept biorefinery (Clark and Deswarte 2008). The proper selection of bio/thermochemical conversion methods is based on inputs used and outputs coming from the biorefinery industry. Generally, three types of primary biomass conversion methods used in biorefineries are biochemical, thermochemical conversion, and chemical methods.

6.3.1 Thermochemical Conversion Method

The thermochemical conversion method uses heat (with/without air/oxygen) for the thermal degradation of biomass into end products. Combustion, gasification, and pyrolysis processes fall under the thermochemical conversion method, which is used to produce heat energy, biofuels, and biochemicals. Since the agricultural residues have a low bulk density in nature, the size reduction and drying are common biomass pretreatment steps adopted before applying the thermochemical conversion technologies. In the case of residues with higher moisture content, the hydrothermal liquefaction process is well suitable, whereas low moisture feedstocks are found suitable for combustion or pyrolysis or gasification process.

6.3.1.1 Gasification

All constituents of biomass feedstock subjected to higher temperatures (700–900 °C) with a restricted amount of oxidizing agent (air/oxygen/steam) supply in a gasifier can yield a gaseous biofuel. This gaseous fuel is referred to as syngas or producer gas, which can be used as fuel in burners or dual-fuel engines for thermal applications and electricity generation, respectively. In terms of typical calorific value, the biogas (21–24 MJ/m^3) is lower than that of syngas (4–10 MJ/m^3) depending on biomass feedstocks and reaction conditions (Tumwesige et al. 2014; Widjaya et al. 2018). The syngas is used as a chemical platform for biofuels or biochemicals. Pre-processing of biomass feedstocks is carried out by drying and size reduction process. The low moisture content of biomass (10–15%) is preferred for the gasification process (Basu 2010), which can be achieved by sun-drying or mechanical drying methods. Generally, the size and shape of the biomass materials are not in uniform shape due to heterogeneous biomass feedstocks. Therefore, size reduction is the main pre-processing step after drying. The size of biomass feedstocks must be reduced to increase the biomass holding capacity of the gasifier and also for enhancing the reaction rates. Most of the agro-residues would contain alkali minerals, and it reacts with silica to form clinkers at time of thermal degradation. For example, the rice husk contains more silica content and forms clinkers in the case of the combustion or gasification process. Therefore, the selection of biomass feedstock for the gasification process is an important one, and feedstocks are tested for their performance in the gasifier to assess their syngas potential.

6.3.1.2 Pyrolysis

The biomass materials subjected to medium temperature without air/oxygen in a pyrolytic reactor yields useful bio-products such as pyrolytic gas, solid product, and liquid biofuel. Typical end product yields (dry basis) produced from different modes of the pyrolysis process is depicted in Fig. 6.2. It depends on reaction conditions used in the pyrolysis process, either biochar or bio-oil generated from the biomass. Biochar and charcoal can be used as a soil conditioner.

6.3.1.3 Combustion

Complete burning of biomass materials in an excess air/oxygen environment in a combustor/furnace/stoves/chulha to produce heat energy. The steam is produced by burning of biomass, which can be used for electricity generation. For example, sugarcane bagasse is used as fuel in steam boiler and electricity is produced in steam turbines. If the agro-residues with higher ash content are used as fuel in the combustion process, ash removal setup should be incorporated in the combustion system for continuous ash removal.

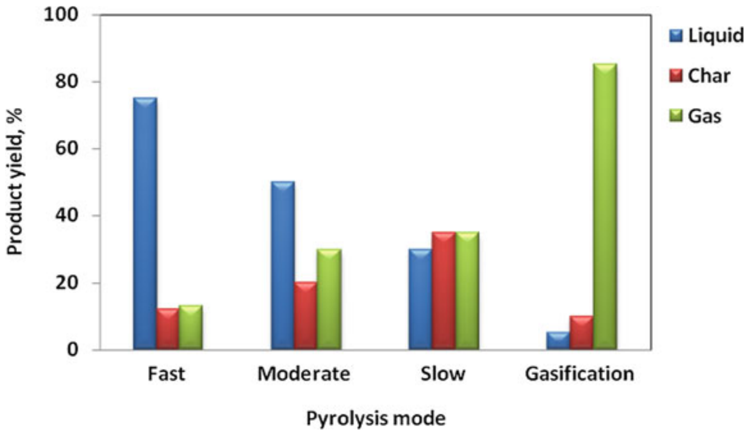

Fig. 6.2 Different pyrolysis modes and end products yield (source: adapted from Bridgwater 2007)

6.3.2 Biochemical Conversion Methods

The agro-residues can be converted into different biofuels like ethanol, butanol, bio-oil, and acetone by using biochemical conversion technologies. Depending on the product and the process, the microbes like bacteria, fungi, and yeast can be used in the biochemical conversion process. The selection of microbes depends on the substrate, process, and end products. The lignin present in the biomass makes complications, and this biomass is not suitable to produce bioethanol/biobutanol through the fermentation process.

6.3.2.1 Biomass Pretreatment

The pretreatment is an unavoidable step for lignocellulosic biomass used for lignin removal and to release the sugars for fermentation. Pretreatment of lignocellulosic biomass is one of the expensive processes, and it accounts for about 18% of the total production cost (Zhang and Shahbazi 2011). Since the compositions of agro-residues from different sources may vary with varieties, crops, seasons, and regions. The major hurdles in the commercialization of agro-residues based biofuels production are the high energy-intensive process and cost involved in different unit operations. Development of low cost and energy-efficient technologies for pretreatment, minimum inhibitors production, and sugar loss, fermentation, distillation process are significant challenges for the production of biobutanol from lignocellulosic feedstocks. Therefore, the major hindrance to the commercialization of alcohol production technology is the biomass pretreatment process.

6.3.2.2 Fermentation Process

Technology for bioethanol production from sugar crops is well established. Furthermore, many bioethanol plants are operated at commercial scale. Meanwhile, a complete package of technology for bioethanol production from lignocellulosic feedstocks is still under development stage. Yeast and bacteria used in the fermentation process can yield alcohol and acid. The fermentable sugars are converted into bioethanol/biobutanol with the help of yeast through the fermentation process.

6.3.2.3 Anaerobic Digestion

The agricultural crop residues can be converted into biogas and biodigesate through the anaerobic digestion process. In this process, the microbial degradation of biomass materials takes place under anaerobic conditions. Most of the primary residues require biomass pretreatment to enhance the biogas yield, and sometimes it performs better for co-digestion of mixed residues with cow dung than crop residue alone. The biodigesate can also be used as manure in the agricultural fields.

6.3.2.4 Hybrid Thermochemical: Biochemical Conversion Technology

The hybrid technology can be used to produce biomass-derived syngas and then followed by ethanol production. In this case, the first bioproduct (syngas) is produced by the gasification process, and further, it might be converted into ethanol by fermentation process (Fig. 6.3). This hybrid technology offers several advantages viz., higher specificity of biocatalysts, lower energy costs, and higher carbon efficiency. The contaminants present in the raw syngas are particulate matter, tar, H_2S, NH_3, alkali compounds, halides, etc. The syngas must be free of these contaminants before used in fermentation. The biocatalysts used for syngas conversion are more sensitive to inhibitors present in syngas (impurities) derived from agro-residues. In order to maintain the excellent quality of syngas, operational parameters used in the

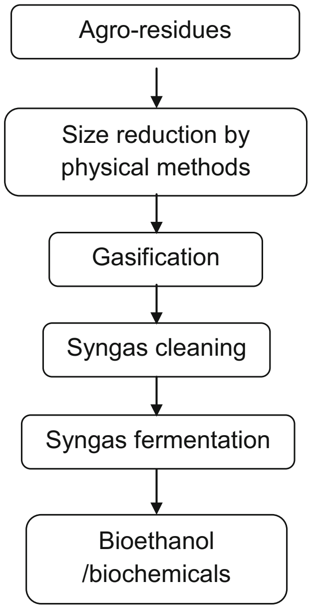

Fig. 6.3 Hybrid technology (gasification and fermentation) for biofuels/ biochemicals production from agro-residues

syngas cleaning system should be optimized for selected crop residue. Syngas is an excellent chemical feedstock for the production of ammonia, methanol, and other derivatives through suitable chemical catalytic conversion, i.e., Fischer–Tropsch synthesis.

6.4 Biofuels Production from Agricultural Residues

6.4.1 Solid Biofuels

The low bulk density biomass materials can be converted into high-density biomass fuel by briquetting technology. Biomass briquette is a solid biofuel and used to replace firewood in steam boilers. However, briquetting technology is an energy-intensive process. Moreover, charcoal is a solid fuel produced from agro-residues through the pyrolysis/carbonization process. The quality of charcoal depends on biomass type and pyrolysis conditions (Zubairu and Gana 2014). The charcoal yield from residues is strongly influenced by lignin content and also biomass compositions.

6.4.2 Liquid Biofuels

Bioethanol and biobutanol are produced from fermentable sugars using appropriate fermentation technology. For the production of liquid biofuels from any agro-residues, biomass pretreatment is a necessary step to separate lignin and also improving the hydrolysis process. Bio-oil is also derived from agro-residues through a fast pyrolysis process. Nevertheless, the yield and composition of bio-oil depend on factors including but not limited to composition of biomass and the operating parameters of pyrolysis process.

6.4.3 Gaseous Biofuels

Syngas and biogas are produced from biomass via gasification and anaerobic digestion process, respectively. The major combustible gases present in syngas are carbon monoxide, hydrogen, and methane, whereas methane accounts for a significant share in the biogas composition. Both these biofuels require the cleaning process to remove impurities for further usage in engines.

6.5 Value-Added Biochemicals Production via Sustainable Biorefinery Approach

More than 90% of chemicals available in the commercial markets are derived from fossil fuels (Fernando et al. 2006). The conventional chemical industries are recently shifting the raw materials from fossil fuels to greener feedstocks. The reasons for this change are rapid depleting of reserves and frequent price hike, and environmental issues. Biomass feedstock has the potential to address chemical requirements from society. Agro-residues contain cellulose, hemicellulose, and lignin. The appropriate technology can be chosen to disintegrate these three components and used as raw materials to produce different platform chemicals or value-added biochemicals. Generally, platform chemicals can be processed to produce a variety of higher value-added products. The valorization of these components of agro-residues are discussed below.

6.5.1 Valorization of Cellulose

Cellulose is a useful component available in the lignocellulosic materials, and it has the potential for fuels or biochemicals production. Annual production and consumption of cellulose are ca. 75 billion tonnes (Kirk-Othmer 2001), and its demand is increasing every year. It consists of long linear fibrils of β-(1,4)-glucopyranoside chains and its degree of polymerization in the range of 800–10,000 units (Kirk-Othmer 2001). Cellulose made of polysaccharides is composed of C_5 and C_6 sugars that can be used as carbon sources after different pretreatment processes (Sun and Cheng 2002; Moncada et al. 2013). In the lignocellulose biomass, cellulose is tightly embedded with the other two components viz., hemicellulose and lignin. Generally, the cellulose is insoluble in water due to a highly crystalline nature. Application of the hydrolysis process for monomer sugars production from cellulose is a more difficult and challenging task than that of hemicellulose. The cellulose can be separated from the residues and used to produce different platform chemicals such as sorbitol, xylitol, succinic acid, lactic acid, furfural, 5 HMF, and Itaconic acid. Details of optimized process conditions and biochemicals yield for cellulose and hemicellulose substrates obtained from different agro-residues are presented in Table 6.2.

6.5.2 Valorization of Hemicellulose

Hemicellulose can have a variety of C_5, C_6 sugars, and also sugar acids (Saha 2003) and highly soluble in water. Cellulose and hemicellulose made of polysaccharides. After biomass pretreatment, these polysaccharides are used as a carbon source for further process (Sun and Cheng 2002; Moncada et al. 2013). Different routes used to converting C_5/C_6 sugars into various chemicals and aromatic furfurals and furfural are presented in Table 6.2.

Table 6.2 Different platform chemicals and their yield from cellulose and hemicellulose derived from lignocellulosic biomass

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
Sorbitol			
Cellulose	$Ni_{4\cdot63}Cu_1Al_{1\cdot82}Fe_{0.79}$, pretreatment: heating-stirring, 214.85 °C, 180 min	68.07%	Zhang et al. (2014)
	0.4% Ru–3% Ni/AC, ball-milling, 205 °C, 60 min	70%	Ribeiro et al. (2017)
MCC (microcrystalline cellulose)	5% Ru/$NbOPO_4$-pH2, ball-milling, 160 °C, 1440 min	69.10%	Xi et al. (2013)
	3.0% Ru/SiO_2-SO_3H, ball-milling, 150 °C, 600 min	61.20%	Zhu et al. (2014)
	0.4% Ru/AC, ball-milling, 205 °C, 60 min	68%	Ribeiro et al. (2015)
	4.0 wt.% Ru/C, 245 °C, 0.5 h, 6.0 MPa	30%	Luo et al. (2007)
	1.0 wt.% Ru/CNT, 185 °C, 24 h, 5.0 MPa	36%	Deng et al. (2009)
	2.0 wt.% Pt/BP2000, pretreatment: ball-milled, 190 °C, 24 h 5.0 MPa	82%	Kobayashi et al. (2011a)
Hydrolytic hydrogenation of cellulose	2 wt.% Pt/BP2000, ball-mill, 190 °C, 24 h, 5 MPa	49%	
	1 wt.% Ru/CNT, pretreatment: H_3PO_4, 185 °C, 24 h, 5 MPa	69%	Deng et al. (2009)
	2 wt.%, ball-mill, 190 °C, 18 h, 0.8 MPa	30%	Kobayashi et al. (2011b)
	3 wt.% Ni/CNF, pretreatment: ball-mill, 190 °C, 24 h, 6 MPa	50%	Van de Vyver et al. (2010)
	Pt/C, $H_4SiW_{12}O_{40}$, 60 °C, 24 h, 0.7 MPa	54%	Ogasawara et al. (2011)
	5 wt.%, Ru/C H_2SO_4, 160 °C, 1 h, 5 MPa	33%	Palkovits et al. (2010)
	2.5 wt.% Pt/Al_2O_3, 190 °C, 24 h, 5 MPa	25%	Fukuoka and Dhepe (2006)
Xylitol			
Corncob hydrolysate	*Candida intermedia* FL023, pH: 5.0, 30 °C, 48 h	40%	Wu et al. (2018b)
Corn cob	*Candida tropicalis*, pH: 6.0, 30 °C, 42 h	61.00%	Misra et al. (2013)
	Candida tropicalis, pH: 6.0, 30 °C, 27 h	55%	Jiang et al. (2016)
	Candida tropicalis CCTCC M2012462, pH: 6.0, 35 °C, 14 h	38.80%	Kumar et al. (2018)
Sugarcane straw	*Candida guilliermondii* FTI 20037, pH: 4.5, 30 °C, 48 h	70%	Hernández-Pérez et al. (2016)

(continued)

Table 6.2 (continued)

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
Sugarcane bagasse	*C. tropicalis*, pH: 5.0, 30 °C, 24 h	30.74%	Vallejos et al. (2016)
	Kluyveromyces marxianus IIPE453, pH: 4.5, 45 °C, 40 h	31.50%	Dasgupta et al. (2017)
Sorghum Stover	*Corynebacterium glutamicum*, pH: 6.5, 30 °C, 16 h	96.50%	Kumar et al. (2018)
Bamboo culm	*Candida magnolia*, 30 °C, 48 h	10.50%	
Cashew apple bagasse	Kluyveromyces marxianus CCA 510, pH: 5.0, 30 °C, 96 h	6.76%	de Albuquerque et al. (2014)
Succinic acid			
Corn stalk and cotton stalk	Anaerobic batch, *A. succinogenes*	15.8 g/L	Li et al. (2010b)
Corn fibre hydrolyzate	Anaerobic batch, *A. succinogenes*	70.3 g/L	Chen et al. (2011)
Corn stover	Anaerobic batch, *A. succinogenes*	56.4 g/L	Li et al. (2011)
Cornstalk enzymatic	Batch, *E. coli*	57.8 g/L	Wang et al. (2011)
Corn straw	Anaerobic, fed-batch, *A. Succinogenes*	53.2 g/L	Zheng et al. (2009)
Cane molasses	Anaerobic batch, *A. Succinogenes*	46.4 g/L	Liu et al. (2008)
	Fed-batch, *A. succinogenes*	55.2 g/L	
Orange peel	Batch, *F. Succinogenes*	1.75 g/L	Li et al. (2010a)
Wheat straw	Batch, *F. Succinogenes*	1.55 g/L	
Softwood dilute acid	Batch, *E.coli*	42.2 g/L	Hodge et al. (2009)
Sugarcane bagasse hydrolyzate	Anaerobic batch, *A. Succinogenes*	22.5 g/L	Borges and Pereira (2011)
Lactic acid			
Cellulose	Al(III)–Sn(II), pretreatment: ball-milling, 189.85 °C, 120 min	65%	Deng et al. (2018)
MCC	10% ZrO_2–Al_2O_3, pretreatment: ball-milling 199.85 °C, 360 min	25.30%	Wattanapaphawong et al. (2017b)
	Er/K10(S)-3, pretreatment: mechanical stirrer, 240 °C, 30 min	67.60%	Wang et al. (2015)
	ZRO-7 ZrO_2, pretreatment: ball-milling, 199.85 °C, 360 min	21.20%	Wattanapaphawong et al. (2017a)
	Er/deAlb-2, pretreatment: mechanical stirrer, 240 °C, 3 min	57.90%	Wang et al. (2017)
Wood hydrolysate	E. faecalis RKY1, batch	93 g/L	Wee et al. (2004)

(continued)

Table 6.2 (continued)

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
Wheat bran hydrolysate	*Lb. bifermentans* DSM 20003, batch with cell immobilization	62.8 g/L	Givry et al. (2008)
Wheat straw hemicellulose	*Lb. brevis and Lb. pentosus*, batch	7.1 g/L	Garde et al. (2002)
Cassava bagasse	*Lb. casei* NCIMB 3254, batch SSF	83.8 g/L	John et al. (2006)
Defatted rice bran	*Lb. delbrueckii* IFO 3202, SSF	28 g/L	Tanaka et al. (2006)
Sugar cane bagasse	*Lb. delbrueckii subsp. delbrueckii* mutant Uc-3, batch SSF	67 g/L	Adsul et al. (2007)
	Lc. lactis IO-1, batch	10.9 g/L	Laopaiboon et al. (2010)
Alfalfa fibres	*Lb. plantarum*, SSF	46.4 g/L	Sreenath et al. (2001)
Corn cobs, 100	*C. acremonium*, R. oryzae	24 g/L	Miura et al. (2004)
Avicel, 17.5	*T. reesei*, *Lactobacillus delbrueckii*	8.4 g/L	Brethauer and Studer (2015)
Furfural			
Wheat straw	[bmim][HSO_4], 160 °C	36.2%[a]	Carvalho et al. (2015)
Pubescens	H2O, 160 °C	1.2%[b]	Luo et al. (2010)
	Water, 180 °C	Less than 1%[b]	Luo et al. (2014)
	Water, microwave, 200 °C	1%[b]	Luo et al. (2017b)
	Water, cyclohexane, 160 °C	1%[b]	Xu et al. (2012)
	Water, $AlCl_3$, 120 °C	26%[a]	Luo et al. (2014)
Birch wood	H_2O, H_2SO_4, 147 °C	0.91%[b]	Brazdausks et al. (2014)
Cardoon	CPME/H_2O, 1 wt.% H_2SO_4, 170 °C	100%[c]	Molina et al. (2012)
Maple wood	THF/H_2O, 1 wt.% H_2SO_4, 170 °C	87%[c]	Cai et al. (2013)
Poplar	THF/H_2O, $AlCl_3$-NaCl, 160 °C	64%[c]	Yang et al. (2012)
Corn stover	90% GVL-H_2O, 0.025 M H_2SO_4, 170 °C	96%[a]	Alonso et al. (2013)
	GVL, SC-CaCt-700, 200 °C	66.3%[b]	Li et al. (2017)
	Water, $AlCl_3$, 140 °C	11.09%[c]	Yi et al. (2013)
Bagasse	THF-H_2O (2:1), 0.4 M HCl, 200 °C	71%[b]	Li et al. (2014)
	H_2O/p-xylene, HUSY, 170 °C	99.5%[b]	Sahu and Dhepe (2012)
Corncob	H_2O, 0.9 mmol H_2SO_4, 160 °C	56%[b]	Wang et al. (2014)
	H_2O 0.10 wt.% H_2SO_4, 190 °C	93%[b]	Luo et al. (2019)
	GVL, SPTPA, 175 °C	73.9%[b]	Zhang et al. (2017)

(continued)

Table 6.2 (continued)

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
5 HMF			
Fructose 1%wt	HCl (pH = 1), 150 °C, 2 h	27%	de Souza et al. (2012)
Glucose 1%wt	HCl (pH = 1), 220 °C, 2 h	26%	
Fructose 100 g/L	0.1 M H_3PO_4, 1 wt.% CaP_2O_6, 1 wt.% a-Sr $(PO_3)_2$, 200 °C, 5 min	22–39%	Daorattanachai et al. (2012)
Glucose 100 g/L	0.1 M H_3PO_4, 1 wt.% CaP_2O_6, 1 wt.% a-Sr $(PO_3)_2$, 200–230 °C, 5 min	4–21%	
Fructose 100 g/L	0.1 g/mL TiO_2, 200 °C, 5 min	22 %	Watanabe et al. (2005)
Fructose 2 wt.%	TiO_2, 200 °C, 1 min	17.8%	Qi et al. (2008)
	ZrO_2, 200 °C, 5 min	30.6%	
Glucose 2 wt.%	TiO_2 (half of the substrate), 200 °C, 5 min	18.6%	
Glucose 100 g/L	100 g/L TiO_2, 200 °C, 5 min	20%	Watanabe et al. (2005)
Fructose 30 wt.%	0.25 M HCl, 180 °C, 2.5–3 min	25.5 mol.%	Román-Leshkov et al. (2006)
Fructose 10 g/L	0.1 g/mL $Nb_{0.2}$–WO_3, 120 °C, 1–3 h	27–30%	Yue et al. (2016)
Glucose 10–100 g/L	0.1 g/mL $Nb_{0.2}$–WO_3, 120 °C, 3 h	12–34%	
Fructose 10 g/L	10 g/L titanate nanotube, 120 °C, 0.5 h	16%	Kitano et al. (2010)
Fructose 0.05 M	H_2SO_4, pH = 1.5–5, 240 °C, 120 s	14.9 –40.6 mol.%	Salak Asghari and Yoshida (2006)
Fructose 6 wt.%	Cr-$VOPO_4$·$2H_2O$, 80 °C, 1 h	48.5 mol.%	Kang et al. (2018)
Glucose 0.055 M	100 g/L H_3PO_4/Nb_2O_5·nH_2O, 120 °C, 3 h	47.9 mol.%	Nakajima et al. (2011)
Glucose 0.05 mol./L	350–400 °C, 0.2–1.7 s	0.1–6.1%	Aida et al. (2007)
Glucose 1 wt.%	Amorphous ZrP (catalyst/glucose = 1:1 − 1:4), 240 °C, 60–240 s	3.2–23.5 mol.%	Asghari and Yoshida (2006)
Glucose 10%	1% $CrCl_3$·6 H_2O, 130 °C, 360 min	13.0 wt.%	Zhou et al. (2017a)
Cellulose	Solvent: [EMIM]Br, Catalyst: SPPS, pretreatment: Stirring, 180 °C, 240 min	68.20%	Li et al. (2018)
Levulinic acid			
10% sugar cane bagasse (with 69% of sugar polymer)	0.55 M H_2SO_4, 150 °C, 8 h	63 mol.%	Girisuta et al. (2013)
6.25% wheat straw	3% H_2SO_4, 210–230 °C, 30 min	19.2 wt.%	Chang et al. (2008)
6% wheat straw	3% H_2SO_4, 210 °C, 42 min	41 wt.%	Chang et al. (2009)

(continued)

Table 6.2 (continued)

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
9.1% pretreated rice husks	4.5% (v/v) HCl, 160 °C, 56 bar and 70 min	54.50%	Bevilaqua et al. (2013)
9.1% pretreated rice husks	4% (v/v) H_2SO_4, 170 °C, 60 min	45.70%	
5% cotton	1 M HCl, 150 °C, 2 h	44 mol.%	Victor et al. (2014)
10 wt.% corn stalk	0.5 M $FeCl_3$, 180 °C, 40 min	48.89 mol.%	Zheng et al. (2017)
Corn stalk	0.05 mol./L $FeCl_3$, 230 °C, 10 min	48.73 mol.%	Zhi et al. (2015)
73 g/L olive tree pruning	37% HCl, 11.5 meq, 200 °C, 1 h	20.1 wt.%	Galletti et al. (2012)
73 g/L poplar sawdust	37% HCl, 11.5 meq, 200 °C, 1 h	29.3 wt.%	
73 g/L paper sludge	98% H_2SO_4, 8.3 meq, 200 °C, 1 h	15.4 wt.%	
73 g/L paper sludge	37% HCl, 11.5 meq, 200 °C, 1 h	31.4 wt.%	
100 g/L furfural residue	2% H_2SO_4, 180 °C, 2 h	66.6 mol.%	Xu et al. (2015)
1 wt.% water hyacinth (C6-sugars is 26.3 wt.%)	1 M H_2SO_4, 175 °C, 30 min	53 mol.%	Girisuta et al. (2008)
9% Miscanthus (40.7% glucan)	0.10–0.53 M H_2SO_4, 160–200 °C	58–72 mol.%	Dussan et al. (2013)
10% sorghum flour	8% H_2SO_4, 200 °C, 30 min	32.6 wt.%	Fang and Hanna (2002)
14 wt.% pennisetum alopecuroides	8% H_2SO_4, 190 °C, 60 min	50.49% theoretical	Yuan et al. (2016)
62.5 kg/m^3 H. tuberosus L.	H_2SO_4 (2 kg/m^3), 160–200 °C, 10–35 min	32.3 wt.%	Jeong (2015)
Cellulose	[C4(Mim)$_2$] [2(HSO_4)($H_2SO)_2$], pretreatment: stirring, 100 °C, 180 min	55%	Khan et al. (2018)
Itaconic acid			
Olive & beet waste	*A. terreus* CECT 20365, 30 °C, 5 days, pH: 5.5	44 g/L	Nikolay et al. (2013)
Glucose	*Ustilago maydis*, 34 °C, 5 days, pH: 3.0, 180 rpm	29 g/L	Rafi et al. (2012)
	A. terreus DSM23081, NRRL1960, NRRL 1963, 33 °C, 7 days, pH: 3.1, 120 rpm	91 g/L	Kuenz et al. (2012)
	A. niger, 33 °C, 10–13 days, 180 rpm	1.4 g/L	Blumhoff et al. (2013)
	A. terreus TN-484-M1, 37 °C, 6 days, pH: 2.0, 220 rpm	82 g/L	El-Imam and Du (2014)

(continued)

Table 6.2 (continued)

Biomass substrate	Catalyst, pretreatment, and growth conditions	Yield	References
Glucose and sucrose	*A. terreus*, 30 °C, 14 days, pH: 3.5	54 g/L	
Various starches	*A. terreus* NRRL1960, 35 °C, 6 days, pH: 3.4, 500 rpm	18.4 g/L	
Jatropha cake	*A. terreus*, 9 days, pH: 1.5, 400 rpm	48.7 g/L	El-Imam et al. (2013)
Glucose, glycerol	*A. terreus*, 37 °C, 6 days, pH: 4.5, 200 rpm	30.2 g/L	Vassilev et al. (2012)
Sago starch	*A. terreus* SKR10, 40 °C, 6 days, pH: 2, 295 rpm	48.2 g/L	Dwiarti et al. (2007)
POME	*A. terreus* 282743, 30 °C, 5 days, pH: 5.8, 150 rpm	5.76 g/L	Jahim et al. (2006)
Starch hydrolysate	*A. terreus*, M-8, 35 °C, 4 days, pH: 2.5–2.8	55 g/L	El-Imam and Du (2014)

[a]Yield of furfural was based on the weight of C_5 fraction in biomass
[b]Yield of furfural was based on the moles of C_5 fraction in biomass
[c]Yield of furfural was based on the weight of the starting materials

6.5.3 Valorization of Lignin

The lignin is an essential component in the lignocellulosic biomass feedstocks, which acts as a shield to prevent microbial degradation and protect the cellulose. Lignin is a highly branched structure; aromatic polymer and helps in tight intact with holocellulose. Several biomass pretreatment methods are used to remove this component to tap the cellulose and hemicellulose. Lignin monomers and dimers, including phenols, alkylphenols, aromatic aldehydes, aromatic acids, etc. can be derived from lignin using different conversion processes. Furthermore, the heating value of lignin is higher than other components present in the biomass. The effective utilization of lignin (both soluble and insoluble) to produce different value-added chemicals are presented in Table 6.3.

6.6 Challenges in Commercialization

The biomass supply chain involves supplying of wastes/residues from the biomass production area to energy conversion facilities (Mafakheri and Nasiri 2014). Generally, the agro-residues are of low bulk density in nature. In other words, these feedstocks occupy more space as compared with the same weight of high-density biomass materials. Due to this physical property, either we use more vehicles or more trips of a transport vehicle for conveying the residues from agricultural fields to the biorefinery industry area. This approach would increase the overall transport cost as well as more human resources will be required for loading and unloading the feedstocks.

Table 6.3 Chemicals derived from lignin through different conversion methods

Feedstock	Lignin (soluble / insoluble)	Conversion method	Catalyst used	Value-added chemicals	References
Lignin	Klason birch lignin	Heterogeneous hydrogenolysis	Pd/C	4-*n*-propanolsyringol	Lan et al. (2018)
	Oxidized birch lignin		Ni/MgAlO-C	Mixed aromatics	Wang et al. (2018)
	Alkali lignin		Pd/C + $CrCl_3$	Monomeric phenols	Shu et al. (2018)
	Olive tree lignin		Ni10%Al-SBA	Monomers, dimmers, and trimers	Toledano et al. (2014)
	Poplar sawdust		Pd/C-H_3PO_4	Monomeric phenols	Renders et al. (2016)
	Vanillin		Pd/PRGO/Ce-MOF	2-Methoxy-4-methyl phenol	Ibrahim et al. (2017)
	Acetophenone		FeNiB	Ethylbenzene	Regmi et al. (2018)
	Diphenyl ether		Ru/C	Mixed aromatics	Wu et al. (2018a)
	Organosolv lignin		$ZnIn_2S_4$	*p*-hydroxyl acetophenone	Luo et al. (2017a, b)
	1,3-Dilignol		$[Ru(Cl)(H)(PPh_3)_3)_3]$	Guaiacol	vom Stein et al. (2015)
	Guaiacylglycerol-guaiacyl ether		Vanadium Schiff-base catalysts	Monomeric phenols	Parker et al. (2016)
	Benzophenone		[Pd(tpy)Cl]Cl	Diphenylmethane	DeLucia et al. (2018)
	Lignin (soluble and insoluble)	Gasification	CaO, MgO, K_2CO_3, Na_2CO_3	CO, CO_2, H_2, CH_4	Li et al. (2015)
		Pyrolysis	K_2CO_3, Na_2CO_3, CaO, Al_2O_3, Fe_2O_3, Ni/Al_2O_3, Rh/CeO_2/SiO_2	Bio-gases (C_1–C_4 hydrocarbons), bio-oils, bio-chars	Carrier et al. (2017) and Collard and Blin (2014)
		Acid hydrolysis depolymerization	Mineral acids (HCl, H_2SO_4, H_3PO_4), Lewis acids (metal chlorides, metal triflates, metal oxides), acidic zeolites, organic acids, acidic ionic liquids, etc.	Lignin monomers and dimers, including phenols, alkylphenols, aromatic aldehydes, aromatic acids	Deepa and Dhepe (2014) and Deuss et al. (2016)

(continued)

Table 6.3 (continued)

Feedstock	Lignin (soluble / insoluble)	Conversion method	Catalyst used	Value-added chemicals	References
	Lignin (soluble and insoluble)	Base hydrolysis depolymerization	NaOH, KOH, $Ca(OH)_2$, LiOH, $NaCO_3$, KCO_3, CaO, hydroxytalcite (HTC), basic zeolites, basic ionic liquids, etc.	Lignin monomers and dimers, including phenols, alkylphenols, aromatic aldehydes, aromatic acids, etc.)	Dabral et al. (2018) and Katahira et al. (2016)
		Reductive conversion	Metals or bimetals (e.g., Ni, NiMo, CoMo, Ru, Rh, Pt, Pd, PdZn) on various supports (e.g., C, SiO_2, Al_2O_3, CeO_2, TiO_2,MgO, and zeolites, etc.)	Phenols, alkylphenols, alkyl benzenes, linear and branched hydrocarbons, cyclic hydrocarbons	Chen et al. (2016) and Klein et al. (2016)
		Oxidative conversion	Metal chlorides (e.g. $CuCl_2$, $FeCl_3$, $CoCl_2$, $LaCl_3$), metal sulphates (e.g. $CuSO_4$, $CoSO_4$, $Fe_2(SO_4)_3$), metal oxides (e.g., CuO, Fe_2O_3, TiO_2), Pt or Pd supported on Al_2O_3, CeO_2, TiO_2, etc.	Aromatic alcohols, aldehydes, and acids	Behling et al. (2016) and Prado et al. (2016)
	Alkaline lignin	Oxidation	Pd/Al_2O_3	Phenolic aldehyde	Sales et al. (2006)
	Steam-explosive cornstalk		$LaCo_1xCuxO_3$	Phenolic aldehyde	Deng et al. (2010)
	kraft lignin		$H_3PMo_{12}O_{40}$	Phenolic aldehyde	Voitl and Rudolf von Rohr (2008); Voitl and Rohr (2009)
	Veratryl alcohol		Co(salen)	Phenolic aldehyde	Kervinen et al. (2005)
	Veratryl alcohol		Mn(TSPP)Cl	Phenolic aldehyde	Kumar et al. (2007)
	Vanillyl alcohol		MTO	Phenolic aldehydes	Crestini et al. (2005, 2006)

	2-Phenoxyethanol		(dipic)V^{V}(O)(OiPr)	Phenolics	Hanson et al. (2010)
	Benzyl alcohol		TEMPO/Br_2/$NaNO_2$	Phenolic aldehyde	Liu et al. (2004)
	Guaiacol	Hydrogenation and Hydrodeoxygenation	Pt/C	Cyclohexanol	Güvenatam et al. (2014)
	4-Propylguaiacol		RuZrLa	Propylcyclohexanol	Xu et al. (2016)
	Syringol		RuZrLa	Propylcyclohexanol	Xu et al. (2016)
	Guaiacol		Ru/C + MgO	Cyclohexanol	Nakagawa et al. (2014)
	Syringol		Ru-MnOx/C	Cyclohexanol	Ishikawa et al. (2016)
	Eugenol		Co/TiO_2	Propylcyclohexanol	Liu et al. (2017)
	Guaiacol		NiCo/Al_2O_3	Cyclohexanol	Zhou et al. (2017b)
	4-Propylguaiacol		Ni/$SiO_2-Al_2O_3$	Propylcyclohexanol	Schutyser et al. (2016)
	Guaiacol		Ni/SiO_2	Cyclohexanone	Bykova et al. (2011, 2012)
	4-Allylsyringol		Pd/C and H_3PO_4	Propylcyclohexane	Zhao et al. (2009, 2011)
	Eugenol		Ru/CNT	Propyl cyclohexane	Chen et al. (2015)
	Guaiacol	Hydrodeoxygenation	1Mo/C	Phenol	Chang et al. (2013)
	4-Propylguaiacol		NiMo/Al_2O_3	4-Propyl phenol	Joshi and Lawal (2013)
	Guaiacol		Re/ZrO_2	Phenol	Ruiz et al. (2010)
	Guaiacol		CoMoS	Benzene	Bui et al. (2011)
	Guaiacol		Ni_2P/SiO_2	Benzene	Wu et al. (2013)

Furthermore, the biorefinery industries also require additional space for drying and storage of these wastes. This could be overcome by establishing a common collection point from nearby agricultural fields and pre-processing of biomass feedstocks at the field itself. The collection of agricultural residues depends on several factors such as its price, transporting cost, the time gap between crop harvest and sowing of consecutive crop, the quantity used for in situ burning, other applications, collection, and storage of individual crop residues. For handling of bulk quantity of biomass without pre-processing, the biomass handling machinery such as balers/binders can be used to bundle the biomass in the form of bales. The transportation cost is directly proportional to the distance between the biomass collection point and the biorefinery site. In other words, higher transportation costs could be incurred for the biorefinery site located far away to the collection point and vice versa. The biomass supply chain may be achieved in three ways viz., direct biomass procurement from agricultural growers, mediators, and contract farming between industry and growers. Alternatively, a mobile biomass pretreatment unit can be used to pretreat the biomass and hydrolysate/solid residue will be sent in separate transport vehicles to biorefineries. The sustainability of agricultural residues based biorefinery factories depends on

- Types of biomass and their availability nearby factory site
- Seasonal availability of agro-residues
- Good biomass supply chain and logistics
- Technical and economic feasibility of the biorefinery technologies

Through proper supply chain management, the overall transport cost can be minimized. This kind of practice would result in lesser storage area and human resources requirement, leading to sustainable operation of biorefineries. The influencing factors for biomass supply chain and logistics are biomass types and seasonal availability, collection and storage area, biorefinery sites, pretreatment types, and transportation mode (Sharma et al. 2013). The biomass supply chain logistics have a significant share of the total cost of biofuel production, which consumes about 20–35% of total processing cost (Rentizelas et al. 2009). If the cost of raw materials, as well as transport costs are higher, it would reflect on the economic returns of the biorefinery project. Therefore, biomass supply chain design plays a vital role in a sustainable biorefinery industry. The major bottlenecks for commercialization of biochemical conversion technology for bioethanol production from agro-residue are energy-intensive processes, higher pretreatment and enzyme costs, difficult to scale up, the low fermentability of mixed sugar stream, the generation of inhibitory soluble compounds, and higher capital investment.

6.7 Conclusion

The different types of agro-residues generated from selected crops and their compositions have been reviewed. The biomass feedstocks also have the potential to produce multiple bio-products through appropriate technology. Different types of bio-products can be derived from agro-residues via the biorefinery approach, and the biochemicals from cellulose, hemicellulose, and lignin were briefly discussed. In order to commercialize the biorefinery technologies, the cost and energy efficiency and process efficiency must be up-scaled through optimization of the process parameters.

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7 Biotechnological Interventions for Production of Flavour and Fragrance Compounds

Tripti Malik and Seema Rawat

Abstract

Flavour and aroma are the important attributes which determine the sensory perception of food, pharmaceutical and cosmetic products. Traditionally, flavour and aroma compounds are extracted from plant and animal sources. In order to meet the huge demand and expenses for various products, the artificial chemicals are now being added. Due to the chemo-phobia and health hazards, artificial flavours and fragrances are not acceptable by the consumers. Biotechnological methods provide better and eco-friendly substitutes for artificial flavour and fragrances. The bio-routes for their synthesis are based on enzymes methods, de novo microbial processes, and bioconversion/biotransformation using microorganisms. Solid-state fermentation carried out by microorganisms can produce a variety of potentially valuable aromatic compounds. Different agro-industrial wastes such as plant residues, bran, straw, flowers, fruit pods can be used as the raw materials which reduces the manufacturing costs of these bio-products and also solves the problem of environmental pollution. Advances in genetic and metabolic engineering are newer approaches of biotechnology which has opened a fenestella in the production of flavour and fragrances.

Keywords

Bioeconomy · Biotransformation · de novo microbial processes · Enzymes · Flavour · Fermentation · Fragrance · Metabolic engineering · Plant tissue culture

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7.1 Introduction

'The Creator, in making man eat in order to live, persuaded him by appetite and rewarded him by pleasure' is a famous quote by French gastronomist, Jean Anthelme Brillat-Savarin of the nineteenth century. The human beings are being rewarded by food that not only provides us nutrients but also gives us a pleasurable feeling. Foods which are found pleasurable alleviate our mood making us feel good with their appearance, taste and aroma (Fernández-Vázquez et al. 2013; Licon et al. 2019). '*Quot sapit nutrit*' (from Latin) is interpreted as, 'If it tastes good, it's good for you' or what pleases the taste also nourishes (Macdonnel 1828). The senses of taste (flavour) and smell (odour) are the two chemical senses perceived by the humans. Aroma is an odour with a pleasant connotation in smell, while flavour is defined as a strong or pleasant taste (Mottram and Elmore 2003). Flavour is defined as a distinctive taste of something as it is experienced in the mouth. The sensory characteristics of taste and smell co-exist, are highly correlated and are also stimulated together (Licon et al. 2019). Hence the terms 'flavour' and 'aroma' include the global integral perception of all the senses that are involved (smell, taste, sight and touch) with the edible products (Astray et al. 2007). Studies have shown that flavour and odour perceptions are the consequence of a complex phenomenon which is due to the properties of certain chemicals (Licon et al. 2019). '*Flavours, sensu lato*' are a group of compounds with sensorial characteristics (Janssens et al. 1992). Both flavours and fragrances can be naturally or artificially derived and are categorized according to their origin (Spudic 2015). The chemical composition of natural substances is responsible for flavour and aroma (Zviely 2002). There are about 6500 flavours known but of these only 300 are commonly used (Scragg 2007).

These pleasing characteristics are not only used for food items but also widely used globally for enhancing the advent of beverages, detergents and pharmaceutical products among the consumers. Furthermore, flavours and fragrances are also blended to impart attractive taste and aroma to processed foods and beverages, and a pleasing scent is also imparted to non-edible products such as perfumes, toiletries, household cleaners, etc. (Triumph Venture Capital (Pty) Limited et al. 2004).

7.2 Flavourings and Fragrance Chemicals

Many volatile and non-volatile compounds which are present in complex matrices are responsible for the flavour and aroma of food items. Humans have been flavourings their food using spices and culinary herbs, which contain essential oils and certain aromatic compounds (Opara and Chohan 2014). These compounds stimulate the receptors of smell and/or taste which leads to the production of an integrated psychological response in humans (Mottram and Elmore 2003; Longo and Sanromán 2006; Astray et al. 2007). While 'the non-volatile compounds contribute essentially to the taste sensations, the volatile ones influence both taste and aroma of food items' (Guichard and Salles 2016; Vilela 2018; Sánchez-Rodríguez et al.

2019). These chemically defined substances which act on the senses of smell and taste are termed as ‘flavour compounds’ or ‘aromatic (aroma) compounds’ (Triumph Venture Capital (Pty) Limited et al. 2004). These aromatic compounds vary widely in their structures and may contribute to the overall flavour of a food. On the basis of chemical structure, these compounds can be classified into hydrocarbons, alcohols, aldehydes, ketones, acids, esters or lactones (Gatfield 1988; Bicas et al. 2010). These compounds may be present in low concentrations which can be as low as 1 part in 10^{12} (Rodríguez and Fernandes 2017). Both flavourings and fragrances are either present naturally or added artificially to the food items. The compounds used for flavourings and fragrances can be categorized into: (1) natural compounds, (2) nature-identical compound and (3) artificial compounds (Zviely 2002; Joint FAO/WHO food standards programme 2005; Fisk 2015). The natural compounds are directly obtained from natural resources by physical methods such as pressing, sublimation, distillation, chromatography and filtration (Zhang et al. 2018). Essential oils, a class of such natural compounds, are the volatile substances which are naturally derived from different parts of the aromatic plants (Cowan 1999; Dhifi et al. 2016). These aromatic oils represent a cocktail of multiple chemical components in variable amounts (Patrignani et al. 2015). These substances have been known since ancient times and have been utilized enormously in different sectors for their pleasing aromas. Most essential oils are directly used as flavours in the edible as well as other products (Surburg and Panten 2006). Their wide application in the food items, cosmetics, pharmaceuticals and toiletries can be attributed to their aromatic, anti-oxidant, immuno-modulatory and physiological properties (Singh and Malik 2008; Malik and Singh 2010; Maen and Cock 2015). Further, a variety of essential oils have also been found to show antimicrobial activities against different microorganisms (Vandamme 2003; Malik et al. 2011, 2015; Hyldgard et al. 2012; Silva et al. 2013; Sirohi et al. 2016). In addition, food technologists and scientists are now also formulating edible packaging for functional foods and pharmaceutical products containing a defined concentration of these fragrant essential oils and their components (Antosik et al. 2017; Malik and Singh 2015; Malik 2017; Sarkic and Stappen 2018).

Nature-identical compounds are chemically isolated from aromatic raw materials or are produced synthetically but are chemically identical to their natural counterparts. These are produced by chemical transformation methods as they give satisfactory yields and good production rates (Astray et al. 2007; Poornima and Preetha 2017). Large-scale synthesis of aroma chemicals was started in the late nineteenth century, with the methyl salicylate (1859), benzaldehyde (1870), vanillin (1874) and coumarin (1878). Presently, there are about 5000 different aroma chemicals that include both natural and synthetic product.

At present, approximately 5000 different aroma chemicals are available in the market which include both synthetic and natural product (Personal Care Magazine 2009). These synthetic ingredients are nowadays playing a major role in the fragrance and flavour industry due to their convenient availability and the relatively lower cost as compared to natural molecules, as the natural sources are relatively limited. Health agencies and administrations have often not assessed the safety concerns of number of chemicals critically. For example, Food and Drug Administration have not assessed the safety of most of the secret chemicals which are being used in different fragrances and sprays. These constitute proprietary chemical formulas and because of the competition in market the composition of these products are kept secret; fragrance secrecy has been considered to be legal due to a giant loophole in the Federal Fair Packaging and Labeling Act of 1973. According to the act, the cosmetics ingredients have to be properly listed on product labels, but fragrance ingredients are exempted. Although, some fragrance ingredients may pose potential health risks to the consumers (EarthTalk 2012). The 'synthetic' label associated with these compounds also decreases the economic interest (Bicas et al. 2010). Nature-identical compounds can also be obtained via enzymatic reactions which are highly specific, less expensive; their methods of production yield less by-products and the products are comparatively pure (Cheng et al. 2015). Artificial flavour substances are those compounds which have not yet been identified in plant or animal products but can be used for the human consumption. In different countries, important aroma chemicals like cinnamic aldehyde, benzaldehyde, methyl salicylate, coumarin, phenyl acetaldehyde and vanillin were chemically synthesized between 1830 and 1890. Due to their enormous potential, industries were set up in Germany (1874), Switzerland (1876), the USA (1913) and Japan (1922). Eucalyptol, ethyl vanillin, eugenol, etc. are some examples of the artificial compounds which are nowadays widely used in different food, cosmetic and pharmaceutical preparations (Surburg and Panten 2006). The development of these artificial compounds is based on the close interaction of multiple disciplines including flavourists, chemists, toxicologists, technologists and chefs (Paravisini and Guichard 2017; Wicochea-Rodríguez et al. 2019). As the business and market of artificial flavouring substances has grown enormously, the government authorities have now laid the foundation for the legislation on their incorporation in foodstuffs and other items. According to the Food and Drug Administration (FDA), USA, the function of artificial flavour compound is to impart flavour, which is not derived from a spice, fruit or fruit juice, vegetable or vegetable juice, edible yeast, herb, bark, bud, root, leaf or similar plant material, meat, fish, poultry, eggs, dairy products or fermentation products thereof. In Europe, all the flavour agents which are artificially added for edible use have to be characterized and have to fulfil the criteria which are laid in the Regulation (Ec) No. 1334/2008 of the European Parliament (Sabisch and Smith 2020). The permission for a new chemical to be used in products is given by an expert panel which is assembled by the Flavour and Extract Manufacturers Association (FEMA), which reviews the toxicological and usage data for each proposed chemical to assess its safety. A list of the permissible chemicals, known as GRAS, for 'Generally Recognized as Safe', is published periodically which includes the flavour chemicals that can be used in food flavours. There are 2244 compounds in the FEMA- GRAS list (Smith et al. 2011).

The artificial chemicals have the advantages of easier availability and relatively lower costs as compared to natural molecules. However, safety, toxicity, allergic reactions and side effects are the various disadvantages of the addition of chemicals to the food items. Consumers also have a 'chemo-phobia' due to which they do not prefer the consumption of products which are being flavoured by the artificial chemicals. The flavours with greener image are now becoming a preferential choice. The increasing demand for natural flavours has led to a significant shortage of several plant materials. Essential oils and isolated aroma compounds are currently available at prices of more than 5000 US$/kg. Moreover, the production processes of chemically synthesized compounds are not eco-friendly and produce undesirable by-products resulting into environmental pollution. The production cost of these synthetic ingredients is also high (Willaert et al. 2005; Poornima and Preetha 2017).

Further, nowadays, many researchers and industries have switched to biocatalytic flavour synthesis due to consumer's inclination towards natural flavours (Longo and Sanromán 2006). Due to disadvantages of both nature-identical and artificial flavour compound and more interest in natural products, newer strategies are being explored for the production of natural flavours.

The biotechnological methods are better alternative methods for the flavour production. These methods are sustainable and eco-friendly unlike the global warming and pollution issues associated with chemical industries. White biotechnology can also be used for the production in flavour and fragrance industry. The biotechnological approach for production of aroma compounds includes (1) Enzymatic methods, (2) Microbial methods-de novo synthesis and biotransformation, (3) Plant tissue culture methods.

7.3 Biotechnological Methods for Production of Flavours

7.3.1 Enzymatic Methods

A significant amount of enzymes are able to directly produce flavour molecules by hydrolysis of larger precursors with higher productivity than direct extraction from plants (Ben Akacha and Gargouri 2015). The enzyme catalysed reactions involve the use of lipases, proteases, glucosidases, hydroxylases, etc. Chang et al. (2001) reported the use of lipases from *Staphylococcus epidermidis* in the synthesis of various flavour esters in aqueous media. Lipase produced by *Mucor miehei* has been found to be highly selective towards flavour active short-chain fatty acids. Butanoic, hexanoic, octanoic and decanoic acid are produced which can be used as flavouring agents as they have cream-like/butter-like flavour (Chen and Yang 1992). Mesifurane [2,5-dimethyl-4-methoxy-3(2H)-furanone], an important flavour compound in arctic bramble, strawberry and pineapple, is produced by *Candida antarctica* (Nozaki et al. 2000). Proteases were used for obtaining the flavour concentrates in the processing of crayfish as the concentration of benzaldehyde and pyrazines were increased (Baek and Cadwallader 1996). Advances in technology have also led to the use of immobilized enzymes in flavour production. de Temiño et al. (2005) used immobilized alcohol dehydrogenase from *Lactobacillus kefir* to synthesize (R)-phenylethanol from acetophenone in an organic solvent (hexane). The enzyme and its cofactor were entrapped in polyvinyl alcohol gel beads so as to enhance their stability in organic solvents, which enabled both cofactor diffusion and in situ regeneration. Frutarom Ltd. has produced an enzyme for the commercial production of a compound from synthetic ingredients which gives the natural flavour of methyl mercaptan, found in all savoury vegetable or meat-based flavours (BBSRC 2014). Another enzyme which is commercially available is Flavorzyme®, manufactured by 'Novo Nordisk Bioindustrials', can be used to obtain a meat-like flavour from defatted soybean meal (Dubal et al. 2008).

However, long and complicated steps for enzyme isolation and purification are one of the disadvantages of these methods. Similarly, the differences in solubility between reacting molecules are also a drawback of enzymatic processes which are usually performed in aqueous phase (Sarma et al. 2014).

7.3.2 Microbial Methods

de novo synthesis of the flavour by microorganisms involves metabolism on substrates such as carbohydrates (glucose and sucrose), fats and proteins by microorganisms to form different and complex fragrant compounds (Dubal et al. 2008; Braga et al. 2018). The precursors usually used are fatty acids, amino acids and terpenes (Hosoglu et al. 2018). These methods produce a mixture of several aroma compounds, which are actually secondary metabolites produced due to metabolic activities of the microorganisms. As regards the de novo synthesis, the microorganisms through the enzymes such as lipases, proteases, nucleases and some glycosidases transform carbon or nitrogen compounds into flavour compounds. The first 'de novo' synthesis of an aroma compound (2-amino acetophenone) by *Pseudomonas aeruginosa* was reported by Omelianski (1923). Other species of *Pseudomonas* with striking odour properties were also identified such as *aromaticus*, *esterifaciens*, *odorus*, *odoratus*, *jragi* or *nobilis*. The aroma formation was found to be a 'changeable character' which was rapidly lost during 'artificial cultivation' of the bacteria. The production of odour by a microbial culture has been explained due to a single volatile, or due to an entire profile of volatiles, which are also concentration dependent in batch cultivation (Berger 1995). de novo methods can be practically applicable only when known starter cultures having good flavour potential are used (Belin et al. 1992). These methods produce flavours in low concentrations. In order to enhance production, genetic engineering techniques can be applied to de novo processes, which involves expressing the genes from flavour producing microorganisms into other microorganisms. Genes of plant and animal origins that encode useful flavour molecules can also be expressed. However, the application of genetically engineered de novo approaches is sensitive due to the complexity of cellular potential and is also subjected to regulation in the host microorganism.

A limitation of de novo process is that the precursors which are usually added in the medium may be inhibitory to the producer strains. Fed-batch processes can be used to overcome substrate inhibition by slowly feeding the substrate and thereby keeping the concentration of the compound below critical threshold values (Carlquist et al. 2015). However, de novo synthesis is not very promising and economically viable for industrial production as only trace amounts of flavours are produced (Belin et al. 1992). These methods lead to the formation of one major product involving either one (biotransformation) or several (bioconversion) biochemical steps (Cheetham 1997). The biotransformation processes involve different biochemical reactions such as oxidation, reduction, hydrolytic reactions, dehydration and formation of new C–C bonds. In fact, the flavour production in microorganisms is carried out by enzymes which comprise hydrolytic enzymes, transferases, oxidoreductases and lyases (Schreier 1997). The yield of flavoured product in bioconversion and biotransformation processes is also higher as compared to de novo synthesis. Therefore, approaches for production of flavour compounds are also economical (Welsh et al. 1989; Amalraj et al. 2017). In the beginning of the era of aroma production, both de novo and biotransformation methods were used for the production of flavour compounds. The microorganisms were isolated, screened and selected for their unique aroma production properties. But, in order to produce completely new set of flavours and to improve the fragrance yield and notes, the microorganisms have been modified by the techniques of metabolic and genetic engineering, which can also be termed as synthetic biology.

The genetically engineering strains of bacteria for flavour production were first used in 2010, when there was an acute shortage of fragrance oil, extracted from *Pogostemon cablin* (Patchouli), an essential oil used as a fragrance in incense sticks, personal and health care products. Due to heavy rains in Indonesia, the medicinal shrub was destroyed which led to a poor harvest of fragrant oil (Gupta et al. 2015; Mahajan and Phatak 2019). Biotechnological interventions solved the crisis when the firms like Allylix, Isobionics and Evolva used genetically engineering bacteria (e.g. *Pseudomonas* sp.) and yeast (*Saccharomyces* sp.) that could produce plant oils by fermenting sugars (Mahajan and Phatak 2019).The gene coding for a particular aroma character was identified and isolated from its known source. Following the cloning approaches, the target gene was cloned and expressed either in *E. coli* or *Saccharomyces cerevisiae*, thus fragrance producing recombinants were produced. Microbial synthesis of aroma compounds which is classified into different groups is described in the next section.

7.3.2.1 Fruity and Floral Terpenes

Terpenes are the flavoured components of essential oils, consisting of five carbon isoprene units which are assembled to each other, while terpenoids are modified class of terpenes with different functional groups and oxidized methyl group at various C positions (Perveen 2018). Only a few terpenes have been reported to be produced by de novo methods using microorganisms, usually fungi belonging to group Ascomycetes and Basidiomycetes (Gupta et al. 2015). Fungi such as *Kluyveromyces lactis* and *Ceratocystis moniliformis* produce de novo fruity and floral flavoured terpenes such as citronellol, linalool and geraniol (Drawert and Barton 1978; Bluemke and Schrader 2001). However, the methods involving biotransformation of terpenes are milder and produce less toxic wastes and, hence, are better alternative for the production of natural aroma compounds (Dionísio et al. 2012; Bier et al. 2011).The pathway for biotransformation of geraniol into methyl heptenone has been elucidated for *Penicillium digitatum* and citral lyase enzyme responsible for this conversion has been purified (Wolken 2003). Some enzymes which are involved in terpene biosynthesis have been sequenced and characterized. The fragrance of lemon-scented sweet basil (*Ocimum basilicum*) is due to geraniol, produced from geranyl diphosphate, catalysed by geraniol synthase (GES). Iijima et al. (2004) isolated gene for GES, sequenced and expressed in *Escherichia coli*. Similarly, geraniol synthase gene (CtGES) present in geraniol chemotypes of *Cinnamomum tenuipilum* has also been cloned and expressed in *E. coli* (Yang et al. 2004).

Limonene, a cyclic monoterpene, is used widely in citrus-flavored products such as soft drinks and candies, and also in fragrant household cleaning products and perfumes (Duetz et al. 2003). It is the principal precursor in number of biotechnological monoterpenoids production; used for a variety of fine chemicals such as perillyl alcohol or carvone (Marmulla and Harder 2014). Both chiral forms of limonene have different aroma characteristics and hence differ in their applications; (+)-Limonene (also called R- or d-limonene) has a pleasant, orange-like odour whereas the (−)-form (also called S- or l-limonene) has a more harsh turpentine-like odour with a lemon note (Friedman and Miller 1971). d-limonene is present in the oils of citrus fruits (70–98%), it is chiefly produced as a side product from the citrus juice industry (Ciriminna et al. 2014). The production and cost of limonene mainly depends on the availability of citrus oil, which is usually alleviated by various environmental factors such as bacterial disease in citrus plants. In plants, limonene is bio-synthesized from the precursor geranyl diphosphate (GPP) by the enzymatic biotransformation with *d*- or l-limonene synthetase. In microorganisms, GPP is produced via the methylerythritol phosphate (MEP) pathway from pyruvate and glyceraldehyde-3-phosphate or by mevalonate pathway (Carter et al. 2003; Jongedijk et al. 2016). Due to the less amounts of geranyl diphosphate (GPP) in microorganisms, lower yield of limonene is obtained. Hence, the availability of GPP and consequently the yield of limonene in microorganisms have to be increased using metabolic engineering approaches. Willrodt et al. (2014) optimized the synthesis of (*S*)-limonene from glycerol and glucose as carbon sources in a two liquid phase fed batch setup using recombinant *Escherichia coli*. A fourfold increase in the yield of limonene in *E. coli* was observed by limiting the amount of magnesium sulphate in the fermentation medium (Willrodt et al. 2016).

Another strategy includes the use of a truncated version of 3-hydroxy-3-methylglutaryl-CoA reductase (tHMGR), a key regulatory enzyme of the mevalonate pathway to increase limonene production by mevalonate pathway (Willrodt et al. 2014; Zebec et al. 2016). A genetically engineered yeast, *Yarrowia lipolytica*, was used to produce d-limonene and l-limonene by heterologous expression of 10 genes which included d-limonene synthase gene and l-limonene synthase gene, respectively. Hydroxymethylglutaryl-CoA reductase (HMGR) was found to be the key rate-limiting enzyme in the mevalonate (MVA) pathway for improving limonene synthesis in *Y. lipolytica.* It significantly increased the titres of both d-limonene and l-limonene upon overexpression (Pang et al. 2019). Heterologous expression of codon optimized neryl diphosphate synthase-1 (NDPS1) and limonene synthase (LS) in *Y. lipolytica* produced d-limonene with a titre of 23.56 mg/L (Cao et al. 2016).

Biotransformation of limonene to α-terpineol was performed by *Cladosporium* sp. and a yield of 1.0 g/L was obtained (Kraidman et al. 1969). *Penicillium digitatum* and *Fusarium oxysporum* have also been used for this bioconversion (Adams and Demyttenaere 2003; Maróstica et al. 2007). Extracellular and intracellular ligninolytic enzymes of white rot fungi, *Ceripora* sp. ZLY-2010 and *Stereum hirsutum*, also carried out the biotransformation of (-)-α-pinene to valuable terpenoids (Lee et al. 2015).

Biotransformation studies have also been carried for agro-industrial waste residues from which essential oils have already been extracted. In monoterpenic agro-industrial wastes such as turpentine oil and essential orange oil, *Penicillium* sp. caused biotransformation by submerged liquid culture approach. R-(+)-limonene and α-, β- pinenes from the oils were biotransformed by *Penicillium* sp. to produce α-terpineol and perillyl alcohol, and verbenol and verbenone, respectively (Maróstica et al. 2007). In the orange peel residues, limonene was biotransformed into valuable compounds, α-terpineol by *Penicillium italicum* which was also isolated from decayed orange peel (Awny et al. 2017).

The biosynthesis of monoterpenes, sesquiterpenes and diterpenes requires isopentenyl diphosphate (IPP) and its isomer dimethylallyl diphosphate (DMAPP) as the universal building blocks. There are two pathways to biosynthesize IPP and DMAPP: the mevalonate (MVA) pathway in eukaryotes such as *Saccharomyces cerevisiae* and the 2-methyl-D-erythritol-4-phosphate (MEP) pathway in most bacteria, including *Escherichia coli* (Carter et al. 2003). Wu et al. (2019) have improved the production of limonene in *E. coli* by systematic optimization of the metabolic flux of limonene biosynthetic pathway. The heterologous limonene biosynthetic pathway was divided into the upstream, midstream and downstream modules, each of which was carried out by module genes derived from bacteria (*Enterococcus faecalis*), yeast (*S. cerevisiae*) and plants (*Abies grandis* and *Mentha spicata*). The upstream module from acetyl-CoA to mevalonate was constructed by choosing the genes *EfmvaE* and *EfmvaS* from *E. faecalis*, which were expressed in the bicistronic plasmid pMAP1. In the midstream module from mevalonate to IPP and DMAPP, the genes *ScMK, ScPMK, ScPMD* and *ScIDI* from *S. cerevisiae* were expressed under the control of T7 promoter as the monocistronic operon in plasmid pISP2. The downstream module was constructed for the conversion of IPP and DMAPP to limonene; neryl pyrophosphate synthase (NPPS) from *Solanum lycopersicum* and the MsLS from *Mentha spicata* were separately expressed in the plasmid pGLS, under two T7 promoters. Three plasmids pMAP1, pISP2 and pGLS were introduced into strain *E. coli* BW25113 (DE3) to create strain *E. coli* ELIM17. Fed-batch fermentation in a shake-flask was carried for the metabolically engineered strain ELIM78 and the yield of limonene was reported to be 1.29 g/L in 84 h.

The metabolically engineered gene coding for the enzyme S-linalool synthase (LIS), responsible for the formation of the monoterpene S-linalool in *Clarkia breweri* flowers, was isolated and cloned into a binary vector which was introduced into *A. tumefaciens* strain LBA4404. The recombinant bacteria were used to transform two varieties of tomato, viz. UC82B and CB3. Metabolic analysis of fully mature tomato fruits showed the accumulation of S-linalool and 8-hydroxylinalool in ripening fruits, while the other terpenoids such as tocopherols, lycopene, carotene and lutein remained unaltered (Lewinsohn et al. 2001).

A sesquiterpenoid ‘patchoulol’ (which is a main component of patchouli essential oil) is generated by the enzyme sesquiterpene synthase from farnesyl pyrophosphate (FPP). Patchoulol is used as a component in perfumes, incense and natural insect repellents (Croteau et al. 1987). Sesquiterpene synthase, heterologously expressed in several organisms such as *Saccharomyces cerevisiae* (Gruchattka et al. 2013), the moss *Physcomitrella patens* (Zhan et al. 2014) and the green microalga *Chlamydomonas reinhardti*i (Lauersen et al. 2016), has been used for the fermentative production of patchoulol. *Corynebacterium glutamicum* is another bacterium which is considered as workhouse of biotechnology, has been engineered for the production of patchulol by applying different strategies. In the first strategy, a farnesyl pyrophosphate-producing platform strain was constructed by combining genomic deletions with heterologous expression of *ispA* from *Escherichia coli.* Secondly, the limiting enzymes from the 2-C-methyl-D-erythritol 4-phosphate (MEP)-pathway were overproduced to increase the supply of precursor and in the third approach plant patchoulol synthase gene *PcPS* from *Pogostemon cablin* was heterologously expressed (Henke et al. 2018). A combinational genetic engineering strategy was applied in *Saccharomyces cerevisiae*. It included the change in promoter, knockout of regulator ROX1, inhibition of squalene pathway and overexpression of tHMGR. The engineered yeast was used for de novo production of (+)-valencene (Ouyang et al. 2019).

7.3.2.2 Aromatic Compounds in Alcoholic Beverages

Flavours in aromatic beverages are due to higher alcohols and esters, polyfunctional thiols, lactones and furanones and terpenoids. The flavour profile of alcoholic beverages is affected due to the medium-chain alcohols, even when present in low amounts. While fusel alcohols at high concentrations impart off-flavours, low concentrations of these compounds and their esters impart the basic flavours and aromas to wine (Belda et al. 2017). Initial fermentation is carried out by a large number of non-*Saccharomyces* yeast genera (*Candida*, *Debaryomyces*, *Hanseniaspora*, *Hansenula*, *Kloeckera*, *Metschnikowia*, *Pichia*, *Lachancea*, *Brettanomyces*, *Kluyveromyces*, *Schizosaccharomyces*, *Torulaspora*, *Zygosaccharomyces and Saccharomycodes*) that contribute significantly to the overall aroma profile of the wine by producing flavour-active compounds (Esteve-Zarzoso et al. 1998; Romano et al. 2003). Pyruvate, the metabolic intermediate of glycolysis, is the precursor for the de novo synthesis of higher alcohols.

In yeasts, higher alcohol with aromatic characters is produced via the Ehrlich pathway, synthesized either from amino acids which are transported across the cell membrane or through de novo biosynthesis of amino acids and their α-ketoacid intermediates (Holt et al. 2019). The alcohols such as 2-butanol, 1,2-butanediol and 2-phenylethanol (2-PE) have unique organoleptic properties. 2-phenylethanol (2-PE), a unique aromatic alcohol, has a delicate fragrance of rose petals (Karami and Jandoust 2016). PE disguises the aroma of rose flower in such a realistic manner that the popular saying by William Shakespeare, 'A rose by any other name would smell as sweet', can be reframed as 'A rose by any other name is phenylethanol'. It is widely used in perfumes, cosmetics, pharmaceuticals, foods and beverages (Carlquist et al. 2015). It is also used as a raw material to produce other important flavour compounds, such as 2-phenylethylacetate (Etschmann et al. 2002) and phenylacetaldehyde (Guo et al. 2017).

Kluyveromyces marxianus has been determined to be a promising candidate for industrial production of 2-PE (Fabre et al. 1997; Wittman et al. 2002). Genome engineering has been done in *Saccharomyces* by introducing allele variation through sequential oligonucleotide recombination. Designer synthetic DNA oligonucleotides have been introduced in the original genome, which allow the combinatorial alteration of pathway genes of aromatic compounds. In the successive rounds of transformation, the yeast genome is gradually re-modelled towards the production of a flavoured metabolite (Mitchell et al. 2015). In a targeted metabolic footprinting method, at low initial nitrogen concentrations, *Saccharomyces cerevisiae* strain KU1 produced higher quantities of esters and fatty acids, whereas M522 produced higher concentrations of isoacids, γ-butyrolactone, higher alcohols and 3-methylthio-1-propanol (Carrau et al. 2008).

7.3.2.3 Esters

Among esters, acetate esters are usually relevant from flavour viewpoint. These are ethyl acetate (apple aroma), isoamyl acetate (banana-like aroma) and 2-phenylethylacetate (honey- and rose-like aroma) (Verstrepen et al. 2003). *Sachsia suaveolens* and *Oidium suaveolens* are known to produce certain fruity odours due to methylbutanols and other esters (Hattori et al. 1974). The yeasts *Hanseniaspora guilliermondii* and *Pichia anomala* are potent 2-phenylethyl acetate and isoamyl acetate producers, respectively (Rojas et al. 2001). The alleles which confer superior production of phenylethyl acetate have been identified to be wild-type TOR1 allele and a superior FAS2BTCD allele in *Saccharomyces cerevisiae* using polygenic analysis. A hybrid diploid *Saccharomyces cerevisiae* yeast strain was developed by crossing two descendants from the unrelated industrial yeast strains, 'ale' yeast and the other was a bioethanol production yeast. Exchange of both superior alleles in the ER18 parent strain increased 2-PEAc production to 70%. The polygenic analysis combined with CRISPR/Cas9-mediated allele exchange comprises a novel strategy which could be used for the creation of cis-genic yeasts having a novel flavour profile which could be used for the production of alcoholic beverages (de Carvalho et al. 2017). Lomascolo et al. (2001) have selected *S. cerevisiae* mutants which can convert L-phenylalanine added in the medium via deamination, decarboxylation and subsequent reduction into 2-phenylethanol. A high yield of the fragrant ester (>2 g/L) was obtained by solvent extraction of the fermentation broth. Double coupled system was used to identify non-*Saccharomyces* yeasts from *Agave duranguensis*, which showed that *Pichia fermentans* can be used for the biotechnological production of isoamyl acetate (Hernández-Carbajal et al. 2013). *E. coli*, genetically engineered for the synthesis of banana flavour, nicknamed as 'Eau d'coli', was developed by expressing *ATF1* gene from *S. cerevisiae* which converts isoamyl alcohol in the growth media to isoamyl acetate. The gene was cloned between a bacterial ribosome binding site and a transcriptional terminator to make a three part 'banana-odour generator'. A bacterial promoter that is primarily active during stationary phase controls the expression of *ATF*1 gene. For the best production of the banana fragrance, the cellular chasis bore a mutation in the *tnaA* gene, which inhibits indole production and thus effectively eliminates the putrid smell that characterizes the usual smell of *E. coli* culture (Dixon and Kuldell 2011).

3-methylbutyl-acetate, a fruity ester, has been synthesized de novo by the yeast *Williopsis saturnus*. The yield was improved by feeding fusel oil as a cheap source of precursor branched alcohols in the fermentation process (Vandamme 2003). *Geotrichum klebahnii* has been reported to produce de novo various ethyl esters of branched carboxylic acids, giving a pleasant fruity flavour. Ethyl-2-methylbutyrate is formed when medium is supplemented with isoleucine (Janssens et al. 1989). Another ester, ethyl acetate is responsible for an 'apple' aroma. Lai et al. (2019) reported the production of ethyl acetate in 'Kaoliang', a wheat-based koji prepared using sorghum as a substrate, by *S. cerevisiae* as the dominant strain along with other yeasts *Kazachstania exigua* and *Candida humilis*.

7.3.2.4 Ketones

The most important flavoured ketone is Diacetyl (2, 3-butanedione) which is responsible for the buttery aroma of many dairy products. Lactic acid bacteria, especially *L. lactis* biovar, produces diacetyl from co-fermentation of citrate and lactose (Papagianni et al. 2007). The characteristic aroma of raspberry is because of para-hydroxyphenyl-butan-2-one. The first biotechnological strategy for the production of raspberry ketone involves the de novo synthesis by basidiomycetes *Nidula niveo-tomentosa* using L-tyrosine or L-phenylalanine as the natural precursor. The second strategy is a two-step bioconversion which involves hydrolysis of betuloside, a glycoside of 4-4-(hydroxyphenyl)-2-butanol. The hydrolysis releases betuligenol which gets transformed to ketone by *Acetobacter aceti* (Schrader 2007).

7.3.2.5 Fruity Lactones

Lactones are the compounds responsible for flavours like oily-peachy, creamy, fruity, nutty and coconut. Specifically, γ- and δ-lactones with equal or less 12 carbons are well-known for their great variety of taste and aroma (Dabbou et al. 2016). γ-decalactone and δ-decalactone are responsible for typical flavour of peach and apricot (Greger and Schieberle 2007). A yeast *Sporobolomyces odorus* de novo produces 4-decalactone (up to 1.6 mg.L) which gives a peach odour (Welsh et al. 1989). Another lactone which is widely used for its coconut odour is 6-pentyl-2-pyrone which is produced by fungus *Trichoderma viride* (Fadel et al. 2015). *Tyromyces sambuceus* and *Cladosporium suaveolens* efficiently generate coconut-flavoured lactones γ-decalactone and δ-dodeca-lactone from ricinoleic acid and linoleic acid, respectively (Kapfer et al. 1989; Allegrone et al. 1991). The yield of lactones carried by yeasts via de novo fermentation is low, which can be increased by supplying a limiting intermediate or precursor molecule to the fungal culture.

Ricinoleic acid, the main constituent of castor oil, has been converted to γ-decalactone via partial β-oxidation, by yeasts such as *Sporidiobolus salmonicolor* and *Yarrowia lipolytica*. A yield over 10 g/L has been reported along with the production of undesirable side product hydroxy-γ-decalactone. *Saccharomyces cerevisiae* converts hydroxy-γ-decalactone into 3, 4 unsaturated γ-decalactone, which is then stereoselectively reduced into the desirable γ-decalactone by the yeast (Vandamme 2003).

7.3.2.6 Phenolic Aldehydes

Phenolic aldehydes which constitute nice flavours are anisaldehyde and some derivatives of protocatechualdehyde (3, 4-dihydroxybenzaldehyde), such as vanillin, veratraldehyde and heliotropin (Braga et al. 2018). Vanilla flavour is due to the phenolic aldehyde vanillin, is widely used for its pleasant, sweet and intense aroma in ice creams, cookies, cakes, in soft beverages and cosmetics. About 6000 tonnes of vanilla is consumed worldwide each year (Priefert et al. 2001). Natural vanilla is a complex mixture of flavours which is obtained from cured vanilla pods belonging to *Vanilla orchids*, *Vanilla planifolia*, *Vanilla tahitensis* or *Vanilla pompona,* where it contributes to about 2% (w/w) of the dry matter (Green Protocols n.d.). Although flavour and fragrance profile of the vanilla extracts shows more than 200 components, Vanillin (4-hydroxy-3-methoxybenzaldehyde) is the characteristic key component of vanilla flavour comprising of various functional groups like aldehyde, ether and phenol (Green Protocols n.d.). It is also used as a precursor for various pharmaceutical formulations and finds application as a food preservative (Hassan et al. 2016). Also, synthetic vanillin is used in the production of deodorants, air fresheners, cleaning products, antifoaming agents or herbicides. In the green beans, vanillin is present in the conjugated, β-D-glucoside form, which has no trace of the characteristic vanilla flavour (Green Protocols n.d.). The flavour develops during the 6 months long fermentation or curing process of green pods. During curing, vanillin β-D-glucoside and related β-D-glucosides are acted upon by enzymes β-D-glucosidases releasing vanillin (1–3%) and related phenolics (Walton et al. 2003). The annual global sales of vanillin were reported to be more than 15,000,000 kg in 2010. It has been reported that less than 1% is obtained from vanilla pods, while remaining is obtained by the chemical methods (Green Protocols n.d.). The cultivation of vanilla beans and the isolation of vanillin from vanilla pods is a laborious and costly process. About 500 kg of vanilla pods have to be processed to produce 1 kg of vanillin, for which approximately 40,000 vanilla orchid flowers have to be hand-pollinated. The cost of natural vanillin is quite high due to the limited availability of vanilla pods, fluctuations in harvest yields, labour intensive cultivation and curing of vanilla pods (Sinha et al. 2008).

Vanillin was first isolated by evaporation of vanilla extract so as to obtain it in a dry and crystallized form by Gobley (1858). In 1874, Tiemann and Haarmann, synthesized vanillin from coniferin present in tissues of pine tree. A company named ‘Haarmann’s Vanillinfabrik’ was founded for its production, which was later joined by Reimer. The first chemical method of synthesis of vanillin was using guaiacol as the substrate (Ciriminna et al. 2019). Guaiacol (a petrochemical constituent) and glyoxylic acid are still used these days for the chemical synthesis of vanillin (Esposito et al. 1997). Reimer-Tiemann method (1876) was also adopted; eugenol (obtained from clove oil) was reacted with potassium hydroxide and refluxed with an alkaline solution of chloroform and then oxidized by nitrobenzene to produce vanillin (Havkin-Frenkel and Belanger 2017; Ciriminna et al. 2019). The reaction between glyoxylic acid and guaiacol is a two-step process: First is the condensation process which is promoted by base and in the second step, vanillyl mandelic acid is oxidatively decarboxylated to produce vanillin, catalysed by copper (II) in an aqueous alkaline medium at 80–130 °C (Kumar et al. 2012; Fache et al. 2016). At present, the chemical synthesis of vanillin has been carried out at 5 industrial plants worldwide, fulfilling about 85% global demand of vanillin. The cost of synthetic vanillin is $10–20/kg, sold mainly to ice cream and chocolate manufacturers, and to flavour and fragrance companies. For meeting the remaining demand, vanillin was produced from lignin via an alkaline oxidation process. The alkaline aqueous solution of lignin is prepared with oxidants (such as nitrobenzene), at high temperature and pressure. The depolymerisation of lignin releases crude vanillin containing structurally similar compounds like acetovanillone and syringaldehyde (Schultz and Templeton 1986; Shakeri et al. 2013).

In 2015, major food companies, including General Mills, Hershey's, Kellogg's and Nestlé, took a vow to eliminate artificial flavours and other synthetic additives from food items in the USA. At the same time, the bad orchid harvesting season in Madagascar, the highest producer of vanilla, led to a soar in the market prices (vanilla beans @$225/kg and pure vanilla price > $11,000/kg). In June 2018, the price of vanilla beans was further increased to $527/kg. This multi-fold increase in vanilla price between 2012 and 2018 has to be accomplished by alternative vanillin production methods which are environment friendly. Although direct bioconversion of glucose to vanillin has not been known in any naturally occurring microorganisms, a recombinant *E. coli* for de novo biosynthesis of vanillic acid from glucose via a designed shikimate pathway was developed in which vanillic acid was enzymatically reduced to vanillin by aryl aldehyde dehydrogenase (Li and Frost 1998). In de novo method, biosynthesis of vanillin from glucose was explored in the yeasts, *Schizosaccharomyces pombe* and *Saccharomyces cerevisiae.* Three genes, viz. 3-dehydroshikimate dehydratase from the dung mould *Podospora pauciseta*, an aromatic carboxylic acid reductase (ACAR) from *Nocardia* and O-methyltransferase from *Homo sapiens,* were incorporated in both the yeasts. The production of vanillin was determined to be 65 and 45 mg/L in *S. pombe* and *S. cerevisiae*, respectively, which was also free from any contaminating isomers and production was carried out in the usual media and growth conditions (Hansen et al. 2009). Certain natural substances like lignin, ferulic acid, eugenol, and isoeugenol can be used for the biosynthesis of vanillin. A gene mining method was devised for producing a carotenoid cleavage oxygenases (CCO) protein which was named 'SeNCED'. The gene from *Serratia* sp. ATCC 39006 was cloned and overexpressed in *E. coli*. The enzyme was used to catalyze the side chain double bond cleavage of isoeugenol and 4-vinylguaiacol to yield vanillin (Tang et al. 2018).

Ni et al. (2015) synthesized vanillin from glucose and other substrates (L-tyrosine, xylose and glycerol). The metabolically engineered strain produced 97.2 mg/L vanillin from l-tyrosine, 19.3 mg/L from glucose, 13.3 mg/L from xylose and 24.7 mg/L from glycerol. Ferulic acid is the best-explored substrate for production of vanillin whose degradation pathways in microorganisms produce vanillin as an intermediate. Based on the different initial reactions involved in ferulic acid bioconversion five major pathways can be distinguished in microorganisms which are (1) CoA-independent retro-aldol reaction, (2) CoA-dependent retro-aldol reaction, (3) CoA-dependent β-oxidation, (4) non-oxidative decarboxylation and (5) a reductive pathway. Some microorganisms have developed multiple pathways for bioconversion of ferulic acid. *Pseudomonas fluorescens* has been reported to metabolize ferulic acid by three pathways which are decarboxylation (Huang et al. 1994), reduction (Martinez-Cuesta et al. 2005) and via a CoA-dependent retro-aldol reaction mechanism. The retro-aldol mechanism involves elimination of an acetate moiety from the unsaturated ferulic acid side chain resulting into vanillin formation. White rot fungi can convert ferulic acid to vanillic acid, which is further converted to vanillin. *Aspergillus niger* carries out transformation of ferulic acid into vanillic acid. In the second step, *Pycnoporus cinnabarinus* or *Phanerochaete chrysosporium* further converts vanillic acid into vanillin (500 mg/L) (Stentelaire et al. 2000). Several microorganisms have metabolism pathways for formation of vanillin from ferulic acid (FA) (Tang et al. 2018). In a pathway known as coenzyme-dependent deacetylation pathway, FA is converted to feruloyl-CoA catalysed by the enzyme, feruloyl-CoA-synthetase (Fcs). In the next step, enoyl-CoA-hydrolase (Ech) forms vanillin. The engineered *E. coli* and other bacterial cells containing Fcs and Ech can effectively convert FA to vanillin (Yang et al. 2013; Chakraborty et al. 2017). HCHL gene of *Pseudomonas fluorescens*, encoding *p*-hydroxycinnamoyl-CoA hydratase/lyase, was expressed in two transgenic hairy root (HR) lines of *Beta vulgaris*. These *HCHL* expressing cell lines exhibited conversion of inherently available phenypropanoid precursor (ferulic acid) into vanillin (Singh et al. 2015).

The chemical constituents of essential oils such as eugenol and isoeugenol can be converted, by several microorganisms such as *Pseudomonas putida*, *Corynebacterium* sp., *Arthrobacter globiformis* to vanillin (Furukawa et al. 2003; Zhao et al. 2005; Vilela 2018). Barghini et al. (2007) converted ferulic acid to vanillin using *E. coli* JM109 cells in which ferulic acid-degrading genes from *Pseudomonas fluorescens* BF13 were expressed. The natural pathway of vanillin production in plants was mimicked in *E. coli*. The metabolically engineered strain produced vanillin in different amounts 97.2 mg/L (l-tyrosine), 19.3 mg/L (glucose), 13.3 mg/L (xylose) and 24.7 mg/L (glycerol) (Ni et al. 2015).

Biotransformation approach can be used for the production of vanillin from certain natural precursors like lignin, eugenol, isoeugenol, ferulic acid and phenolic stilbenes. Production of flavour compounds can also be carried out using microorganisms. Vanillic acid has been found as a main intermediate in lignin and ferulic acid degradation, and in contrast to vanillin, it has found to be accumulated in remarkable amounts (Andreoni et al. 1995). The first biotransformation process for production of vanillin was carried out with *A. niger* ATCC 9142 using isoeugenol.

The yield was found to be quite low and efficiency was only 10% (Abraham et al. 1988). The excrement of herbivorous animals has been used for the production of plant polyphenol using the subcritical water. This unusual discovery has been awarded Nobel Prize. Vanillin, protocatechuic acid, vanillic acid and syringic acid were produced by the method, which was used as the intermediate materials of the medicines and vanilla flavourings (Yamamoto et al. 2008).

Vanillin can also be produced by phenolic biotransformation by *Aspergillus luchuensis* (a fermentation starter fungus). During the production of 'awamori' (a fermented beverage), vanillin was also produced. It involves a two-step process catalysed by the enzymes, CoA ligases and feruloyl-CoA hydratase followed by a two-carbon elimination of ferulic acid which produces vanillin and acetyl-CoA. The production mechanism can be explained as the side chain cleavage of ferulic acid through Coenzyme A (CoA) and feruloyl-CoA hydratase/lyase, to form vanillin and acetyl-CoA (Taira et al. 2018).

Furanones comprise the aromatic chemicals present in many fruits such as pineapple, strawberries, mangoes, raspberries. 2,5-dimethyl-4-hydroxy-3(2H)-furanone (DMHF) marketed as Furaneol® imparts strawberry flavour in dilute solutions and caramel-like flavour in concentrated form (Vandamme 2003). Soy sauce yeast *Zygosaccharomyces rouxii* can also produce DMHF in the medium supplied with D- fructose-1,6-biphosphate (FBP) and glucose. Since FBP is readily available, microbial process is a cheaper alternative (Dahlen et al. 2001).

7.3.2.7 Grassy Aroma

The 'grassy' aroma found in damaged green tissue (e.g. cut grass) and in aromas of many fruits and vegetables is formed via the degradation of plant polyunsaturated fatty acids (PUFA) such as linolenic acid which are acted upon by lipoxygenases and hydroperoxides. Although, these enzymes have not been detected so far in bacteria or fungi, but the genes for lipoxygenase and hydroperoxides lyase have been expressed in yeast cells and green note flavour by fungal fermentation has been obtained from linolenic acid added in the medium (Gallo et al. 2001).

7.3.2.8 Musk Aroma

Lactones with a musk aroma are found in some plants such as ambrette seed oil, galbanum, whereas the keto musk aroma is produced by musk deer and civet cats. Being obtained from animals, these are very expensive and unethical. Mutants of *Torulopsis bombicola* were developed which were able to convert palmitic acid into ω-hydroxypalmitic acid ester, which can then be cyclised into hexadecanolide lactone musk.

Ambrox, an important ingredient of Ambergris, has a musk like fragrance. It is a rare product which is produced in the digestive tract of the sperm whale (*Physeter macrocephalus*) (Leffingwell and Leffingwell 2011). Chemical synthesis of this musky compound is carried using a terpene, sclareol (Extracted from the *Salvia sclarea* plant) as starting material, which is first converted to sclareolide and then into Ambrox®. The fungus *Hyphozyma roseoniger* and the yeast *Cryptococcus* sp. can use sclareol as a sole carbon source and can accumulate sclareolide, which is chemically converted into Ambrox (Cheetham 1993). A fermentation process was performed at Nippon Mining Co. for the production of a dicarboxylic acid which is alpha-omega-alkanoic acid for macrocyclic musk molecules. *Candida tropicalis* has been mutated to give high yields of α-ω-alkanoic acid from C10-C18 alkanes, 120 g of product/L is produced on 20 m^3 scale (Cheetham 1999).

7.3.2.9 Synthetic Biology

Synthetic biology has become a new tool in the synthesis of aromatic molecules because of the declining cost of DNA synthesis, rapid advances in bioinformatics tools and expanding omics databases. Now in a heterologous microbial host it has become possible to resolve single and multienzyme gaps in a heterologous microbial host. Synthetic biology plays a revolutionary role in the creation of *Saccharomyces cerevisiae* and *E. coli* as an aroma factory. It allows for the production of a completely new set of microbial-derived flavours. In *S. cerevisiae* genome the repetitive sequences were removed, LoxPsym sequences were introduced at the 5' ends of all the genes in the yeast genome which are considered individually non-essential. These are the sites which allow inducible homologous recombination downstream of all non-essential genes which is mediated by the action of the site-specific Cre recombinase. Rapid gene deletion, duplication or inversion is promoted at these LoxPsym sites, the process is known as SCRaMbLE (Synthetic Chromosome Rearrangement and Modification by LoxPsym-mediated Evolution), which allows for the rapid synthetic rearrangement and evolution of fermentation. Thus, a large library of genomically divergent yeasts has also been created (Wyk et al. 2018).

7.3.2.10 Metabolic Engineering

The most recent approach in metabolic engineering involves tools and strategies which employ engineering the microbial cells to follow a biosynthetic module. The biochemical pathways involved in the production of these compounds have to be understood. This further requires the identification of the genes and enzymes involved in the synthesis of volatile compounds. The concept of metabolic engineering of aroma has also been previously applied to a variety of food items such as fruits, vegetables and herbs (tomato, potato, etc.), milk products and alcoholic beverages (Dudareva and Pichersky 2008).

Rational metabolic engineering and inverse metabolic engineering are the two approaches used for production of bioflavours. Defined genetic manipulations are made in genome to carry out a metabolic pathway of interest. Inverse metabolic engineering strategy is carried; genes are knocked-out/knocked-in to get a desired aromatic phenotype (Turanlı-Yıldız et al. 2017). The aromatic chemicals which are derived from microorganisms are usually shikimate (SHK) and aromatic amino acids like L-phenylalanine (L-PHE), L-tyrosine (L-TYR) and L-tryptophan (L-TRP). These aromatic compounds can be categorized into intermediates and derivatives of the shikimate (SHK) pathway and aromatic amino acids, e.g. L-phenylamine (PHE), L-tyrosine (TYR), L-tryptophan (TRP) and their derivatives (Huccetogullari et al. 2019).

A shikimate pathway intermediate (3-dehydroshikimate) has been converted to vanillin in a multi-step conversion through heterologous expression of four genes from *Podospora pauciseta*, *Nocardia iowensis*, *Corynebacterium glutamicum* and *Homo sapiens*. Brochado et al. (2010) used genome-scale metabolic modelling to identify gene deletion targets in *S. cerevisiae* in order to improve vanillin production. The deletion of genes *PDC1* and *GDH1* resulted in a fivefold increase in production of vanillin.

7.3.2.11 Process of Solid-State/Submerged Fermentation for Production of Aroma Compounds

The process of solid-state fermentation (SSF) is used in the production of biologically active secondary metabolites, which can also be used for the bioflavours (Prabhakar et al. 2005; Singhania et al. 2009; Ray and Behera 2011). SSF is a three-phase system, a gas phase (also called headspace), a solid phase and a liquid phase, which is in the form of a thin layer of moisture, around the solid phase. In SSF, the microorganism grows on this layer of moisture in the absence or near absence of free water (Thomas et al. 2013), whereas submerged fermentation (SmF) involves submersion of the microorganism in an aqueous solution containing all the nutrients needed for growth. SmF utilizes free flowing liquid substrates, such as molasses and broths. The bioactive compounds are secreted into the fermentation broth (Subramaniyam and Vimala 2012). SmF has also been used for the production of aroma compounds by using several microorganisms. A higher yield is obtained in SSF as compared to submerged fermentation. In addition, SSF has lower production costs, lower demand for energy and water as well as less amount of liquid wastes are produced (Rodríguez and Sanromán 2006; Singhania et al. 2009; Soccol et al. 2017). The disadvantage of SSF over the SmF is the difficulty in monitoring of process variables such as pH, moisture and nutrient availability. In the scaling-up, there is also a problem of heat mass transfer associated with the use of solid substrates (Pandey 2003; Soccol et al. 2017). The application of SSF in large scale is limited (Singhania et al. 2010; Salihu and Alam 2012) as the aroma compounds are either produced in the solid matrix or in the headspace which can be lost or stripped when aeration is required (Try et al. 2018).

Rossi (2009) have used the fungi *Ceratocystis fimbriata* for the production of a variety of aromas using citric pulp (CP), a waste from the citric juice production industry as the substrate for fermentation. Other materials such as carbon sources (sugarcane molasses, soya molasses) and nitrogenous sources (soya bran or urea) were also checked for the production of aromatic compounds. Gas chromatography of the headspace showed the best production of volatile compounds (99.60 μmol/L g), when the citric pulp was supplemented with 50% of soya bran, 25% of sugarcane molasses and mineral saline solution. The production of a number of fruity esters, namely isoamyl acetate, phenylethyl acetate, ethyl dodecanoate, decanoate and octanoate from orange peel, has also been reported by Mantzouridou et al. (2015).

The solids derived from coffee such as coffee pulp and coffee husk can also be used for the production of flavour compounds (Pandey et al. 2000). *Ceratocystis fimbriata* was grown in two media constituted from steam treated coffee husk supplemented with 20 and 35% glucose. A prominent pineapple aroma resulted due to the production of 6.58 and 5.24 mmol/L/g total volatiles (TV) in the respective media. Different aromatic compounds such as acetaldehyde, ethanol, isopropanol, ethyl acetate, ethyl isobutyrate, isobutyl acetate, isoamyl acetate and ethyl-3-hexanoate were identified in the headspace of the cultures. When leucine was added, the total volatiles increased to 8.29 mmol/L/g. A strong banana odour was detected as ethyl acetate and isoamyl acetate were found to be produced. However, the biosynthesis of volatile compounds was not improved by the addition of soybean oil and in fact it was reduced due to the addition of mineral salts (Soares et al. 2000). In a study, five different agro-industrial residues were evaluated as substrate for cultivating a strain of *Kluyveromyces marxianus*. The yeast produced fruity aroma compounds when cassava bagasse and giant palm bran (*Opuntia ficus-indica*) were used as substrates. In the experiment, the influence of different parameters on the production of volatile compounds was tested. The parameters included initial pH of the substrate, addition of glucose, incubation temperature, initial substrate moisture and the size of inoculum. Using a 2^5 factorial design, both the parameters, namely addition of glucose and initial pH of the substrate, were found to be statistically significant for the production of aroma compounds when palm bran was used as a substrate. The addition of glucose did not have a significant role when the substrate was cassava bagasse, but 2^2 factorial designs showed the addition of glucose to be statistically significant at higher concentrations. Nine and eleven aroma compounds were found to be produced from palm bran and cassava bagasse, respectively, when headspace analysis of the culture was done by gas chromatography. These compounds included alcohols, esters and aldehyde. Ethyl acetate, ethanol and acetaldehyde were the major compounds produced, while two compounds remained unidentified in both the cases. Esters produced were responsible for the fruity aroma in both the cases. When the substrate was supplemented with 10% glucose, 418 and 1395 μmol L^{-1} headspace $g^{-1}$of ethanol (palm oil) and ethyl acetate (cassava bagasse) were produced at highest concentration (Medeiros et al. 2000). *Trichoderma viride* has been reported to ferment the fruits of *Pandanus tectorius* by using SSF approach. The aromatic compounds produced belonged to the classes of alkanes, alcohols, ketones, pyrones, furanes, monoterpene and sesquiterpenes. GC/MS analysis showed 17 peaks which corresponded to alkenes hydrocarbons (tetradecane, tetracosane, tetracosahexaene, pentadecane, hexacosane, heptadecane and octadecane), alcohol (phenol), amide (9-octacenamide) and monoterpene aldehyde (9-octadecenal) (Darmasiwi et al. 2016).

Following solid-state fermentation and distillation of sorghum, a fermented product Kaoliang is prepared, further blended and aged by yeasts *Saccharomyces cerevisiae*, *Kazachstania exigua* and *Candida humilis*) to form yellow water, a by-product of fermentation. The optimization of fermentation process led to the enhanced production of aroma compounds, such as ethyl acetate, isoamyl acetate and 2-phenylethanol in the yellow water (Lai et al. 2019). Boratyński et al. (2018) carried out solid-state fermentation (SSF) on linseed and rapeseed cakes inoculated with different strains of filamentous fungi producing aroma lactone such as 1-phenylethyl acetate, a mixture of 'trans' and 'cis' whisky lactones, γ-decalactone, δ-decalactone, and cis-3a,4,7,7a-tetrahydro-1(3H)-isobenzofuranone, γ-decalactone, 1-phenylethyl acetate. Hosoglu et al. (2018) also proved that increasing the initial concentration of both yeast extract (YE) and glucose in the fermentation medium favoured both the growth of the yeast and production of fusel alcohols (isoamyl alcohol) in a bioreactor. When compared with SmF, this method of fermentation was found to lower the capital by approximately 78%. As the agronomic waste residues are usually utilized, therefore, it also provides a solution to the environmental hazards. Apple pomace was used as a substrate, inoculated with basidiomycete, *Tyromyces chioneus*. A pleasant flavour mixture, giving a combined aroma of stewed fruit and plum purée, was generated by the biotransformation using submerged cultures of the basidiomycete *T. chioneus.* GC-MS analysis showed that 3-phenylpropanal, 3-phenyl-1-propanol and benzyl alcohol were identified as potent aroma chemicals. E)-cinnamic acid was also identified as a precursor for 3-phenylpropanal and 3-phenyl-1-propanol for biotransformation (Bosse et al. 2013).The leaves of *Eucalyptus cinerea* from which essential oil has been extracted are used as a substrate and inoculated with two edible mushrooms *Pleurotus ostreatus* and *Favolus tenuiculus;*1,8-cineole was transformed to new aroma compounds which were 1,3,3-trimethyl-2-oxabicyclo[2.2.2]octan-6-ol and 1,3,3-trimethyl-2-oxabicyclo[2.2.2]octan-6-one (Omarini et al. 2015).

Olive mill waste fermentation was carried out by *Rhizopus oryzae* and *Candida tropicalis*, in shake cultures and bioreactor cultures. The concentration of d-limonene was determined as 185.56 μg/kg and 249.54 μg/kg in the fermented olive mill waste by *R. oryzae* and *C. tropicalis* in shake cultures, respectively, whereas in the bioreactor, it was determined to be 87.73 μg/kg and 11.95 μg/kg *R. oryzae* and *C. tropicalis*, respectively (Guneser et al. 2017).

de Aráujo et al. (2002) reported the production of 6-pentyl-α-pyrone (6-PP), related to coconut aromas, by *Trichoderma* sp. via solid-state fermentation and submerged fermentation methods. A higher yield of 6-PP concentration was found when sugarcane bagasse was used as a solid support. Kabbaj et al. (2002) reported the production of aroma compounds, using *Pleurotus ostreatus* JMO 95 fruit body and its mycelium as inoculum, by solid state and submerged state of fermentation. The aromatic spectra showed that the main aromatic compounds octan-3-one (sweet and fruity odour) and octan-3-ol (hazelnut and sweet herbaceous odour) were produced in the similar proportions on the agar surface and on the solid support culture, while the proportion was found to be low in SmF. Dairy flavour compounds such as *diacetyl*, *butyric acid and lactic acid are produced by semisolid maize-based using mixed cultures of Lactobacillus acidophilus and Pediococcus pentosaceus* (Escamilla-Hurtado et al. 2005).

7.3.2.12 Bioreactor Model

Packed-bed reactor and the fluidized bed reactor are used for the aroma compound production by microorganisms and enzymatic methods. The bioreactors can be operated in different modes such as batch, fed-batch and continuous. In the batch operation method, no fresh material is introduced or removed from the bioreactor while processing, whereas in the fed-batch culture, the feed is added continuously to the bioreactor in order to keep both nutrient levels and the growth rate maintained at a predefined value. When the bioreactor operates in the continuous manner fresh media is introduced and the product is also removed continuously. For example, a nylon-immobilized lipase from *C. cylindracea* in batch continuous-flow reactors has been used for the synthesis of ethyl propionate, isoamyl propionate and isoamyl butyrate in the continuous mode (Carta et al. 1991). Amyl caprylate has been synthesized using fluidized bed reactor inoculated with *C. rugosa* lipase immobilized on Sepabeads in both batch and continuous mode (Saponjic et al. 2010).

In situ removal process (ISPR) follows the production of the aromatic chemical by fermentation. On the basis of the physico-chemical properties of the target aroma product, a particular ISPR method can be followed involving the extraction, immobilization, evaporation, permeation. In addition, bioreactor/separation units are configured accordingly and also operated under the suitable conditions (Stark and Stock 2003). Červeňansky et al. (2018) designed a hybrid system for biocatalytic synthesis of 2-phenylethanol (2PE). Being toxic to the production strain, PE was continually removed from the fermentation broth using a membrane separation in a hybrid system consisting of a batch bioreactor and an extractive membrane module, which prolonged the production cycle and hence the efficiency of the process was enhanced. The volatile compounds were isolated and concentrated from the matrix by the processes such as steam distillation/extraction or supercritical CO_2 extraction or the solid phase microextraction (SPME) (Maarse 1981). Janssens et al. (1989) reported the stripping of acetate esters from the fermentation broth using the aeration-air of the fermentation which were then adsorbed on activated coal at the exhaust of the fermentor, and solvent extraction was used for its subsequent recovery.

Immobilized cell technology is used to protect microbial cells which are used in bioflavour production. Immobilization of microbial cells protects the cells from physico-chemical changes, inhibitory substances and contaminations. It also enhances substrate utilization, rapid fermentation rates and stability of the product (Nedović et al. 2016). In the processes of bioflavour production, the most widely used immobilization technique is the entrapment of cells within porous polymeric matrices and adsorption on various support materials. The carrier used in the immobilization process is important as it can affect and also control the flavour profile of the final product. The factors which determine the choice of the carriers are viz., its specific requirement, conditions for maintenance of immobilized cell viability and metabolic activity, cost effectiveness, ease of handling, adherence due to large surface area and presence of functional groups, food grade purity (Kourkoutas et al. 2010). For example, encapsulation in calcium alginate beads was used to immobilize *Saccharomyces cerevisiae*. The immobilized cells showed better growth performance and also improved de novo synthesis of phenylethyl acetate, ethyl hexanoate, octanoate, decanoate and dodecanoate. Due to immobilization, bioflavour production carried out in repeated batch fermentations of orange peel hydrolysate, was successfully maintained after six consecutive cycles of a total period of 240 h (Lalou et al. 2013).

7.3.3 Plant Tissue Culture Methods

Transgenic crop plants with higher yield, improved quality and desired characteristics of texture, aroma and flavour have been developed by inserting genes of known function (Speirs et al. 2000; Lewinsohn et al. 2001). Plant tissue culture method (PTC) is the culturing of plant cells on solid or in liquid culture. Although, the methods of PTC have been in use for the past hundred years, but they have been introduced for the production of aroma compounds only in the 1970s. It is now used for the commercial production of existing and novel flavours (Fu 1999; Boskovic-Dörnenburg and Knorr 2010). Tissue culture methods have already been employed for propagation of commercially important plants, for example, CFTRI has standardized the technology and methods of processing for the mass propagation of *Vanilla planifolia* by tissue culture techniques (https://www.cftri.res.in/technologies/MFP/vtc.pdf). One of the advantages of PTC is that unlike whole plants, these methods are not limited to geographic locations or the seasons. The aroma compounds can be isolated from cells or the medium with relative ease. However, this production method is quite expensive as the precursors are the compounds which are produced in relatively low amounts. The additional expenses are the cost of the medium and the purification of the compounds for food grade. Moreover, PTC can only be used effectively in systems for which the biochemical pathway of the aroma compounds is already known (Harlander 1994; Hrazdina 2006).

Plant cell cultures are normally grown under sterile conditions in which a part taken from the plant, known as an explant, is surface-sterilized. The explant is placed on a solid medium which contains major and minor salts, a carbon and energy source, normally sucrose and the growth regulators auxins and cytokinins to form an undifferentiated mass of cells called callus. When callus is added to a liquid medium, it forms the suspension cultures (Harlander 1994). Suspension cultures generally have a faster growth rate, are more homogeneous than callus material and thus can be cultivated on a large scale in bioreactors. High yielding plant cultures are screened and selected. The culture conditions are manipulated to stimulate the accumulation of secondary products. Other methods such as elicitation, permeabilization, product removal, immobilization and differentiation can also be used to enhance the production of secondary products (Scragg 2007). The transformed shoot cultures of *Mentha* exhibited the synthesis of monoterpenes in mint oil (Rhodes et al. 1991).

The flavour compound/ aroma such as 2,3-butanedione, apple aroma, cinnamic acid, caryophyllene, basmati flavour, cocoa flavour, flavanol, garlic, monoterpenes, onion, triterpenoid and vanillin have been produced from plant tissue cultures of *Agastache rugosa* (Kim et al. 2001), *Malus sylvestris*, *Nicotiana tabacum* and *Lindera strychnifolia* (Drawert et al. 1984), *Oryza sativa* (Suvarnalatha et al. 1994), *Theobroma cacao* (Townsley 1972), *Polygonum hydropiper* (Nakao et al. 1999), *Allium sativum* (Ohsumi et al. 1993), *Perilla frutescens* (Nabeta et al. 1983), *Allium cepa* (Prince et al. 1997), *Glycyrrhiza glabra glandulifera* (Ayabe et al. 1990), *Vanilla planifolia* (Dornenburg and Knorr 1996), respectively, via tissue culture methods. Multiple shoots of *Vanilla planifolia* were induced from nodal explants under influence of different concentrations of plant growth regulators such as kinetin. The in vitro cultured plantlet exhibited more amounts of vanilla flavour compounds in the cultured plantlets. It was found that enzymes of lignin biosynthesis (cinnomoyl CoA reductase and coniferyl alcohol dehydrogenase) as well as the enzymes potentially involved in benzoate biosynthesis (O-methyl transferase and glutamyl transferase) were induced by kinetin (Renuga and Saravana Kumar 2014).

The callus cultures of garlic (*Allium sativum*) and onion (*Allium cepa*) have been used for the synthesis of the flavour precursor, alliin. Allyl thiol and allyl cysteine, at a concentration of 10 mM, were incorporated into the callus medium for cultures of garlic and onion callus (Hughes et al. 2005). Addition of S-alk(en)yl donors or presumed biosynthetic intermediates aided in the synthesis of cysteine sulphoxide by tissue culture method in both onion and garlic (Jones et al. 2004). Normal and cell suspension cultures of flavour rich tuberous roots of *Decalepis hamiltonii* were used for the enhanced production of metabolites through ferulic acid (FA) feeding to the culture medium. Flavour metabolites such as 2-hydroxy-4-methoxy benzaldehyde (2H4MB), vanillin, 4-Methoxy Cinnamic acid derivatives and aromatic alcohols were produced as flavour metabolites (Matam et al. 2017). Using plant tissue culture method, flavour molecules can also be produced following biotransformation. Cell culture of Peganum harmala (African rue) converted geranyl acetate to geraniol and linalyl acetate to linalool and α-terpineol (Zhu and Lockwood 2000). Controlled-release polymer discs were made from poly-2-hydroxyethyl methacrylate containing geranyl acetate or linalyl acetate, which produced higher concentrations of their biotransformation products (Zhu et al. 2000). Geraniol is an essential oil constituent commercially produced by Mitsui Chemicals Ltd. by culturing *Geraminea* spp. (Ochoa-Villarreal et al. 2016). The commercial production of aromatic compounds can be carried out by using stirred bioreactors, bubble column bioreactors, air-lift bioreactors and wave-mixed bioreactors with one-dimensional (1-D) motion (Ruffoni et al. 2010; Georgiev et al. 2013).

7.4 Sensory Evaluation of Flavour Compounds

The sensory evaluation has to be performed after the synthesis of aroma compounds. The flavouring and fragrant components of compounds are detected by the head-space analysis. The volatile compounds can be measured by two methods: Gas chromatograph-mass spectrometer (GC-MS) and a GC-MS coupled with an olfactometric port or a sniff port (GC-O). Following the method of gas chromatography, the volatile components of a mixture are separated and then a mass-spectrometer is used to characterize each of the components individually. In GC-O, this system is additionally equipped with a sniff port because of which it is possible for a human to detect the components in the volatile mixture and thus determines the sensory flavour of the sample (Chambers and Koppel 2013). Electronic nose can also carry out the analysis of aroma, which often consists of non-selective sensors which interacts with volatile molecules so that if there is any physical or chemical change, then a signal is sent to a computer which makes a pattern, which is recognized and the compound is identified (Dhar et al. 2018).

Traditionally, the identification of flavours is being carried out by an expert panel. About 4 mL of sample is withdrawn from the shake flasks every second day after production and transferred into 20-mL snap-cap vials, which are then tempered to 40 °C for 5 min. The olfactory evaluation is done by a sensory panel. The panel consists of group of testers (at least three) who have exceptional sensory perceptions, thus can describe the fragrant products on the basis of taste, smell or texture. The odour intensity is rated on a scale ranging from one to five level (Bosse et al. 2013; Hootman 1992). The sensory classification of flavouring substances is carried out by the sensory panel and 'Aroma and Flavour Wheels', a pattern is generated by following a standardized system (Simat et al. 2017). The aroma wheel, consisting of three concentric circles of sensory descriptors and references, divides all the fragrant substances into families and sub-families and also characterizes them on the basis of the individual attribute of the substance (Simat et al. 2017).

7.5 Product Formulation/Delivery Systems of Flavours

The fragrance and flavour compounds have to be properly formulated after recovery, so as to maintain its stability, sensory effectiveness and to optimize their delivery in the food items (van Soest 2007). In encapsulation, the flavours are entrapped in a material due to which a protective matrix or shell is created. Encapsulation of flavours has been attempted and commercialized using different methods, viz. spray drying, spray chilling or spray cooling, extrusion, freeze drying, coacervation and molecular inclusion (Renu and Zehra 2015). In the spray drying method, the liquid encapsules are converted to solid (powdery) forms, which enables easy handling and also increases the efficiency of the aroma and flavour (Zuidam and Shimoni 2010). Currently, food industries are preparing nanoparticles of these flavour and aroma emulsions. Nanoencapsules range between 10 nm and 1 um in size (Tamjidi et al. 2013). Due to their very small size, the macro-scale characteristics, i.e. food texture, taste, odour and colour, are improved. This also enhances their characteristics of taste and aroma during their shelf life. Nowadays, liposomes are also used, as they can be tailor-made and have unique characteristics due to which complex flavour patterns can be programmed and released in the food products at pre-arranged rates (Emami et al. 2016). Nanoliposomes with encapsulated essential oil like *Zataria multiflora* are created by thin film evaporation method (Yoshida et al. 2010). Cyclodextrin encapsulations are also prepared which are toxic and inexpensive, poorly absorbed in the upper gastro-intestinal tract but readily metabolized by colon microflora (Astray et al. 2009).

7.6 Bioeconomy, Regulatory Aspects and Legal Status of Flavours

Today, approximately 5000 different aroma chemicals are available in the market including synthetic and natural product (Personal Care Magazine 2009). Flavour and fragrances account for 25% of the total food additives market (Dubal et al. 2008). The flavour and fragrance industry is segmented broadly into three areas: (1) Production of synthetic and isolation of natural aroma chemicals or essential oils/natural products, (2) Blending and compounding of these products into formulations so as to meet specific customer requirements, (3) Sale and use of these formulations in the production of various end-products.

The end-products of these formulations are foods, beverages, detergents and pharmaceutical products which are now produced and utilized in each and every country. The consumption in the global market has increased as these chemicals are not just used individually, but the flavour and fragrances are usually combined and blended, which imparts either an attractive taste or aroma or both to the processed foods and beverages. Not only the edible products but consumer products such as perfumes, toiletries, household cleaners, etc. also have acquired a pleasing scent owing to these wonder chemicals.

The end-use markets of these products are first-world markets. About 50% of these aroma chemicals are used in beverages and the rest are used for the formulations of soaps/detergents and cosmetics/toiletries. The largest market is the USA which accounts for 31% of the total market, followed by Western Europe (29%) and Japan (12%). The remaining market of flavours and fragrances lies in developing countries which have high growth rates as well as high market potential. In 2002, the worldwide flavour and fragrance business, which included the sales of compounded flavour and fragrance products, aroma chemicals as well as essential oils and natural extracts, was estimated to be $15.1 billion (Triumph Venture Capital (Pty) Limited et al. 2004). Due to the enormous growth, the value reached US$28.2 billion in 2017, showed an increase of 4.6% as compared to the previous year. It is expected that the global market value of flavours and fragrance will reach US$28.37 billion in 2023. As the Flavour and Fragrance industry is continually expanding, hence, in the future, it demands a definite and robust investment and research.

The enormous consumption of flavours and fragrances is anticipated to be driven by various factors such as increase in gross national income, rapid urbanization, rise in global population, enhancement of living standards, increase in demand for packaged food and increase in middle class population. As the demand for packaged food has also increased, it has led to the preferential incorporation of essential oil and natural extracts as compared to the synthetic chemicals. The population who consume low calorie or salt and sugar-free diets is another reason for increase in use of flavour additives as a taste appeal is required in dietetic and low-calorie foods (Berenstein 2015). Despite the tremendous rise the market is also challenging, being governed by various determinants like rising prices of raw materials, change in demand by consumers; there are also numbers of barriers for new compounds. The trends and developments in the market of these products are new launches, rise in consciousness about healthy and ethical products, change in consumer's choice and decision.

The high rise in the market of food, cosmetic, pharmaceutical and toiletries is speculated and requires an increased input of natural flavours and fragrances in the industry. It is estimated that the global market share of bio-based chemicals will rise from 2% in 2008 to 22% in 2025 (Biddy et al. 2016). This has paved the way for some biotechnological firms like DSM, a Dutch-based multinational life sciences and materials sciences company and another largest chemical producer company headquartered in Germany BASF (Badische Anilin- und Soda-Fabrik). BASF produced 4-decalactone, a peach flavoured compound, and got it distributed by its subsidiary co. Fritzsche Dodge & Olcott. It involved the bioconversion of triglyceride, 12-hydroxy-9-octadecene acid by *Yarrowia lipolytica*, with a yield of 6 g/L (Janssens et al. 1992). These companies have invested a lump sum amount of $13.5 million in the microbial based production of flavour and fragrance molecules in collaboration with a company named Allylix which is based in San Diego. Although there are no direct reports in literature about the bioeconomy of biotechnologically derived flavour and fragrance products, there is scarce data abut the comparison between their cost-effectiveness as compared to their chemical counterparts. However, there is an enormous difference in the costs of synthetic and natural aroma compounds. On an average, the market price of natural aromas is about 100 times higher than that of synthetic aromas. Essential oils and isolated aroma compounds are currently available at prices of more than 5000 $/kg. An essential oil, patchouli oil is currently produced via traditional agriculture and steam distillation from dried patchouli leaves, for which 100 kg of dried patchouli leaves is required to produce 2.2–2.8 kg of patchouli oil. This process lasts 8 h and 40 L of kerosene is consumed for the production (Kusuma and Mahfud 2007). Hence, the traditional process which is both energy inefficient and resource intensive can be replaced by microbial fermentative processes (Henke et al. 2018). Biotechnologically derived aromas can be a valuable substitute and in order to survive the competition in the market, the price of microbial flavours should range between 200 and 2000 US$/kg.

The biotechnological firms like DSM and BASF (Badische Anilin- und Soda-Fabrik) have invested a lump sum amount of $13.5 million towards the microbial based production of flavour and fragrance molecules in collaboration with another company named Allylix. Independently, Allylix and Isobionics are producing two citrus molecules, viz. valencene from the peel of the Valencia orange and nootkatone from the grapefruit peels. It has been suggested that there is potential for biosynthetic routes to completely replace any natural sources of flavour and fragrance molecules. Hence, now a number of the pharmaceutical and biotechnological companies are collaborating and adopting secretive policies and conditions to develop these natural aroma molecules (Gupta et al. 2015). For example, synthetic 4-decalactone which is the key flavour compound of peach costs 150 US$/kg, the compound from the natural source has the worth of 6000 US$/kg, whereas the biotechnological produced form is priced at 180 US$/kg (Dubal et al. 2008; Bicas et al. 2016).

The most widely used flavouring agent vanilla has a global demand of 12,000 tons/year, artificial vanilla is priced at 15 Euro/year while 50 tons of the natural extracts of flavour is required every year and is priced at a cost of 4000 Euro/year. It is estimated that bio-vanillin (vanilla flavour from biotechnological sources) will have a demand of 5000 tons/year and an average price of 800–1000 Euro/year. The firm 'Evolva' is commercially involved in the production of vanillin which produces a glycoside precursor to the vanillin molecule using a yeast that metabolizes glucose (Singh and Winters 2016). The biotechnologically produced vanillin can be considered economically viable as the synthetic vanillin is priced around US$11/kg, the natural vanilla flavour extracted from fermented pods of Vanilla orchids costs US$1200–4000/kg (Bythrow 2005). EveValencene™, an orange flavour and fragrance ingredient of food items, beverages, personal care and household products, is a fermentation product produced commercially by 'Evolva' (https://www.evolva.com/orange-flavor-valencene). Another valuable flavour is raspberry ketone (para-hydroxyphenyl-butan-2-one) which is present in very low concentrations in the berries (0.1–2.0 ppm or 4 mg/kg of berries), its potential market is 6–10 million Euros (Feron and Wache 2005). Although, the chemically synthesized ketone costs only US$10/kg but the flavour industry and the consumers prefer natural substance. Due to its high cost of extraction and inconspicuous presence (4 mg/kg) in berries, the current market demand of natural raspberry ketone could not be completed; biotechnological interventions are underway to rationalize its production. 'Rose aroma' is another aroma which is also in high demand in the flavour and fragrance industry, coded by 2-phenyl ethanol and 2-phenyl acetate. The chemically produced 2-phenylethanol has a market of 7000 tons/year, whereas the requirement of natural product is 0.5–1 ton/year, is sold at US$1000/kg and is mainly produced by yeast based bioprocess, since its isolation from the natural source is very costly (Schrader 2007).The natural peach aroma compound, gamma-decalactone was priced US$6000/kg, while the synthetic counterpart has been priced at US$150/kg, now the biotechnological aroma has reduced its price to US$300 kg/kg (Dubal et al. 2008).

The global limonene market size is projected to grow from 45 kilo tons in 2015 to 65 kilo tons by 2023 (Global Market Insights 2017). The cost of limonene has also increased in previous years, currently priced at around 20 $/kg (Ciriminna et al. 2014; Lange 2015). Natural lactones are also highly priced like the cost of γ-decalactones was over US$10,000/kg in 1980. But due to the biotechnological production, the prices reduced to US$300/kg (Schrader et al. 2004). Lactones were traditionally produced by chemical synthesis from keto acids, although their bio-production using fungal strains and biotechnological methods is now being favoured. Biotechnological production of γ-decalactones (GDL) and δ-decalactones (DDL) reached to US$1400/kg and US$6000/kg, respectively (Hui 2006).

'Amyris', a biotechnology and renewable products company, has collaborated with 'Firmenich', another company involved in the production of flavour and fragrance, to develop Clearwood. It is a mixture of the sesquiterpenes and alcohols which are found in patchouli oil. A yeast has been genetically engineered to metabolize sugar into the novel hydrocarbon chemical compounds which are found in patchouli oil. The market price of 'Clearwood' is half the price of patchouli essential oil, roughly US$47/kg, and production has reached 400 metric tonnes in 2017. The firm 'BASF' is executing the microbial production of 4-decalactone, a peach aroma which is distributed by its subsidiary company Fritzsche, Dodge and Olcott. This process involves the bioconversion of *Ricinus communis* (castor) seed oil, by *Yarrowia lipolytica*, which is composed of 80% of a triglyceride of 12-hydroxy-9-octadecene acid, also known as ricinoleic acid. Unilever' is involved in the commercial preparation of (R)-S-dodecanolide scale from 5-ketododecanoic acid using *Saccharomyces cerevisiae*. The production is carried out in a 30,000 L fermentor, 5-ketododecanoic acid is used for its buttery flavour in margarines (Tyrrell 1990). 'Hercules Inc' produces butyric acid and ethyl butyrate using *Clostridium butyricum*, converts glucose into butyric acid under anaerobic conditions, which is added for its natural cheese aroma (Sharpell 1985; Dziedzak 1986). 'Unilever' manufactures (R)-S-dodecanolide on a commercial scale using baker's yeast starting from 5- ketododecanoic acid, in a 30,000 L fermentor, the lactone which is produced can be used for flavouring in margarines (Dubal et al. 2008). Today, approximately 5000 different aroma chemicals are available on the market including synthetic and natural product (Personal Care Magaxine 2009).

The global market for aroma chemicals is estimated at US$4727 million in 2018, and is forecast to grow at a CAGR of 5.3% to reach US$6126 million by 2023. Terpenoids represent the largest product category, with a share of 31%, closely followed by benzenoids with 29%. The market for aroma chemicals is concentrated in the EU, the USA and China. Demand is lower in developing markets, as there is little perfumery (blending) activity, and these countries are much more likely to purchase ready-made compounds. The data in reports also showed that 47.13% of demand of the aroma chemicals is in foods and beverages field, 14.29% is used in cosmetics field and 22.99% in personal and household care. Hence, in the next few years, aroma-chemical industry will continue to be highly energetic industry. Sales of Aroma Chemicals have brought a lot of opportunities, hence more companies are entering into this industry with their biotechnological flavours and fragrances.

7.7 Conclusion

In order to meet the growing demand for flavour and aroma compounds, the chemical synthesis is generally preferred. Nevertheless, the chemical synthesis is not only unsustainable but also the synthetic product has lesser market value. Though the flavour and aroma compounds extracted from natural sources are valuable, the extraction processes are costly and inefficient. Also, the availability of plant sources of flavour and aroma compounds is influenced by season and crop geography. So, there is dire need for advanced biotechnological methods to produce flavour and aroma compounds. Incidentally, the developments in the field of genetic engineering, synthetic biology and metabolic engineering have provided opportunities to produce flavour and aroma compounds sustainably. The recent biotechnological approaches are though mostly in their primary stages, but their commercial viability is now getting confirmed. Perfume manufacturing microbes are now mimicking the natural fragrances in a realistic and commercial approach. The practical implementation of biotechnological processes requires the collaboration of researchers, funding agencies, governments and industries, who have to work together for the development of a true bioeconomy. In conclusion, the market-push in the form of high demand of flavours and fragrances can be met by the market-pull in the form of biotechnologically produced microbial flavours and fragrances.

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Phytochemicals for the Management of Stored Product Insects

8

Loganathan Manickam, Irengbam Barun Mangang, and Meenatchi Rajamani

Abstract

Phytochemicals are produced by plants which possess bioactive compounds responsible for plant defence against pests, pathogens, and other natural enemies. India is one of the mega diversity countries in the world, having many kinds of medicinal and aromatic plants. Bioactive compounds from plants will serve as a raw material for phytoinsecticides. It has several advantages over chemical insecticides in terms of biodegradability, safe to non-target organisms, and can be easily extracted from the locally available plant sources. It is an essential component in the Integrated Pest Management (IPM) of field and also stored product pests. Phytochemicals from neem, pyrethrum, sabadilla, and ryania based products are commercially available and are used for the management of agricultural pests. There is a huge demand to develop and employ phytochemicals for the management of stored pests since stored insect pests cause severe damage to the stored produce. The stored product pests reduce the quality of produce, contaminate the produce with uric acid and exuvia, and also produce allergens which results in reduction of commercial value of the products. There is a great potential to use phytochemicals for the management of stored pest and to develop commercial formulations for the benefit of the human beings. The identification of suitable plant material, developing suitable extraction method, proper testing against target organism, and developing formulations are important for integrating these phytochemicals in the IPM of stored product pests.

Keywords

Phytochemicals · Stored product pests · Hydrodistillation · Integrated pest management (IPM) · Insect repellent packaging

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8.1 Introduction

Stored grain pests cause significant damage to grains during storage, resulting in quantitative and qualitative losses to the stored grains and making it unfit for consumption. It attacks most of the cereals and pulses, millets, oilseeds, and processed commodities stored in the public godowns and storage units of food companies (Pourya et al. 2018). Stored product pests are majorly classified into internal and external feeders based on the feeding behaviour. Internal feeders are also called as primary pests which attack whole or unbroken grains, feed within the grains, and cause damages inside the grain. The symptom of damage can be noticed only after the emergence of the adults. External feeders are also known as secondary pests which attack only damaged grains and milled products (Table 8.1). Practice of chemical fumigation to the food grains results in residues in food materials and resistance development in insects (Subramanyam 2018). Stored product pests account to loss of 20–25% during 2010–2011 (Singh 2016). Controlling the stored pest and preventing loss of the food grains are necessary to maintain sufficient buffer stock (Nicolopoulou-Stamati et al. 2016). Chemicals in the form of fumigants are used at present to manage the stored product insects. Considering the safety and efficiency of using botanical insecticides, extensive studies on organic plants and their phytochemical activity are being studied by many researchers for the development of botanical insecticides for stored product pest (D'Incao et al. 2013). This chapter deals with the classification of phytochemicals, mode of action, extraction and testing methods, analysis of phytochemicals and management of stored pests by use of plant based chemicals.

8.2 Phytochemicals

Phytochemicals or phytoinsecticides are the chemicals derived from plant origin. It originates from the Greek word *phyto,* meaning "plant" (Breslin 2017). Each phytochemical has varying structure and performs different functions such as protection, growth acceleration, and reproduction in the plants (Huang et al. 2016). Phytochemicals are found in fruits, vegetables, grains, pulses, nuts, seeds, and other plant foods (Baxter et al. 1998). Since ancient times, medicinal plants and botanicals were used to treat chronic diseases like cancer, diabetes, and coronary heart diseases (Arnason et al. 2013). Certain plants contain phytochemicals (Table 8.2) which possess insecticidal properties against pests (Table 8.3). Phytochemicals can be

Table 8.1 List of internal and external feeders damaging stored commodities

Internal feeders	Rice weevil (*Sitophilus oryzae*), lesser grain borer (*Rhyzopertha dominica*), pulse beetle (*Callosobruchus chinensis*), cigarette beetle (*Lasioderma serricorne*), drug store beetle (*Stegobium paniceum*), angoumois grain moth (*Sitotroga cerealella*), and copra beetle (*Necrobia rufipes*)
External feeders	Red flour beetle (*Tribolium castaneum)*, saw-toothed beetle (*Oryzaephilus surinamensis*), and rice moth (*Corcyra cephalonica*)

Table 8.2 Bioactive compounds in plants

Plant	Bioactive compounds	References
Cymbopogon citratus	Citral	Anggraeni et al. (2018)
Allium sativum	Diallyl disulphide and diallyl sulphide	Plata-Rueda et al. (2017)
Carica papaya	Oleic acid	Ghosh et al. (2017)
Curcuma longa	Curcumin	Gul and Basheer (2016)
Acorus calamus	α and β-asarone	Devi et al. (2014)
Cinnamomum aromaticum	Cinnamaldehyde	Wong et al. (2014)
Andrographis paniculata	Andrographolide	Chao et al. (2009)
Ocimum basilicum	Estragole	López et al. (2008)
Azadirachta indica	Azadirachtin	Sadeghian and Mortazaienezhad (2007)
Mentha spicata	Carvone	Tripathi et al. (2000)
Citrus sinensis	d-limonene	Karr and Coats (1988)

categorized into four major types namely carbohydrates and lipids, alkaloids and other nitrogen containing metabolites, phenolic compounds, and terpenoids (Table 8.4) (Baxter et al. 1998). The bioactive compounds present in the phytochemicals are responsible for ovicidal, larvicidal, reduced progeny emergence, toxicity, and repellency. Phytochemicals can be extracted using different methods viz., solvent extraction, microwave assisted extraction, ultrasonic assisted extraction, and can be utilized for pest management (Altemimi et al. 2017).

8.3 Extraction Methods

Pre-extraction and the extraction procedures are important in processing bioactive constituents from plant materials. Traditional methods such as maceration and Soxhlet extraction using solvents are commonly used. Solvent preparation, solvent sample ratio, extraction procedures, and methods for extraction are to be considered when separating the compound of interest.

8.3.1 Solvent Extraction Method

The basic step for initiating solvent extraction is drying of the plant either through sun drying or hot air oven. This step is followed by pulverisation of the plant. It can be performed using mechanical means like mortar and pestle or a mixer. Other techniques that can be used are enzymatic degradation and chemical degradation. This helps in homogenisation with the solvent by allowing the solvent to penetrate the ruptured walls overnight at chilled condition (4 °C). Then it is filtered on the next day using muslin cloth or filter paper followed by evaporation of the solvent using

Table 8.3 Phytochemicals and their effectiveness against different stored pests

Description of botanical	Effectiveness	References
Essential oil of *Mentha viridis*	90% mortality against adults of *Callosobruchus maculates* at 4% concentration	Singh (2016)
Essential oil of *Rosmarinus officinale*	85% mortality against larvae of *Tribolium castaneum* at 3% concentration	Singh (2016)
Essential oil of *Pistacia atlantica*, *P. kurdica,* and *P. khinjuk*	Strong toxicity against adults of *Callosobruchus maculatus*	Pourya et al. (2018)
Essential oil of citronella	90–100% repellency against adult of *T. castaneum*	Licciardello et al. (2013)
Extract of *Xylopia aethiopica*	Effective toxicity in controlling *T. Castaneum* with 95% ethanol extract but no repellent activity	Babarinde and Adeyemo (2010)
Rhizome of *Drynaria quercifolia*	Effective pesticidal activity at 0.88–1.77 mg/ cm^2 using ethanol extract and repellency at 0.94 to 0.23 mg/cm^2 against *T. castaneum*	Khan et al. (2014)
Catmint oil (*Nepeta cataria*) and hydrogenated catmint oil	Effective repellency against *T. castaneum and T. confusum* adults	Arthur et al. (2011)
Acetone extract of *Curcuma longa* and *Allium sativum*	Effective reduction in emergence of larvae for *T. castaneum*	Ali et al. (2014)
Methanol extracts of *Acorus calamus* and *Illicium verum* fruit	100% mortality of *Sitophilus oryzae* and *Callosobruchus chinensis*	Kim et al. (2003)
Extracts of *Clausena excavate, C. lansium*, and *C. emarginata*	Repellent activity against *Liposcelis bostrychophila* (100%, 98%, and 96%, respectively)	Guo et al. (2018)
Essential oil of *Amomum villosum*	Contact toxicity against *T. castaneum* and *Lasioderma serricorne*	Chen et al. (2018)
Leaf extracts of *Cleistanthus collinus*	Toxicity and repellency against adults of *S. oryzae* and *T. castaneum*	Guru-Pirasanna-Pandi et al. (2018)
Essential oil of *Cyperus rotundus*	90–95% repellency against adults of *O. surinamensis*, *T. granarium*	Janaki et al. (2018)
Essential oil of *Cuminum cyminum* L.	Mean repellency activity of 92.58 against *T. castaneum*	Khorrami et al. (2018)
Essential oil of *Artemisia dubia*	Fumigant toxicity and repellency against *T. castaneum* and *Liposcelis bostrychophila* with LC_{50} values of 49.54 and 0.74 mg/L	Liang et al. (2018)

Note: Effectiveness of botanicals tested at laboratory scale only

rotary evaporator at the respective boiling point of the solvent (Khare et al. 2018). The solvent used for the extraction process of bioactive components from the botanicals varies based on the solute which is going to be extracted. Commonly used solvents are hexane, chloroform, ethyl acetate, acetone, methanol, and water listed based on the polarity in ascending order (Hassan et al. 2018; Shrivastava and Mishra 2019).

Table 8.4 Classification of phytochemicals

Sl. no.	Types of phytochemicals	Sub categories
1	Carbohydrates and lipids	Monosaccharide, disaccharide, oligosaccharide, polysaccharide, sugar alcohol and cyclitols, organic acid, fatty acids, hydrocarbons, acetylenes, thiophenes, and miscellaneous aliphatics
2	Alkaloids	Amaryllidaceae, betalain, indole, isoquinoline, lycopodium, pyrrolidine, piperidine, pyrrolizidine, quinolone, quinolizidine, steroidal, tropane
3	Phenolics	Anthocyanins, coumarins, flavonoids, lignans, phenols, quinones, tannins, xanthones
4	Terpenoids	Mono- and sesqui-terpenoids, diterpenoids, triterpenoid saponins, steroid saponins, phytosterols, carotenoids

8.3.2 Microwave Assisted Extraction (MAE)

Microwave heating is a process by which high frequency alternating electric field heats the dielectric material from inside to the outside (Marić et al. 2018; Kaderides et al. 2019). Microwave produces electromagnetic radiation consisting of alternating electric and magnetic wave which travels perpendicular to one another. The frequency of the electromagnetic radiation is 300 MHz to 300 GHz. The ISM bands which are used commonly in microwave are 915 MHz and 2450 MHz. In MAE, microwave radiation is supplied to the solution in short intervals. It causes heating of the mixture through ionic conduction and dipolar rotation. It takes lesser time to heat up the sample and provides uniformity. Exhaust fans and fumes detector should be provided in the laboratory and domestic microwaves are not advisable for use.

8.3.3 Ultrasound Assisted Extraction (UAE)

Ultrasound refers to sound waves with frequencies between 20 and 100 kHz (Chuyen et al. 2018; Wen et al. 2018). The use of ultrasound is often combined with other treatments at moderate intensity. When ultrasonic wave hit the surface of the solution it produces compression and shear waves. When both waves are combined together it produces instantaneous change in temperature and pressure that causes cavitations, shear disruption, weakening of cell wall, and free radical production in the plant tissues. This process produces heat which is cooled by placing the extraction container on an ice bath.

8.3.4 Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction is efficient, environmentally friendly, powerful, and faster. Hence it has been widely recognized as a green sample preparation technique. In supercritical fluid, distinct liquid and gas phases do not exist

(Sánchez-Camargo et al. 2019). It can effuse through solids like a gas and dissolve materials like a liquid (CO_2), ethylene, ethane, propylene, propane, and nitrous oxide are some examples of substances which can exist in the supercritical state. Comparatively CO_2 is best suitable for use as it is non-flammable, odourless, easily disposable, and available at low cost. Most importantly it has a lower critical point. SFE is a technique of extracting the bioactive component from the sample using supercritical fluid like CO_2 as the solvent (Yousefi et al. 2019). The Supercritical fluid used can easily be removed by depressurizing the sample where the solvent will turn to a gaseous state. Moreover, the risk of heating up the equipment is not there in case of SFE.

8.3.5 Hydrodistillation

Hydrodistillation is a conventional method used to extract essential oils, flavonoids, and other bioactive compounds from various plants. This method does not use organic solvents for extraction. Water or stream is used for the extraction of bioactive compounds from the plants. The basic steps involved in this extraction method are cleaning and cutting of plants, followed by soaking in distilled water at 1:2.5 ratio. The contents are then transferred into a round bottom flask, which is fitted to Clevenger apparatus and condenser. It is distilled for a period of six hours (Solanki et al. 2019).

8.3.6 Soxhlet Extraction

Soxhlet extraction technique is usually employed for the removal of fats from the sample using soxhlet apparatus (Azwanida 2015). The sample is kept in the thimble and the thimble is attached to the soxhlet flask where the solvent is added and it is connected to the condenser. When the apparatus is turned on, the solvent gets heated where evaporation and condensation takes place. N-Hexane (69 °C), petroleum ether (40–80 °C), and ethanol (78 °C) are the common solvents used in this technique.

8.3.7 Solid Phase Extraction (SPE)

Solid phase extraction is a sensitive method used for concentrating and purifying analytes from a solution by sorption onto a disposable solid phase (Płotka-Wasylka et al. 2015; Andrade-Eiroa et al. 2016). It consists of two phases: a mobile phase and a stationary phase. The mobile phase carries the molecules to be extracted. In normal phase SPE, the stationary phase absorbs the non-polar molecules while the polar molecules get eluded later. In reverse phase SPE, the stationary phase absorbs the polar molecules eluding the non-polar molecules at the end.

8.4 Testing Methods to Determine the Efficiency of Phytochemicals against Stored Pests

8.4.1 Area Preference Test

Area preference test is the most commonly used test against stored pests which was first validated by McDonald et al. (1970). Whatman filter paper can be used to perform area preference test. It should be cut into halves and treated separately with the extract and the solvent, respectively. After evaporating the solvents completely, the halves of the filter paper were reattached using adhesive tape and placed inside a petri dish leaving small gaps in between. The stored product insects, about 10 or 20 adults of same age were released in the middle of each petri plate and placed in a dark environment. The number of insects that moved to the treated and untreated sides of the filter paper were counted and noted down. The repellency percentage (%) was then calculated using the equation given below (Licciardello et al. 2013),

$$R(\%) = \frac{C - T}{C + T} \times 100 \tag{8.1}$$

where, R is the repellency percentage, C is the no. of insects available on the control half of the filter paper, T is the no. of insects available on the treated half of the filter paper.

8.4.2 Feeding Preference Test

The feeding preference of insect differs and each plant possesses various phytochemicals (Vet et al. 1983). The odour secreted by the host attracts the insects. An olfactometer is a device used for testing the feeding preference of stored product insects. Two arm and four arm olfactometer are available. The behaviour of insect movement differs for each type of odour secreted by the host. The insects should be released in the middle of the treatment chamber and the behaviour of the insects can be monitored. It has an insect drop point and a vacuum point. Air pump unit and vacuum unit are provided in a single controlling chamber. One end of silicon tube is connected to the middle-bottom of the acrylic chamber and the other end of the tube is attached to the vacuum connector. The remaining three silicon tubes were used to connect between the three air ways provided by the controlling unit to the three-ways of the acrylic chamber leaving one end of the treatment chamber as control (Defagó et al. 2016; Mangang et al. 2019).

8.5 Analysis of Phytochemicals

Purification of the active compound is the key step in analysing the phytochemicals (Obouayeba et al. 2015; Thakor et al. 2016). Column chromatography and thin layer chromatography are the most widely used purification technique. Chromatography is used to separate the active components based on polarity of stationary phases like silica, alumina, cellulose, and polyamide (Coskun 2016). In both chromatography techniques, the analytes are separated based on the amount of affinity between two phases. The mobile phase carries the solution to be purified. After purifying the bioactive compounds, it is subjected to structural clarification using spectroscopic techniques viz., mass spectroscopy, infrared spectroscopy, UV visible spectroscopy, and nuclear magnetic resonance (Dias et al. 2016).

8.5.1 IR Spectroscopy

Infrared light is an electromagnetic radiation which has a wavelength longer than visible light (0.7–1000 μm). Usually tungsten bulbs were used to produce infrared light and analytical applications are confined to the middle infrared range (3–8 μm), as the absorption of organic molecules is high in this region (Schulz and Baranska 2007; Baker et al. 2014). The light source is focused using a concave mirror to the sample area and the amount of light which pass through the sample is detected using thermocouple, pyroelectric, or photo-conducting detectors. Frequencies of infrared light absorbed are detected by the detector and plotted on a chart (frequency on *X*-axis and intensity of absorption on *Y*-axis).

8.5.2 UV Visible Spectroscopy

UV visible spectrophotometer measures the absorbance based on the transmittance by the light source (UV range: 185–400 nm, visible range: 400–800 nm) when it passed through a sample. It is calculated using Beer Lambert's law which states that absorbance is equal to the multiplication of absorbance constant, path length, and sample concentration (Priya et al. 2012). It uses deuterium arc lamp (190–420 nm), tungsten lamp (350–2500 nm), or xenon lamp (180–900 nm) as light source and it is focused to a monochromator using mirror or lens. The monochromatic light passes through the sample in the absorption cell (quartz, fused silica, or glass) and gets detected using photodiode or photo multiplier tube detector (Banu and Cathrine 2015; Altemimi et al. 2017).

8.6 Insect Repellent Packaging

The critical step towards maintenance of safer food with increased shelf life is packaging. However, the problem of insect infestation had been troubling the food retailers and wholesalers. Infestation may occur during production, storage, or transportation. In recent years, the research on insect repellent packaging is growing. The efficacy of packaging materials incorporated with essential oils such as citronella, rosemary, and oregano was studied (Licciardello et al. 2013). Microencapsulation technique was used to encapsulate cinnamon oil in the packaging material (Jo et al. 2015).

8.7 Constraints of Using Phytochemicals in Pest Management

The use of chemicals during storage is a regular practice used to keep the produce free from insect infestation. Several research were conducted on phytochemicals to use them as an alternative to chemicals. It was proven as an effective method at laboratory scale. Yet, the use of phytochemicals at commercial scale is required. Many problems were encountered during use of phytochemicals. Quantity of phytochemical required, their persistence in the environment, and effectiveness against various stages of pests are to be considered. Phytochemical degrades more rapidly in the environment than the chemicals and are slow in action. Hence, it is not feasible to use it as a sole method.

8.8 Conclusion

There are 50,000 medicinal plants and botanicals available across the world. Yaseen et al. (2019) reported that 59.37% out of 30,000 plants were documented to have medicinal use present in the Royal botanical garden, Kew. Research and concerted efforts are required to commercialise the use of phytochemicals as a tool in the integrated pest management of stored product insects. Micro- and nano-encapsulation techniques can be used to encapsulate the phytochemicals and to improve its release profile. Use of phytochemicals along with other biological method aid in the safety of human health, well-being, and also sustainability of ecosystem.

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9 Assessing the Impact of Indigenous Knowledge Systems on Sustainable Agriculture: A Case Study of the Selected Communities in the City of Tshwane Metropolitan, Gauteng Province, South Africa

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Abstract

Indigenous farming methods as a part of the indigenous knowledge system (IKS) are complex, environmentally friendly, sustainable, cost-effective, culture-specific and play a vital role in the cultivation of vegetables and livestock among indigenous communities. The use of IKS has been beneficial to those practising indigenous farming methods; however, its benefits are highly dependent on the agricultural models that are utilised. There is an association between the implementation of IKS in agriculture and the natural form of the products produced. The link of the two concepts of the method of farming and the form of products enables the increase of food production, with a positive impact on food security in communities. The focus of this study was to assess the impact that the usage of IKS has on sustainable agriculture and to establish how this impact also affects food security in the selected communities of the City of Tshwane Metropolitan. The study was conducted in the geographical area of the City of Tshwane Metropolitan, but in different localised geographical areas. The objectives of the study are: (1) To describe and identify challenges and issues faced in sustainable agriculture in selected rural communities in the City of Tshwane Metropolitan; (2) To identify best practices in using IKS ensuring food security through sustainable agriculture in selected rural communities in the City of Tshwane Metropolitan; and (3) To identify ways in which indigenous knowledge and its practices and innovations might enhance livelihoods in a manner that is

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ecologically sustainable, economically viable, and socially acceptable. The collection of data was done through semi-structured face-to-face interviews utilising a questionnaire as a guide. The interviews were conducted with farm owners and workers in different geographical areas of the City of Tshwane Metropolitan. The observation method assisted in reducing some of the challenges in this research, for example, the language barrier (with the majority of the participants, the interview had to be conducted in the local language of either Sepedi, Setswana, Zulu, or the local dialect informally known as "Pretoria taal"). Purposive sampling was used and the sample researched was from a small holder farmer database provided by the Agricultural Research Council-Vegetables and Ornamental Plants (ARC-VOP). The findings of the study can be a base for a more in-depth focus on the knowledge and the best practices that exist in the selected communities, which could reduce food insecurity and encourage the growth of agriculture in these communities and households. Although the data was collected in one municipality area, the location of each participant was in a different geographical area that allowed a much broader knowledge base and practices in the field of IKS and sustainable agriculture. The results indicated that although the participants appreciated the benefits of IKS, as it is associated with natural farming of produce, the benefits of modern technology could also be utilised where the combination of a variety of knowledge systems could enable the farmers to get more yield on their crops. The commercially focused farmers indicated that they utilised both methods in their agricultural practices to enhance production and meet the current food demand. The usage of IKS and other traditional agricultural practices seemed to be more prevalent in community-based farming rather than those in commercial farming. One of the underlined benefits of IKS sustainable farming, although IKS is only recently being documented, is that it gives an opportunity for communities to come together and share stories of success or failures and lessons learned. Indigenous knowledge is normally shared in the local language, which makes it easy to understand. The combination of modern technology and traditional farming techniques enables effective and faster farming activity using less energy. Hence, one of the recommendations is an in-depth study of how to utilise the positive and functional attributes of IKS to modern farming and to commercial agricultural practices. This can allow the enhancement of both schools of thoughts and yield positive results. For example, in the interview session with the representative and farming expert from Agri-Skills, the researcher got the opportunity to see farming tools designed by Agri-Skills, which incorporate traditional farming methods with the latest technology to enhance the farming process. These farming tools are mainly used in the rural farming areas, which have limited resources. The study thus recommends that the sharing of IKS and incorporating it with technology and modern agriculture can create a new dynamic, agricultural practice that will benefit commercial farmers, community or primary farmers, and households with functional gardens.

Keywords

Indigenous knowledge system · Gauteng Province · South Africa · Sustainable agriculture

9.1 Introduction

The presence of indigenous knowledge systems (IKS) in communities that practise such systems cannot be ignored as people of such communities have always gained knowledge through experiences and practices they have engaged in for the longest of time. The differentiating factor of these knowledge systems is that most of them are not formally documented and their presence is more prevalent in storytelling and practices. Human beings have been producing knowledge and strategies enabling them to survive in a balanced relationship with their natural and social environment over many centuries (de Guchteneire et al. 1999). Indigenous knowledge (IK) is mainly tacit, unique, non-systematic, derived from local experiments, innovations, creativity, skills, and experiences and embedded in the minds and activities of communities with long histories of close interaction with the natural environment across cultures and geographical spaces (Lwonga et al. 2011). These statements briefly paint a picture of the characteristics of the type of knowledge system that is present in communities; however, the majority of this type of knowledge system is not documented formally, which influenced and encouraged the interest in the topic and study.

The rapid development globally due to globalisation and urbanisation has created serious challenges with regard to the usage and distribution of natural resources that are currently at our disposal. These problems were identified in a United Nations Development Programme (UNDP) report as cited by Gupta (2011): challenges of global warming; rapid loss of biodiversity; crisis-prone financial markets; growing international inequality; and the emergence of new drug-resistant disease strains and genetic engineering. As a result of these challenges, communities frequently experience the need to go back to the knowledge repository, to access knowledge and experiences that have been passed on from one generation to the next and to apply these in their day-to-day practices and activities. Due to IKS being part of the way communities engage and perform tasks, the usage and impact of it are not always conscious and documented, for example, the knowledge of when to plant which crop without referring to any documented material, natural ingredients to use for medicinal purposes, and techniques to preserve food using the sun, like dried “morogo”. However, urbanisation and integration with other communities are increasing the possibility of essential IKS being lost and not fully utilised.

The contributing factor to the reduction of the use of IK in communities can be attributed to the shift from the extended family unit to nuclear families (smaller family unit) and the latter engaging less with extended families. This results in the weakening of links with the grandparent generation, who are the repository of much knowledge and the second filial generation (the second and third generations in communities), which is alienated and removed from IKS due to the power of modernity and urbanisation (Eyong 2007). Knowledge erosion is a threat, as it becomes not only difficult to conserve what we do not know, but also the rapid degrading of natural resources. It, therefore, becomes essential and necessary that a method is established to “go back in time” and establish solutions based on the past to the current challenges, in order to ensure a good future and sustainability of the resources that are currently utilised for day-to-day survival (Eyong 2007).

Briggs (2013) identifies the following challenges that are experienced in the usage of IK systems in sustainable development:

- Indigenous knowledge is locally and geographically specific
- The integration of IKS with formal science

These challenges were investigated further in this study as it seeks to establish and find a workable solution to them. Due to IKS being of a historic nature it may be beneficial to find a manner in which it could be integrated into the current agricultural practices and to identify best practices in which IKS could be elevated from local to regional and, perhaps, to national practices. The manner in which natural resources are currently consumed is starting to become a major concern globally, as the demand for resources is increasingly higher than the capacity of production. Using IK as an alternative, an additional or combined knowledge system is able to yield benefits for sustainable agriculture and create alternatives and options in ensuring the sustainability of resources and food security in communities. Environmental changes that are currently being experienced may be best countered by diversified indigenous survival strategies and adaptive responses developed at a household level and at community levels (Eyong 2007).

Aluma (2004) states that “discussions on agriculture and food security (or rural livelihoods as a whole) reveal that the primary drivers for local change are a deteriorating natural resource base (loss of natural habitat, deforestation, soil degradation), declining agriculture productivity, loss of indigenous cultivation practices, and conflicts over access to and the utilisation of natural resources”. The usage of IKS also enables smaller farmers to engage in sustainable agricultural practices and be instrumental in the increase of food security in local communities and in the country.

This study investigated the key conceptual elements of IKS, namely sustainable agriculture and food security by understanding the impact thereof and the relationship they have on each other. The impact of IKS on sustainable development may be deemed beneficial or detrimental in addressing the current sustainability issues that most rural communities are experiencing, especially in the area of encouraging and implementing sustainable agriculture. In order to achieve a beneficial impact, solutions need to be identified to deal with establishing the importance and relevance of IKS and to introduce an effective method to integrate IKS in modern living, preserve the knowledge and experiences in order to use it effectively in food security, as well as to develop and apply the principles of sustainable agriculture.

Understanding and appreciation of IKS are essential for promoting sustainable agriculture development. IKS provides a cultural basis for non-formal agricultural programmes that is absent in technology transfer approaches (William and Muchena, 1991). The effective application of IKS in sustainable agriculture also enables a variety of biodiversity in the land. This growth in biodiversity is also based on sustainable land management. Sustainable land management, which is a knowledge-based procedure, helps integrate land, water, biodiversity, and environmental management to meet the rising food and fibre demands while sustaining the ecosystem services and livelihoods (World Bank 2008). The proper management of land and its resources will also be essential in ensuring that communities are able to meet the requirements of the growing population.

In the management of land for sustainability, it is essential to ensure that the land is properly utilised in order to enable full satisfaction of current food and land requirements and also for the future generation. Sustainable land management success also involves the inclusion of not only the western knowledge system but also the integration of all systems that are available in the community. In sustainable land management (SLM), the World Bank (2008) states that in order to optimise the usage of resources, the following activities are involved:

- Preserving and enhancing the productive capabilities of cropland, forest, and grazing land;
- Sustaining productive forest areas and potentially commercial and non-commercial forest reserves;
- Maintaining the integrity of watersheds, for water supply and hydropower generation needs and water conservation zone; and
- Maintaining the ability of aquifers to serve the needs of farm and other productive activities.

The management of land in accordance with the above activities ensures that biodiversity in the land increases. The usage of IKS in this regard ensures that there is a continuous and effective sustainable land management and that communities focus on IKS-knowledge as integration with other systems (World Bank 2008). There is a significant contribution that IKS has on global biodiversity and conservation initiatives in communities.

Nakashima and Roué (2002) state that most regions that are biodiversity-rich are normally areas that still apply IKS in the sense that the persistence of traditional ways of life has gone hand-in-hand with the maintenance of ecological systems and the conservation and even enhancement of biodiversity. In conjunction with ensuring the future availability of resources and the dealing with current usage, it is beneficial to find solutions in repairing the damaged resources and restore them and mitigate the adverse effects of earlier misuse (Nakashima and Roué 2002). To mitigate the misuse of resources and to make decisions about what needs to be done can be achieved by implementing a method of assessing the environment utilising IKS.

The problem that was investigated was whether selected (rural) agricultural communities in the City of Tshwane Metropolitan understand the impact of IKS in their agricultural practices. Furthermore, how the knowledge was acquired and what initiatives these communities were engaged in, in order to ensure that the knowledge of their agricultural practices is preserved and shared within the communities. The study also further probed how the usage of IKS has affected sustainable agriculture by ensuring the preservation of natural resources to ensure the availability of such resources in the future (the beneficial effect).

9.2 Aim and Objectives

The aim of the study was to decipher the impact of indigenous knowledge system on sustainable agriculture in the selected communities of the City of Tshwane Metropolitan, Gauteng Province in South Africa. The specific objectives of this research have been identified as follows:

- To contextualise the impact of IKS by defining and exploring related concepts;
- To define and systematically analyse the impact of IKS on sustainable agriculture;
- To describe and identify the challenges and issues faced in sustainable agriculture in the selected rural communities in the City of Tshwane Municipality;
- To identify best practices in the utilisation of IKS to ensure food security through sustainable agriculture in selected rural communities in the City of Tshwane Municipality; and
- To identify ways in which indigenous knowledge and its practices and innovations might enhance livelihood in a manner that is ecologically sustainable, economically viable, and socially acceptable.

9.3 Research Methodology

Research is systematic, that is, it is the adoption of a coherent strategy or a set of principles to study an issue of interest (Chilisa 2012). This process includes the gathering of data in order to understand or explore the knowledge base in a particular area or topic. Such a coherent strategy usually commences with the identification of an area of interest to study; a review of the literature to develop further understanding of the issue to be investigated; and the choice of a research design or strategy that will inform the way the sampling of respondents is performed, the instruments for data collection, the analysis, interpretation, and reporting of the findings (Chilisa 2012).

9.3.1 Research Design

This study was based on IKS and how the identified communities in the City of Tshwane Metropolitan interacted with the environment, with specific reference to sustainable agriculture. In this research an approach to how IKS needs to be investigated is defined which informed the decision to follow the qualitative research method. However, the quantitative research method was needed in order to give a broader understanding of the community and the decision to utilise IKS in sustainable agriculture. It was these two views that informed the choice to use a mixed-method research approach. A mixed-method research approach is regarded as a third major research approach or research paradigm, along with qualitative and quantitative research (Johnson et al. 2007). In the article "Toward a Definition of Mixed Methods Research" Johnson et al. (2007) define mixed-method research as the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts, or language into a single study or set of related studies. The utilisation of the mixed method guaranteed a more real reflection and application of the considered variables in practice.

The study focused on exploring and highlighting IKS and sustainable development within the context of sustainable agriculture. The research procedure selected for this study incorporated a literature review and an empirical study that employed semi-structured interviews and observations in selected communities of the City of Tshwane Metropolitan in the Gauteng Province. The observation method enabled the gathering of data from the communities that led to a comparison of the IKS used and the determination of the best practice in those systems. Further, literature review was undertaken to establish the depth of completed research and to collate the research findings on the topic. The literature was utilised as a method to establish a relationship between IKS and sustainable development focusing on sustainable agriculture.

9.3.2 Research Setting

The research was conducted in the geographical area of the City of Tshwane Metropolitan in the communities of Bronkhorstspruit, Centurion, Cullinan, Winterveld, Soshanguve, and Hammanskraal in the Gauteng Province. The communities of the City of Tshwane Metropolitan have been selected as those who utilise indigenous knowledge within their agricultural practices. The research undertook to understand the impact of IKS on sustainable agriculture in these communities. The research enabled the establishment of similarities and differences in the manner in which indigenous knowledge within sustainable agriculture is exploited. The impact of indigenous knowledge and how the participants benefited from applying it were analysed, and its importance and benefit to the community were highlighted.

9.3.3 Sampling

"You cannot study everyone, everywhere doing everything" (Punch 2003). Although the study was being limited to the mentioned communities in one municipality in the Gauteng Province, it would have been challenging and arduous for all the people within the community to be contacted and interviewed. Therefore, a sample was used. Sampling is a technique employed to select a small group with a view to determining the characteristics of a large group (Brynard and Hanekom 2006). The method of sampling that was applied was one that focused on community members that constantly use IKS to sustain themselves and use it in sustainable agriculture. The sampling for the research was based on a list of agricultural practitioners provided by the Agriculture Research Council-Vegetables and Ornamental Plants (ARC-VOP) and from informal interviews with participants of Agrifest, the conference at the Mexico Embassy, and the session at the Agri-Skills institution.

Punch (2003) identified a number of non-probability sampling techniques, and in this study, the researchers used the combination of two non-probability sampling methods namely; convenience sampling and purposive sampling. Wysocki (2008) defines the two sampling techniques as follows:

- Convenience sampling is the use of subjects who are available, but not necessarily representative of a population and
- Purposive sampling is a method in which each element is selected by the researcher for a specific purpose.

These methods were selected to enable the collection of data from the abovementioned communities engaging in the use of IKS in sustainable agriculture, so as to be more focused on and specific to the field. With the assistance of the particulars entered into the database provided by the Agricultural Research Council-Vegetable and Ornamental Plants (ARC-VOP), the possible participants were contacted telephonically, and the purpose of the study and method of data collection were explained. It was during this time that permission and availability of the participants were requested and once granted, appointments were organised based on the availability of the participants. The focus and choice of the participants were based on the work that they have done in the field of indigenous knowledge and their understanding and practice of sustainable agricultural methods.

9.4 Data Collection

Data collection was conducted by means of semi-structured face-to-face interviews which were conducted at 14 farms in the City of Tshwane Metropolitan with farmers and IKS practitioners in the selected communities. Babbie and Mouton (2001) highlight and emphasise the following general rules for face-to-face interviews, which were considered at the time when the interviews were conducted. These rules cover the following aspects and were followed by the researcher:

- characteristics of the interviewer (language, age, ethnicity);
- familiarity with questions (know the field that is being researched);
- recording responses exactly (do not make own assumptions/interpretations about the answers rendered), and

- probing for responses (ensure that the interviewee understands exactly what is asked and that the response is applicable to what was asked).

As the research followed a mixed-method approach, both quantitative and qualitative data collection methods were utilised.

9.4.1 Quantitative Data Collection

In the study, a semi-structured questionnaire was utilised to gather data. This questionnaire was utilised in order to give a flow of the required information and some element of structure in the gathering of data. The questionnaire was instrumental in allowing and giving the researcher an opportunity to probe more and have a systematic flow of information. However, it is essential to state that the quantitative data was mainly focused on the biographic data. Quantitative data collection focuses on data that can be measured, it is effective at answering the "what" or "how" of a given question, it is concerned with collecting and analysing data that is structured and can be represented numerically. The statistical information was utilised to plot different biographical attributes that could influence the usage of IKS in sustainable agriculture. The quantitative data forms a good foundation for understanding and better probing the qualitative data.

9.4.2 Qualitative Data Collection

Qualitative research is the development of concepts which help us to understand social phenomena in natural (rather than experimental) settings, giving due emphasis to the meanings, experiences, and views of the participants (Pope and Mays 1995). Qualitative research is aimed at understanding and solving social problems and phenomena. It is aimed at answering the question of "why" and "how". In the study, the focus was on understanding why communities use IKS, how they use IKS in sustainable agriculture and the impact, and benefit that the choice of the farming process has on them and the community. Qualitative research furthermore aims to help researchers to understand the world in which they live and why things are the way they are; it is concerned with the social aspects of our world and seeks to answer questions about:

- Why people behave the way they do?
- How opinions and attitudes are formed?
- How are people affected by the events that go on around them?
- How and why cultures have developed in the way they have?

These questions were aligned in the process of collecting data as the researcher needed to understand why the choice of a particular agricultural process, the view of the participants on the subject of IKS, and how the agricultural choice impacts the community and their businesses. These factors and explorative questions were incorporated into the research questions and form the basis for achieving an understanding of the research objectives. For the purposes of this research, semi-structured interviews were conducted utilising the questionnaire as a basis and guideline in the data collection. The researcher spent time with the selected communities to observe how they use indigenous knowledge in their agricultural practices. The said observation was unstructured although, as stated above, a questionnaire as an instrument was utilised for direction and giving a guide on the type of information that needed to be probed further. McKechnie (2008) defines unstructured observation as follows: In unstructured observation, the researcher enters the field with some general ideas of what might be salient, but not of what specifically will be observed. Therefore, observation is holistic, unstructured, and unfocused, with the investigator attempting to document as much as possible about the setting and its participants in order to discover themes of interest. The unstructured observation was also chosen as it is not constrained by checklists and a coding scheme (McKechnie 2008).

9.4.3 Data Analysis

Data analysis is the range of processes and procedures whereby the researcher moved from the data that had been collected, into some form of explanation, understanding, or interpretation of the people and situations that are investigated. The process of analysing is complex and begins with a set of data that on its own bears no meaning but through the analysing of this data, information, and meaning is derived from it. This ensured that the researcher was in a position that makes sense of the responses received in order to derive meaning from the total data collected (De Vos 2011).

The process of data analysis afforded the researcher to answer the research questions and present the collected data in a systematic manner that gave the data meaning and told a story of the field of interest. As mentioned earlier, both qualitative and quantitative data were collected. The data was collected from a semi-structured questionnaire which has two sections for quantitative data and qualitative data. The first part of the questionnaire (Section A) consisted of biographic and background information and the second part (section B) qualitative information. To provide meaning to the data collected, the presentation of the findings and results was done in a narrative manner.

The participants of the study included IKS farmers and practitioners living in the selected communities in the City of Tshwane Metropolitan's geographical area. The farmers ranged from commercial farmers to community farmers (practitioners), who also had functional household gardens (these are people who use their own yards to grow different types of crops for their families). The analysing of this data followed the deductive approach. The application of the deductive approach includes the establishment of patterns or themes (Creswell 2013), which were utilised in the data analysis.

9.5 Results and Discussion

Table 9.1 shows the geographical distribution of respondents in the City of Tshwane Metropolitan. There were a total of 26 farmers and farm workers interviewed and a total of 14 farms visited. The representation of gender from the list of respondents was equal. From the participants interviewed during the data collection, one of the aspects that was observed was that the female participants focused on community-based farming and primary agriculture. The farms of the female participants were, therefore, more focused on community growth and selling of the produce on a community level in the surrounding areas. The male counterparts, on the other hand, were more focused on commercial farming and business growth; the business models of these farmers were on a larger scale and selling their produce at larger markets outside their immediate communities.

The age groups of the participants were also diverse, with most of the participants in the early and late fifties. All 26 farmers who participated in the study are of African descent and are originally from South Africa, with an exception of one participant who was a citizen of Lesotho; she has however been residing in South Africa for more than 20 years. Nineteen of the participants had completed their matric level as their highest qualification. Two of the participants indicated that they have a qualification in agriculture, one participant had a diploma in agriculture and was a teacher for 20 years before moving into the agriculture field after retirement. Also, one of the participants completed his master's degree in agriculture about five years ago. Twenty-three of the participants had also taken part in courses provided by agricultural institutions more specifically at the Agriculture Research Council (ARC). All the participants stated that they participated in study groups within the community to improve their knowledge in the field. There were three participants engaged in peanut farming and production industry (this group of farmers utilised mixed agricultural practices in their production process and the farming practices) who were offered the opportunity to study agriculture in China

Table 9.1 Study area (City of Tshwane Metropolitan) and distribution of respondents

Area		No. of respondents	No. of farms
Centurion	Mnandi	2	1
Bronkhorstspruit	Onspoed	2	1
	Sokhulumi Village	5	2
	Boschkop	1	1
Cullinan	Onverwacht	1	1
	Refilwe	1	1
Winterveld	Soutpan	2	2
	Jackalasdans	3	1
Hammanskraal	Temba	2	1
	Majaneng	6	2
Soshanguve	Block P	1	1
Total		26	14

in a youth development programme after the completion of their matric; in this programme they managed to learn farming practices from a Chinese perspective which included both modern and indigenous practices.

The number of years engaged by the respondents in the agricultural field was analysed. Thirty-nine per cent of the participants indicated that agriculture has been part of their lives since childhood. Eight per cent of the participants indicated that agriculture has been the only form of employment they have known as their parents worked on farms and they also started off working on farms. Twenty-three per cent of the participants indicated that entering the field of agriculture was not exclusively based only on the passion, but also on other factors such as unemployment, gap in the field of agriculture (with regard to youth involvement), lifestyle changes, community building, and creating innovative ways of farming while using traditional knowledge to conserve the environment.

The reduction of food insecurity is achieved by the availability of nutritious food in the local proximity of the community. The availability of food near the residence of communities benefits the community as it reduces travel costs to acquire needed resources, like vegetables and livestock. The participants at Cullinan, Winterveld, and Bronkhorstspruit indicated that during the harvest of crops such as spinach, onions, tomato, chomolia (kale), mealies, and potatoes, the excess produce is donated to a charity organisation, creches, and child-headed households within the communities. There were respondents who have adopted poor families and donated vegetables to them on a regular basis.

The following key statements were made by the participants when the elaboration of the impact, the current work, and agricultural practices had and will have on sustainable agriculture:

- Sustainable employment, which entails the employment of community members on a permanent basis or on long-term contracts.
- Encouraging and increasing food security by ensuring the availability of food to the communities and in the food markets in the City of Tshwane Municipality.
- The enablement and encouragement of the growth of the agricultural sector in general, and reigniting agricultural participation and interest in the sector especially to the African community.
- Contributing to the education knowledge base by participating in research initiatives and being part of the school system by teaching pupils in high school about agricultural practices.
- The participants also created and participated in support activities to upcoming farmers who need advice, information, guidance, and mentorship in the field of agriculture.

The impact on the community is also aligned with the understanding and usage of IKS in sustainable agricultural practices.

9.5.1 The Contextualisation of IKS

The contextualisation of IKS was achieved by exploring the participants' understanding and views of indigenous knowledge systems. In the data collection process, there were various views on the understanding of the concept that identified similarities and differences in how this knowledge system impacts on agricultural practices. Indigenous knowledge is the local knowledge that is unique to a given culture or society. It is the basis for local-level decision-making in agriculture, health care, food preparation, education natural resources management, and a host of other activities in rural communities (Warren 1991). The contextualisation of IKS included how the knowledge was acquired and the understanding of the relationship between the concept of sustainable agriculture and IKS.

In exploring the concept of IKS, it was imperative to indicate and establish the participants understanding of IKS, which influenced the direction of the interaction and observation process. The following is a descriptive summary of the definitions of IKS provided by the participants:

- The application of indigenous knowledge in agricultural practices encourages the utilisation of land and crops in its natural form without adding any artificial chemicals.
- IKS is defined as knowledge that has been part of the community for generations and it has transferred from one generation to the next through different sharing tools and mechanisms like storytelling, and it is taught practically by the elderly within families and close communities.
- IKS consists of knowledge that is formed from beliefs and cultural practices and defines the manner in which communities and individuals act and behave towards certain concepts and situations.
- The application of indigenous knowledge supports and encourages the use of indigenous crops, which are locally grown and are not available in other locations.
- IKS is the type of a knowledge base that encourages working with nature to optimise the crop and livestock production rather than working against it and utilises experiences on how people in the bygone years used to operate in different sectors of life.

The identified commonality in the responses with regard to IKS was that IKS is a generational type of knowledge which evolves over time that encourages the usage of products in its natural form. This type of knowledge is normally transferred through storytelling and practical experiences which can both be a benefit as previously shown and a challenge in instances where the knowledgeable person is no longer staying in the community. One of the highlights in the data capturing sessions was there is a clear understanding of IKS and its relation to agriculture by the younger generation farmers as well. The importance of utilising IKS was mostly associated with using natural resources rather than utilising man-made chemicals in fertilisation and pest management. One of the examples is using chillies, garlic, and other herbs to create "pesticides". This method is cheaper to maintain and, as stated by the respondents, more effective in pest management. The question of whether IKS is used in their chosen agricultural practices was replied to in the following manner:

In the questionnaire, the option for choosing the usage of both modern knowledge systems and IKS was not provided for. During the data capturing session one of the observations and findings was that 40% of the participants utilised both systems in their agricultural practices. There was a participant who exclusively stated that because of the commercial focus and business model of their farm, the participant's choice of farming was based on a technique which they deemed as sustainable and environmentally friendly called hydroponics[1]. However, with other crops that require more time and maintenance, traditional farming methods were preferred, and these participants also understood the principles of IKS in farming. The choice to include the hydroponics technique to these participants was also to ensure the sustainability of the environment. The economic impact is that this type of farming enabled the farmers to provide the crop throughout the year, even when the crop is out of season in South Africa. The decision to combine multiple knowledge systems could be an indication that the participants took time to identify the best practices and advantages of both systems to enhance their production and have more yield on the crops. There was an indication from the majority of the participants that the choice to utilise traditional farming methods and practices is essential for certain types of crops and has an impact on the crop that is produced.

Ninety per cent of the farmers stated that the knowledge and the experience were generational family knowledge, which has been passed on from one generation to the next over the years, either through storytelling or practical participation in farming through the experiences of family members. These farmers came from families that had generations of farmers and they currently farm on the inherited land. About half of the farmers obtained knowledge from parents who had functional gardens.

Additional sources of knowledge acquisitions were also identified in the study. The respondents were able to acquire and share knowledge from participating in study groups with other agricultural practitioners; these groups are organised in the areas that the participants are located. The farmers also have networks where they engage and interact with colleagues on other farms, engagements with agricultural suppliers, and for the livestock farmers, sessions with veterinarians also provided an opportunity to learn both modern animal care and traditional animal care. The knowledge is further acquired through storytelling sessions in the community and engagements with community members during community meetings where farmers share their experiences and best practices. There are also institutions that took an effort to engage and teach rural communities about farming and farming techniques that are economically feasible, which included the usage of IKS. The foundation for

[1]A system where plants are grown in growth media other than natural soil. All the nutrients are dissolved in the irrigation water and are supplied on a regular basis to plants. (ARC, n.d.: online).

farming was one of the explicitly mentioned institutions which focused on encouraging and supporting natural farming practices; these farming practices involve working in conjunction with nature and optimising its positive aspects to create a better production. The Agriculture Research Council (ARC) was also mentioned in their contribution to the harvesting and testing of indigenous plants and distribution of the seeds from these plants to the farmer.

The existence of IKS is also seen as having a relation to an association with sustainable agriculture. Gold (2007) defines sustainable agriculture as "an integrated system of plant and animal production practices having a site-specific application that will, over the long term, achieve the following requirements: satisfy human food and fibre needs, enhance environmental quality and the natural resource base upon which the agricultural economy depends on. Its social impact on the communities that engage in this practice is visible as it sustains the economic viability of farm operations and enhances the quality of life for farmers and society". For participants to acquire this knowledge, it is beneficial that they apply it in practice and learn from its application. The length of experience in the practice of IKS also contributes to sustainable agriculture. Although not all participants utilised IKS exclusively, sustainable farming is still a focus of importance to them as conservation of the environment is important for their livelihood and the sustainability of their agricultural businesses.

During the data collection sessions, it became evident that there is an association between the application of IKS with natural farming methods. When discussing the concept of IKS and sustainable agriculture, the majority of the participants referred to natural and organic farming which encourage the reduction of or no usage of chemicals on their crops and livestock. The practices used for sustainable agriculture included how planting is done, the selection of crops that are planted and when they are planted. Planting different crops on the land by rotation ensures that the soil is healthy and kept in good form and it is still usable in the future. Another example given for sustainable agriculture is resting the soil by not farming for a certain period which allows the soil to heal and gain its nutrients back. During the study, the practice of mulching was also noticed; this practice entails the covering of the soil to protect it from damage. The covering can be done by different natural products which include compost, grass cuttings, straw, leaves, peanut shells, used coffee grounds as well as grounded eggshells. These examples and usage of traditional methods ensure that the soil is protected and provide favourable soil environment for crop production.

9.5.2 Challenges of the IKS on Agricultural Practices

- *Sharing knowledge for the continuation of IKS practices*
  The respondents stated that it is difficult to share the knowledge, especially with youth; this phenomenon is mostly prevalent in rural areas where farming is the main source of income and the land is available for agricultural activities. The participants indicated that it is better to share information more practically and

visually; this becomes a challenge to sharing knowledge with the youth as they are not always willing to learn or spend time in the field. In rural areas, the youth are not willing to learn without monetary compensation.

- *Impact of sustainable agriculture on food security*
  Due to the fact that the usage of IKS and sustainable agriculture requires time and patience, its effect on food security is not always immediate and it takes time for the results and the benefits to be realised.
- *Funding for IKS practices*
  Although the practice of IKS is less expensive than modern farming practices, there is a challenge in obtaining funding as the indigenous farming practice takes time. Half of the farmers (who are mostly male farmers) indicated that if their focus is on commercial farming and on a bigger scale, the amount of time taken in the usage of IKS will have a negative impact on the financial sustainability of the farm.
- *Water shortage*
  The majority of the farms are situated in areas where water availability is scarce. This demands for the creation of a workable water irrigation system. However, this is not always possible due to limited funds. The farmers in areas like Onspoed, Onverwacht, Temba, Soshanguve, and Refilwe opted for using water supplied by the appropriate municipal water reticulation system. However, water use is expensive for farmers, especially those involved in community-based farming projects.
- *Communal land*
  Out of the 14 farms visited, nine of them are not owned by the participants but by the chief or "moshate" (royal house); the participants are given the land either on lease or free-holding as it was vacant land. However, the participants in the nine farms are not completely comfortable with such an arrangement because they are aware that their removal from the land is possible at any given time. It is also important that these farmers who use communal land have been farming on it for five to ten years.
- *Infrastructure*
  Lack of machinery and farming tools drives the farmers to adopt traditional farming methods.
- *Market Availability*
  The availability of local farmer's market area was identified as a challenge in achieving economic growth in farming, especially for small holder farmers. Since the major markets are situated in the City of Tshwane and Johannesburg Metropolitans, the farmers have to incur huge transport cost to transport the produce from their farm to markets. Those farmers who focus on community farming preferred local markets so as to reduce their transport expenses.
- *Information sharing, time, and seed production*
  As there is limited time to share information in formal settings, for example, at conferences, classrooms, or formal agricultural events, the farmers (respondents) prefer that people interested in IKS agriculture come to their IKS farming on-site facilities and have practical sessions with them. Further, the farmers' indicated

that there is a limited time in their work schedules as they are dependent on the environment and this time constraint limits their focus on innovation and experimenting with new methods of farming because there is a preference for tried and tested methods. There is a need to comply with seed production regulations before creating a new strain of seed: this is seen as a deterrent and limits innovation and production of diverse crop varieties.

9.5.3 Benefits of the IKS on Agricultural Practice

- In the farms located near the township and urban areas, the youth in these areas are willing to learn more about farming and participate in the activities which are not the same in rural areas. The youth in more urban areas (for example, in Winterveld and Temba) have to rent out land or find creative and innovative ways to use limited spaces to practice agriculture.
- IKS farming techniques are affordable and sustainable. Using IKS enables one to keep the crops and livestock as natural as possible without the use of chemicals or any artificial product to increase the size of the produce. For example, poultry farmers stated that chickens and eggs produced using indigenous knowledge and traditional farming processes have different quality traits as compared to those in that are reared on conventional farms.
- The usage of IKS in sustainable agriculture enables small holder farmers and households to grow their own produce. The growing of own crops enables the community to feed themselves, thus increasing food security in areas where resources are limited.
- There are institutions like the Foundation for Farming that encourage and support the use of indigenous knowledge, natural farming techniques, and indigenous plants and the foundation assists farmers in using these methods. The Agriculture Research Council, for example, has seeds for indigenous crops like “morogo” and “leraka”.
- There is an interest in learning more and exploring traditional farming methods and to find out more about how ancestors used to farm and how the knowledge can be utilised to enhance the production and keep produce in its natural form by reducing or eliminating the use of chemicals on crops and livestock.
- The application of IKS in farming has afforded the farmers additional benefits. In their view, this method of farming has afforded them the opportunity to add value to the agricultural produce by producing naturally grown crops which have a high nutritional value. In the instance of hydroponics production, it was stated that this type of practice enables production throughout the year as the environment is controlled and produce is affordable as they are locally produced. This type of farming is beneficial to the environment as there is limited damage to the ground and the water used can be reused; there is also less usage of chemicals which enabled the conservation of the resources especially the soil.

- Additionally, it was further indicated that crops produced using traditional methods have a longer shelf life. Adoption of traditional practices enables the farmers to produce multiple products from one crop: e.g., at the peanut farm, the peanut plant leaves and peanut shells are used as animal feed, while the actual peanut-seed is used for producing peanut butter and peanut snacks. Further, the farmers' engaged in piggery farming expressed that traditional farming allows the animal to breed at a natural pace rather than fast-tracking the process with technological practices that are used in commercial farming for profit purposes.

9.6 Best Practices of IKS, Sustainable Agriculture, and Food Security

"Best practices are defined as a procedure that has been shown by research and experience to produce an optimal result". A best practice is based on the actions, experiences, and lessons that the participants have gathered over the years in their fields of practice. These practices have become a norm to the participants and are perceived to be trusted methods that the participants have experimented on with trial and error to achieve results that have become beneficial to the participants and proved to yield positive results. These identified best practices are presented in a list format with descriptions as provided by all the participants in the study.

1. It was observed that farmers'do not need huge farming spaces when utilising IKS practices and also were encouraged to start a functional food garden to grow vegetables in its natural format.
2. The poultry farmers, for example, used alternative heat-generating processes (homemade solar platforms). The poultry farmers will cover the chicken house with plastic and cotton material during the day which retains heat from the sun. During the rainy season and in winter when there is limited sunshine, the farmers use lanterns made from mayonnaise bottles, a string and paraffin to warm the area. The bottles are placed strategically in the chicken house to ensure that they do not fall down. These methods reduced the reliability of participants on electricity as the supply of electricity is not always guaranteed in these locations.
3. An innovative method to ensure a sterile environment in the poultry farms was the building of a mini-dam at the entrance of the chicken house and fill it with water and sterilising agents. This is done to ensure that there is minimal or no infestation of the pullets (young chickens).
4. The crop farmers produced their own pesticides for pest management on the farms. In some instances, the plants are grown in the farm on different patches of land and are not sold as part of the produce. The plants grown for this purpose are garlic, chillies, and tomato. The farmers create a mixture of the garlic, chillies, vinegar, and tomatoes—the latter because of its acidity, either cooked (if needed urgently) or soaked in water for a period of three days to allow the mixture to ferment and have a much more potent effect. The planting of mint in

between other crops like cabbage, spinach, and onions also assists in the reduction of ants and termites.

5. Crop rotation was observed to be essential, as it ensures efficient land use and soil fertility.
6. In the process of farming, soil resting was also identified. The farmers stated that they stop farming on a particular piece of land for a specified period in order to ensure that the soil replenishes its nutrients. The participants used different natural products to cover the unused land in order to limit damage and erosion during the resting period. The products used for this purpose include (but not limited to) avocado tree leaves, grass and lawn cuttings, manure corn plants.
7. The practice of hydroponic farming (which encompasses the inclusion of modern technology and the usage of a natural product/water) ensures that one can produce more crop per square metre of land available.
8. The farmers in Refilwe observed that the farming of indigenous plants is a good practice, as it created a new market in the industry. The indigenous plants include indigenous *morogo* like *thepe or lerotho* (*morogo* is a green-leaved plant that could be categorised in the same group as spinach or kale; however, the plant leaves are smaller and look flat) and indigenous pumpkin, named *leraka*.
9. Farmers found methods to preserve crops. This is done by par-boiling of crops like *chomolia* (kale), pumpkin leaves, and indigenous *morogo*. After boiling, the crops are dried under the sun (the name used for the dried crop is *Mokhusha*). This method assists in combating poverty and malnourishment as the farmer is able to provide these products to poor communities and they are able to have access to nutritious food over a longer period.
10. Farmers found ways to utilise waste as useful products. For example, chicken manure is used as cattle feed and crop fertiliser. In the latter case, the manure is turned into what is called "chicken tea" by mixing the manure with water in a homemade container for a week or longer and allowed to ferment. The manure is then drained, and the liquid used as crop fertiliser. Fertilisers also can be created by burning grass using the ash as a fertiliser and by drying plants that are regarded as a weed, which are rich in nutrients.
11. The farmers also use natural methods to design the farming area; this is done by identifying and understanding the water flow and direction of the land and underground water system. These methods ensure the optimisation of the water use and limit water wastage. The respondents also indicated that due to the limited water supply in their areas they also applied water to crops during the recommended time (the crops are watered in the evenings after sunset or early mornings before sunrise) to ensure maximum benefit to the crops and reduce water evaporation that occurs during the day.
12. Farmers practice cross-breeding of cattle to increase milk production. The farmers stated that one needs to understand why they cross-breed and know which cattle to breed. The traits preferred by farmers for cross-breeding of livestock are milk yield and meat content.

The above-mentioned practices are those identified by the respondents as the preferred practices they utilise in their farming. These practices are shared with those interested in agricultural practices through knowledge transfer activities that are described subsequently.

9.7 Knowledge Transfer Activities and Enhancement of Community Through Innovation

Indigenous knowledge systems have been critical to the development of both primary and secondary agriculture in South Africa, enhancing grassroots innovation for food security and improving the quality of life. In this section, the aim was to explore how the respondents engage in actively sharing the knowledge that they have acquired and the methods they used to share this knowledge. The sharing of knowledge and ideas enables the community to expand in their agricultural practices and learn new methods of farming. The sharing of knowledge ignites innovation in the field. Looking at the responses it has become evident that the participants valued sharing their knowledge, skills, and experiences. One hundred per cent (100%) of the respondents participated in knowledge sharing initiatives. Below are the methods and platforms that are used for knowledge sharing, learning, and exchanging ideas.

The respondents are part of forums which they called study groups. These platforms are initiated, established, and introduced to a farmer community in a specific geographical area by the Gauteng Department of Agriculture and Rural Development (GDARD). After the establishment of the study group, the farmers of that particular cluster are responsible for the operations of the study group. The farmers then take over the organising of the meeting and a committee is elected to handle the administrative matters. The meetings group, for example, Refilwe township will have a chapter of the study group and Hammanskraal township will also have its own chapter. If the geographic area is large like Winterveld or Soshanguve townships, for example, there are multiple chapters that are created. All the respondents indicated that they participate in the study group and chapters that are conducted locally.

The occurrence of the meetings is different from one area to the next, for example, in Cullinan, Bronkhorstspruit, and Hammanskraal, the respondents indicated that the meetings occur once a month, whereas the other respondents indicated that the meeting occurs bi-monthly. In Hammanskraal the researcher visited three farms and each farmer from each of those farms attended different study groups although they are eight kilometres apart. According to the respondents, the frequency of the meeting is determined by the participants of each group and the attendance by a member of the group is voluntary. This platform serves as a place for networking, idea sharing, and learning and where the best practices are shared and improved. Furthermore, farmers are able to identify and share business opportunities with each other.

In rural areas, there are various community forums that are conducted. These forums are organised by community leaders or community members when there are matters to be attended to within the community. These forums are aimed at discussing community challenges, current projects, and future projects. On a regular basis, the forums encourage community members to share information on how to better the lives and empower the communities. The participants use these opportunities to share information and knowledge on farming activities as well as the availability of produce on their farms and the creation of household-based vegetable gardens.

All the interviewed farmers indicated that as an agricultural practitioner, the sharing of knowledge among farmers is essential as it allows them to benchmark with each other and improve on their practices. The benchmarking sessions include visits to different farms in other townships, around the City of Tshwane Metropolitan to learn and obtain practical experience on how their counterparts farm and where they engage in peer assistance and sharing of knowledge during the sessions. Those farmers who have been in the operational IKS field for a long time and have gained vast experience in agricultural practices also participate in educating members of communities in various agricultural practices, for example, sharing information on how and when to plant which crop and the type of soil needed for each plant.

The experienced farmers also assist emerging farmers by sharing their experiences and lessons they have learned by engaging in mentoring, monitoring, and evaluation of activities and regular visits to the new farmer's establishment to engage and assist with challenges and to provide motivation. All the interviewed participants indicated that they actively participate in research activities and agricultural studies that are conducted by researchers from different institutions including tertiary institutions (universities, educational institutions), agricultural institutions (including government departments), and other research institutions (Agriculture Research Council, Department of Agriculture, Gauteng Department) to share their knowledge and experiences in the agricultural field. The farmers in Hammanskraal and Bronkhorstspruit indicated that they also participate in agricultural research experiments where they are provided with different seeds of the same crop to test their growth in their climate and also the seeds of indigenous plants that are provided in order to grow the market and increase the knowledge base of the farmers based on the information collected in these experiments. The knowledge they gather in these experiments are shared in the different knowledge sharing platforms (platforms). Participation in agricultural industry events (local and national events) have also been identified as a good platform to network, learn, share knowledge, and showcase their practices on a wider platform.

Ninety per cent of respondents opined that their agricultural practices enabled them to provide nutritious and fresh food/produce to the community in a close vicinity that allows for the economic growth of community and a good opportunity to create a healthy community and employment. Ten out of 14 farm households in the study area stated that they regularly donate produce to charities, primary schools, creches, and disadvantaged households' especially child-headed households and those of the elderly. The farms in Hammanskraal, for example, are run by a cooperative, whose members are elderly people.

These farms provide a safe place for the elderly to spend their days and also contribute to the community economically and to ensure food security. Further, the farmers practising cooperative farming have stated that they have functional gardens at their homes, and they encourage other households to grow different crops to enable the farmers to exchange crops. This practice was highlighted by all the respondents in Refilwe, Soshanguve, Sokhulumi, and Majaneng.

9.8 IKS and Sustainable Agriculture Impact on Food Security

This question was asked to analyse and illustrate how the practice of sustainable agriculture impacts on food security in their respective communities to determine if there is a broader understanding by the respondents of how agricultural practices affect food security and nutrition. Ninety-six per cent of the participants responded that their choice of indigenous knowledge practices has contributed to food security in the community. Four per cent of respondents stated that they supply crop produce to two large markets (Tshwane Fruits and Vegetable Market and City Deep Vegetable and Fruits Market). Further, they stated that the utilisation of the hydroponics agricultural method enabled the availability of crops throughout the year which meant limited imports (from other countries) of vegetables when the crops are off-season. Also, such farms employ local community members leading to employment generation. The following are the paraphrased qualifying statements by ninety-six per cent (96%) of the participants of the study as requested and stated in the questionnaire.

IKS methods are easy to implement for small holder farmers, community farms, and households with functional gardens (these are households that have created gardens in their backyards and produce enough produce to feed their families and share with fellow community members). The advantage of IKS methods is that it enables farmers to manage the cost of running the establishment as they do not utilise middlemen. Further the communities have access to the produce on a more affordable rate as there are no transport and storage fees included in the pricing. In case of livestock farming, the quality of the product is guaranteed as the animals are being fed with natural products like peanut shells and the peanut plant and chicken manure.

The sharing of knowledge within communities has been a vehicle for highlighting the importance of IKS and sustainable agriculture on food security. Few of the respondents opined that the youth needs to be exposed more to farming in general with specific emphasis on understanding the relationship of these concepts (indigenous knowledge systems, sustainable agriculture, and food security) and how growing vegetables in the home garden provide nutritional security and financial relief for not having to buy vegetables. The creation of employment is also a way to achieve food security. The respondents highlighted the importance of the relationship between employment and food security, as well as their understanding that ensuring good agricultural practices is an integral factor in the conservation of the environment.

9.9 Initiatives for Sustainability of IKS in Agricultural Practices

Having discussed the benefits and challenges of IKS in agricultural practices, this section deals with the initiatives for sustainability of IKS in agricultural practices. Respondents indicated that it is not ideal to just share the knowledge and information without engaging the recipients of the knowledge. During the observation session at Refilwe, Mnandi, and Hammanskraal, the authors was able to engage the respondents in the harvesting of spinach, kale, and butternuts and also in the feeding sessions of pullets, while at Onspoed the farmers provided opportunity to the authors to assist in the planting of crops in the Zaza holes created in the process. The successful implementation of the initiatives that encourage the usage of IKS and the practice of sustainable agriculture is highly depended on having recipients who are willing to learn and obtain an in-depth understanding of the agricultural practices. All the respondents stated that for IKS to be successfully implemented and used widely in the farming field, it will be beneficial for emerging farmers and youth to be receptive of the practice. The following initiatives add value to the IKS in agricultural practices.

- The knowledge sharing sessions aim at educating the community on different aspects of sustainable agriculture, and how households can create gardens in order to reduce the level of poverty and improve on food security. These sessions are inclusive of the youth in the community and the elderly who are in need of additional skills in order to create additional income and sustain themselves and their families.
- In the areas that have limited water supplies like Onspoed, Sokhulumi, and Onverwacht, the farmers have established water conservation fora that focuses on acquiring information and practices on methods of water conservation and crop management with limited water resources.
- The youth development initiatives focus on training the youth in IKS pertaining to agricultural practices.
- It was stated by all respondents that mentoring start-up farmers are essential as it creates more growth in the industry; these activities include mentoring sessions and guidance on matters like market penetration plans, understanding the business of agriculture, information on institutions that provide support for emerging farmers, seed and crop selection processes based on the area their farms are situated in, and seed exchange programmes and activities between farmers.

  A prevalent challenge that all the respondents faced was the documentation of indigenous knowledge. The respondents indicated that in their private capacity they are starting to document the lessons they have learned from their experiences. This will enable future generations to understand and have access to information on the application of indigenous knowledge systems in the agricultural practices of their choice.

9.10 Conclusion

The first objective of the study was to conceptualise IKS in the identified communities of the City of Tshwane Metropolitan. The study aimed at establishing and exploring IKS and theories that relate to the application and awareness of this knowledge system. The study explored the contextual setting of IKS and sustainable agriculture, the use of learning components in IKS and sustainable agriculture, and interrelationship between sustainable agriculture and food security. Indigenous knowledge systems are dynamic and are continually influenced by internal creativity and experimentation as well as by contact with external systems. IK is the knowledge base for a society, which facilitates communication and decision-making. IKS encourages small-scale farmers, start-ups, and households garden to contribute to food security as it reduces the complexity of agriculture in the communities. However, the labour intensity of using IKS cannot be disregarded.

The concept and practice of sustainable agriculture have led to the need to find alternative methods to efficiently use the agricultural resources. One of the alternative methods is the application of IKS in farming practices or the combination of both modern farming practices and indigenous farming practices. Further, it was evident from the study that sustainable agriculture and meeting the food requirements of the community are also inclusive of the management of land. Sustainable land management involves the inclusion of not only the western knowledge system but also the integration of all knowledge systems and agricultural practices that are available in the community. Sustainable farming practices also enable to combat food shortages and ensure food security.

The study also focussed on identifying the benefits and challenges that communities' experience in practising sustainable agriculture. Due to the location (rural area of the City of Tshwane Metropolitan), out of the fourteen farms visited, thirteen of them faced the challenge of water shortage which negatively impacted the crop yield. Since the usage of IKS and sustainable agriculture requires time and patience, its application to achieve food security is not always immediate and it takes time for the results and benefits to be realised. However, adoption of IKS has benefits in terms of achieving sustainable development, financial benefits, employment opportunities, and food security.

The study also identified best practices in the utilisation of IKS to ensure food security through sustainable agriculture. The study also illustrated that indigenous knowledge contributed to the three most important factors in food security: availability, access, and utilisation. The adoption of IKS methods reduced the cost associated with buying pest management products and high-tech machines. Food security was ensured through the availability of produce in the local market at an affordable price, creating functional households gardens, the creation of employment opportunities, and ensuring that communities access nutritious food that encourages healthy leaving.

Indigenous knowledge systems are important for the development of both primary and secondary agriculture in South Africa, enhancing grassroots innovation for food security and improving the quality of life. It was evident from this study that knowledge sharing and idea exchange assisted in the growth of the agricultural practice and innovation, by creating new methods or combining best practices from different ideas. The sharing of knowledge and ideas enables the community to expand in their agricultural practices and learn new methods of farming. The respondents are members of forums and agricultural bodies which encourage regular gathering and networking sessions. In these forums, sharing of knowledge is encouraged, which ignites innovation in the field and makes work bearable and find creative ways to increase the IKS database.

In summary, the application and choice to utilise IKS agricultural methods can be viewed as situation dependent. Further, this is also dependent on the agricultural model or approaches each farmer or practitioner preferred, it could be commercial farming, subsistence farming, household gardens, or community farming. The application of IKS in agricultural practices results in the enhancement of the livelihood of the communities in a manner that is ecologically sustainable, economically viable, and socially acceptable. The study thus recommends that the sharing of IKS and incorporating it with technology and modern agriculture can create a new dynamic, agricultural practice that will benefit commercial farmers, community or primary farmers, and households with functional gardens.

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Conflict of Interest The authors declare that they have no conflict of interest.

Web Links

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Tropical Biological Natural Resource Management Through Integrated Bio-Cycles Farming System

10

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Abstract

Biodiversity and net primary productivity in the tropical ecosystems were the highest in the world, about 750 gC/m^2/year. This abundance is because it is supported by high temperatures, rainfall, moisture, light intensity, and rapid organic cycling along a year in the tropical regions. Moist tropical forests are blessed without anyone planting, maintaining, and disturbing them in the long-term periods, so they can function as the lungs of the world to provide oxygen and maintain the earth's climate. Although biological productivity is 10 times, the economic value is only half compared to temperate ecosystems. The new paradigm from extraction into the empowerment of natural resources will provide new challenges to move from the red and green economic concept to the blue economic concept with added values of economy, socio-culture, and environment

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aspect for sustainable development. The synergism between biological resources (flora, fauna, human) and land resources (land, minerals, water, air, microclimate) by the development of Integrated Bio-cycle Management (IBM) through empowerment of life cycle assessment as a closed-to-natural ecosystem would manage our tropical natural resources through multifunctional and multi-product system. Information about agroecosystem, life cycle assessment, biowaste, bioenergy, bioeconomy on tropical natural resources would give valuable concepts for sustainable development of smart tropical agroecosystem management. This integrated farming system can produce food, feed, fiber, fertilizer, wood, energy, water, oxygen, medicine, mysticism, and tourism, so they have added values in environmental, economic, socio-cultural, and health aspects. This system is essential for the sustainable and productive management of tropical natural resources.

Keywords

Bioeconomy · Biogeochemical cycles · Integrated system · Knowledge-based development · Natural resources · Sustainable development · Tropical ecosystem

10.1 Introduction

"Indonesia is known as the emerald of the equator, which has high values of natural resources, although it also has a huge disaster risk" (Agus 2019). "The tropical ecosystem has a high temperature, rainfall, moisture, light intensity, and rapid organic cycling along a year, so they have the highest biodiversity and net primary production in the world" (Agus 2018). "As a part of the ring of fire, the land becomes more fertile because always be supplied by new volcanic materials, which contains a lot of essential nutrients" (Agus 2019).

Tropical natural resources have great potential resources but are still of less economic value because they are still under management that is not on nature-based development (Agus 2019). Agus et al. (2018) reported that high net primary production in a humid tropical forest ecosystem is more supported by a fast organic cycle than decayed acid soil with low fertility. Intensive deforestation and over-exploitation of open mining have been the leading causes of severe land degradation and severe local-global environmental damage (Agus et al. 2018, 2019a, 2019b, 2019c). Excessive exploitation of natural resources in tropical ecosystems has caused significant problems in economic, environmental, and socio-cultural aspects (Agus 2019; Agus et al. 2019d, 2019e, 2020b).

Indonesia as an agrarian-based country produces a variety of agricultural commodities, from food crops such as rice, cassava, and corn, to non-food crops including rubber, oil palm, coffee, tea, cocoa, sugar cane, coconut, and species (Fuglie 2003). As a complete agriculture producer, Indonesia faces an immense challenge in developing a sustainable farming system which covers all aspect: economy, environment, and socio-culture. Covering 55 million hectares (ha) of

190 million ha of total land area (Quincieu 2015), Indonesian agriculture was practically self-supporting in terms of food, especially rice (Soen 1968). With the advantages of high rainfall, humidity, and warm climate, the biomass productivity of tropical agriculture is considered among the highest in the world Agus et al. (2004). However, with management that is still traditional, less effective, and efficient, the productivity of tropical agriculture is lower than in temperate regions (Agus et al. 2011). Indonesian population was predicted to reach 288 million in the year 2050 (ADB 2011). The rapidly growing population results in narrowing the agricultural area, while the demand for agricultural products continues to increase.

Conventional agriculture overcomes those issues by upgrading the yields through fertilizer application. Excessive fertilizer application brings up several environmental damages, such as water pollution and generates higher greenhouse gas emissions (Couwenberg et al. 2010; Toma et al. 2011; Xu et al. 2019). The use of organic matter (biomass) and manure as fertilizer was considered better than chemical fertilizer (Brenzinger et al. 2018; Li et al. 2018; Ren et al. 2017). First of all, resource availability is abundant, so it is economically efficient. Second, biomass (plant materials) is renewable energy since the plants get the energy directly from the sun through photosynthesis (Agus et al. 2011). Biomass is rich in nutrients, which is biologically effective not only to improve soil fertility and crop quality but also protect the environment (Li et al. 2018). Aside from biomass as fertilizer, biomass, and other agricultural wastes, especially livestock wastes in the form of manure, could be converted into biogas (Neelakantan et al. 1978; Sasse 1988; Zahariev 2014). By using the available resources, it allows the cycle of the energy to remain in the system, which is one big goal of bioeconomy.

Sustainable agriculture has become the center of attention for an agricultural scientist to create a better farming system, based on natural resources, and last for future generations. One step to achieve the concept of sustainable agriculture is what we call bioeconomy. Food and Agriculture Organization of United Nations (FAO) defines bioeconomy as the "production, utilization, and conservation of biological resources, including related knowledge, science, technology, and innovation, to provide information, products, processes, and services across all economic sectors aiming toward a sustainable economy" (Global Bioeconomy Summit 2018). Bioeconomy promotes a shift from a non-renewable-based economy to renewable biological resources, and a new biotechnical solution. Bioeconomy is highly connected with the needs-producer sector, such as agriculture, forestry, fisheries, food industry, etc. (Pelli et al. 2018). The application of bioeconomy faces many challenges, especially in Indonesia, which is accustomed to a conventional farming system. Bioeconomy concept was adapted and tried to be applied to Universitas Gadjah Mada (UGM) by developing the Integrated Bio-cycles Farming System (IBFS) (Agus 2018).

Philp (2018) stated that the transformation to a bioeconomy is going to take time. As simple as the transition from coal to renewable fuel during the industrial revolution, it took much effort in decades. The application of bioeconomics still shows its complexity and is a big challenge to implement in certain sectors. Bioeconomy has become a global challenge, as well as in Indonesia. Setting sustainable development as the final goal, the United Nations (1987) stated: "meet the present needs without compromising the ability of future generations to meet their own needs." Bioeconomy application is expected to be applied in all sectors, not only agriculture but also all business sectors, even though there will be a big challenge ahead. Adopting a new system in the middle of old conventional paradigm is a big challenge since it is highly related to society. Integrated Bio-cycles Farming System is expecting to facilitate and educate the farmers to maintain and improve their quality of life and the quality of life of future generations to live and act sustainably (Agus et al. 2011, 2018) without leaving aside local wisdom. Further, the transformation from conventional farming systems to Integrated Bio-cycles Farming systems requires a united effort, time, and commitments.

10.2 Sustainable Development in Agroecosystem

The equatorial and tropical region of the Earth are rich in biodiversity and natural resources (Andresen et al. 2018). Natural resources are a key in sustainable agricultural development, and therefore must be managed and utilized as a pathway to future prosperity and environmental sustainability (Sivakumar et al. 2000). Agriculture is an activity of managing biological natural resources assisted by technology, capital, labor, and management to produce agricultural commodities that cover food crops, horticulture, plantations, and livestock in an agroecosystem management unit (Anonymous 2019). The agricultural sector has a considerable contribution in supporting the wealth of nation or economic growth, especially in agricultural countries, in which it has always been a top priority in the pillars of the national development plan. Such contribution is shown through its ability, especially in national food supplies. Additionally, this sector has the potential to produce industrial raw materials, food, fiber, biocompost, biopesticides, bioenergy, and biogas (Kern 2002; Agus 2013).

Efforts to enhance agricultural production are continually made in line with the rapid population growth rate, particularly in developing countries (Stephens et al. 2003). Modern farming through intensification of agriculture has been a shortcut for solving food-related problems. Agricultural intensification is usually featured using advanced technology, mechanical equipment, modern method of cultivation, hybrid seeds from superior genetics, inorganic fertilizers and pesticides, monoculture, and the support of various government policies (Rivai and Anugrah 2011; Prasad et al. 2014, 2017). Nevertheless, the practice of such intensification is mostly targeted to gain high yields while ignoring its potential risk to the environment, including pollution, soil erosion and topsoil degradation (De Neergaard et al. 2008), excessive groundwater exploitation (Maqsood et al. 2005), biodiversity loss and increased resistance to weeds and pests (Zhu et al. 2012), caused by inappropriate agroecosystem management.

According to FAO (2019), there are 10 interlinked and interdependent elements of agroecosystem, namely diversity, co-creation, and sharing of knowledge, synergies, efficiency, recycling, resilience, human and social values, culture and

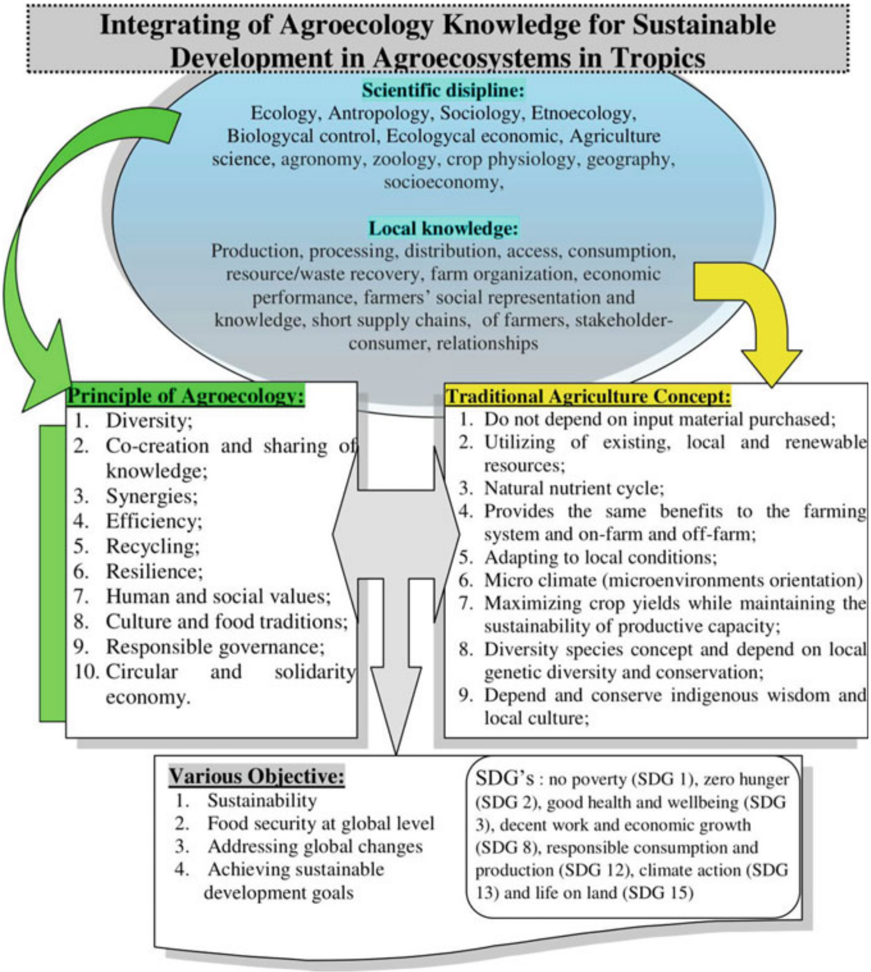

Fig. 10.1 The synergy between agroecological knowledge for sustainable development in agroecosystems and SDGs in the tropics

food traditions, responsible governance, circular and solidarity economy (Fig. 10.1) (Altieri 1995; FAO 2019).

These 10 elements are the guidelines for public policymakers and stakeholders in planning, managing, and evaluating the transition to a global sustainable agricultural model. In general terms, they can be explained as follows (FAO 2019):

- Diversity: The systems optimize the diversity of species.
- Co-creation and sharing of knowledge: Agricultural innovation through a participatory process that requires the commitment of the local community toward the application and development of agricultural systems.

- Synergies: Joint action of several functions that reinforce each other and produce a more significant final effect.
- Efficiency: The practices produce more using less external resources.
- Recycling: In the cycle, recycling means agricultural production with lower economic and minimal environmental costs.
- Resilience: The diversity in the systems supports a more resilient, higher capacity to recover from disturbances, including extreme weather (droughts, floods, or hurricanes), and to resist pests and diseases.
- Human and social values: The system strongly emphasizes on human and social values such as dignity, equity, inclusion, and justice.
- Culture and food traditions: It contributes to food security and nutrition by maintaining the health of ecosystems.
- Responsible governance: Sustainable food and agriculture entail transparent, responsible, and effective governance mechanisms at all lines, from local to national.
- Circular and solidarity economy: The maximum use of resources and reuse of waste in other processes.

In the context of environmental issues, agricultural cultivation is currently carried out with an ecological-based management approach with sustainable agriculture principles in the context of human development as the basis (Sumodiningrat 2000). Sustainable agriculture systems are the management of biological natural resources in producing agricultural commodities to meet human needs appropriately and sustainably while maintaining or improving the quality of the environment and conserving natural resources (Govind and Stigter 2010). In this context, sustainability referred to the economic sustainability that can be achieved by the use of less energy, minimizing ecological damage, and the use of biological cycles in an agricultural community. Sustainable agriculture systems are devised based on usefulness, sustainability, sovereignty, cohesiveness, togetherness, self-sufficiency, openness, fair efficiency, local wisdom, the sustainability of environmental functions, and state protection (Anonymous 2019).

Sustainable agricultural systems in agroecosystems are mostly a paradigm of agricultural management that integrates three elements of economic, ecological, and social dimensions (D'Amato et al. 2019); thus, the benefits can be enjoyed by the present and future generations. Nevertheless, various ecological implications of sustainable agriculture require the understanding of related stakeholders, namely the farmers, the government as a policymaker, and the researcher or mentor (Govind and Stigter 2010). In the economic term, sustainable means that a development activity must be able to support economic growth and utilize the resources and investment efficiently. In the ecological context, sustainable means the activities must be able to maintain the integrity of the ecosystem, maintain the carrying capacity of the environment, and the conservation of natural resources, including biodiversity. In the social context, sustainable development activity should be able to create equitable results, social mobility, and institutional development.

An agroecosystem is an ecosystem concerning agricultural activities carried out by humans under specific characteristics and managed to produce agricultural products. The boundaries of the agroecosystem can be in the form of planting plots, grasslands, more extensive areas, and can be an integrated part with other ecosystems, i.e., dryland, mountain, coastal, and urban agriculture (D'Amato et al. 2019). In tropical agroecosystems, there are biotic and abiotic natural resources with the potential of supporting agricultural activities, including soil, nutrients, water, contour, climate (evenly distributed rainfall in some areas, sunlight throughout the year, temperature, and humidity), and macro- and microorganisms that support agricultural sustainability. Climate is an essential factor that determines the sustainability of the agricultural system (Sombroek and Gommes 1996). Even the varieties that have the highest production will be stunting without the support of climatic factors because the biological response is very climate-dependent (Senanayake 1991). Therefore, farmers have a role in managing and maximizing all available resources in the agroecosystem to gain optimal agricultural productivity by considering the carrying capacity of ecosystems, mitigation, and adaptation to climate change, and environmental sustainability.

Sustainable management of agroecosystems is done based on agroecological science. Agroecology is an integrative study of interactions between biological, environmental, and management factors in agricultural systems, which is the implementation of ecological science in the design and management of sustainable agroecosystems (Gliessman 2018). It can also be defined as an approach that correlates the ecological and socio-economic factors to establish agroecosystems that support agricultural production, agricultural communities, and environmental health (Gliessman 1997). It was initially introduced as a field of study in the 1980s in which it had included a variety of perspectives and efforts to develop integrated concepts and approaches (Rickerl and Francis 2004). Ecological ecosystems emphasize the relationship between organisms and their physical environment and the flow of energy and material through interrelated biophysical systems (Chapin et al. 2002). Moreover, the aim of integrating ecological science and agricultural science is to improve the sustainability of agriculture with an environmental perspective (Gliessman 2007).

Modern agroecosystems are established based on agroecological principles that can be applied in diverse practices and strategies. There are various mixtures, rotations, polycultures, agroforestry, crop-livestock integration, integrated bio-cycle, and at the landscape level (hedgerows, corridors) (Agus 2013; Agus et al. 2019a). Those models can provide options for farmers to be implemented in the field (Altieri et al. 2017). Several agroecological principles can be realized in agroecosystems. There are: (1) optimization of the biomass cycle through the decomposition of organic matter and nutrient cycles; (2) optimization of the population balance of the function of natural predators in pest control; (3) optimization of organic material management through compost to increase the cycle of soil microorganisms; (4) control of the energy, water, and nutrition cycles; (5) the use of various types of plants with proper structure and composition patterns for soil and water conservation; (6) crop rotation and optimization of growing space;

(7) beneficial biological interactions between components in agroecosystems (agriculture and non-agriculture) to produce various products such as biocompost and bioenergy (Altieri et al. 2017; Phelan 2009; Agus 2018; Agus et al. 2019a).

Sustainable agriculture is an implementation of the concept of sustainable development. The sustainable development goals (SDGs) set the global development agenda until 2030. Sustainable agriculture and food system are central to the SDG's process and it directly and indirectly affects all 17 of these goals (Table 10.1). Without proper nourishment, children cannot learn, people cannot live healthy and productive, and societies cannot prosper (FAO 2017). Agroecology provides a tool in the effort to build sustainable food systems and eventually contribute to the targets set in the SDGs (FAO 2018; Farrelly 2016). It is expected that agroecology will contribute to SDGs, particularly no poverty (SDG 1), zero hunger (SDG 2), good health and well-being (SDG 3), decent work and economic growth (SDG 8), responsible consumption and production (SDG 12), climate action (SDG 13), and life on land (SDG 15) (CNS-FAO 2019).

CNS-FAO (Swiss national Committee FAO) (2019) Agroecology as a means to achieve the sustainable development goals. Federal Department of Economic Affairs, Education and Research EAER

10.3 Integrated Bio-cycle Farming System

Our blue planet consisting of 71% Blue Ocean must be supported by blue earth (Agus 2018). A red economy that is only economic oriented has resulted in environmental and life damage. A green economy is oriented towards environmental and healthy values, even though it is expensive and dangerous. The blue economic concept was developed by Gunter Pauli from ZERI Foundation in 2009 (Agus et al. 2016) through the acceleration of the natural cycle process by empowering land resources (land, water, and minerals), biology (plants, animals, and humans) with economic added value, environment, social culture, technology, sustainable management. The blue economy offers efficient investment, increased innovation, increased funding, job creation, development of social capital, and entrepreneurial stimulation (Agus 2018). It is carried out by utilizing waste and abandoned goods into food, energy, and employment, thereby transforming poverty into sustainable development, and scarcity becomes available. The blue economy has provided new creative and innovative opportunities.

Bio-geo-tropical resources have high biomass productivity but are still of less economic value. The Integrated Bio-cycle Farming System (IBFS) is an alternative system that harmoniously combines the agricultural sector, and non-agricultural aspects, in the management of landscape ecology. The cycle of energy, organic matter and carbon, water, nutrition, production, crops, money is managed through 9R (reusing, reducing, recycling, refilling, replacing, repairing, replanting,

Table 10.1 Application of agroecology in agroecosystem management in the tropics based on three sustainable development aspects

SDG aspect	Agroecology practices	Problem detection	Solution concept	References
Environmental	Agroecology for watershed management	1. Land degradation 2. Soil erosion 3. Heavy metal contamination	1. Agroecology solutions include terrace farming, contour planting, or silvipasture system 2. Mixture garden with full cover crops and introducing of revegetation plant species	Aflizar et al. (2016)
	Agroecology for mitigation of greenhouse gases emissions	1. Climate change could become a problem in continuous agricultural production 2. Emissions sources (methane, nitrous oxide) from the agricultural sector is rice fields	1. Mitigation efforts of greenhouse gases emissions from rice field are high yielding rice varieties with lower missions, 2. Intermittent irrigation, 3. Balance and efficient fertilization, 4. Use of ameliorant materials, 5. Integrated food crops-livestock	Wihardjaka et al. (2018)
Social	Agroecology for food security strategy of local community	1. Poverty 2. Food security 3. Malnutrition 4. Semi-arid land condition 5. Adaptation to drought conditions/ limited water	1. The food security strategy is to produce corn in multiple cropping systems 2. Corn as a carbohydrate, legumes as a source of protein, and other plant species as minerals and vitamins 3. Co-management principle is used from preparing land until harvesting 4. Management of crop cycle period 5. Cooperative farming practices 6. Efficient utilization of water resources 7. Use of corn waste as feed and fertilizer 8. Appreciation from the government to existence farmers	Carolina and Hidajat (2016)

(continued)

Table 10.1 (continued)

SDG aspect	Agroecology practices	Problem detection	Solution concept	References
Economic	Agroecology for increase of Forest farmers income	1. Limited productive land cultivation 2. Marginal or critical land condition 3. Unstable market prices	1. Application of the agroforestry system of herbal medicine 2. The income of medicinal plants farming contributes 39% to the income of smallholder forest farmers 3. The role of the government is optimized again in assistance, especially to attract investors or entrepreneurs of the traditional herbal medicine industry	Triyono and Rahmawati (2017)

rebuilding, giving gifts) to get optimal benefits for farmers, community, agriculture, and global environment (Agus 2018). This system is multifunctional and multi-product (Food, Feed, Fuel, Fiber, Fertilizer, Pharmacy, Edutainment, Ecotourism). IBFS is expected to provide additional benefits for farmers with small, medium, and abundant capital, through recycling organic waste into renewable resources to produce high-value production, such as organic fertilizer (liquid and solid), animal feed, and gas energy (Agus 2018).

Integrated Bio-cycle Farming System (IBFS) is an alternative farming system that harmoniously combines the agricultural sector, such as agriculture, horticulture, plantations, livestock, fisheries, forestry with non-agricultural aspects, such as settlements, agro-industry, tourism, the industry managed based on the landscape ecology under an integrated area. Agus et al. (2018) stated that IBFS develops through ICM (Integrated Crop Management), INM (Integrated Nutrient Management), IMM (Integrated Soil Moisture Management), and Integrated Pest Management (IPM). The system must collaborate and develop a network system between ABCG (Academic, Business, Community, and Government) with economical, environmental, and socio-cultural approaches as a feature of Education for Sustainable Development (Agus et al. 2017, 2019f, 2020a). This model facilitates the learning needed to maintain and improve our quality of life and quality of life for generations. It is about equipping individuals, communities, groups, businesses, and governments to live and act sustainably; and provide them with an understanding of the environmental, social, and economic issues involved. Integrated agriculture can support a sustainable and better life and environment (Agus 2018).

The IBFS has general characteristics of integrated farming systems, namely Low input farming, Organic Farming, Bio-dynamic Farming, and Agroforestry systems (Agus 2018, 2019). The key characteristics of IBFS developed at UGM University

Farm are (1) integration of agriculture and non-agriculture sectors, (2) value of environment, esthetics, and economics, (3) rotation and diversity of plants, (4) artificial and functional biotechnology, nanotechnology, pro-biotic, (5) closed organic cycle management and adoption of integrated approach like ICM, HDI, IMM, INM, IVM, (6) management of integrated bio-protection and ecosystem health management, (7) ecological landscape management, agro-politan concept, (8) holistic and integrated system-specific management of plant (Agus 2018).

IBFS is expected to be one of the alternative solutions to increase land productivity, program development, and environmental conservation and rural development (Agus 2018). They will meet the basic needs expected in the short, medium, and long term for food, clothing, and shelter. Thus, IBFS can provide farmers with income on a daily, monthly, annual, and decade basis. The role of micro-, meso-, and macro-organisms in the biogeochemical and nutrient cycles in increasing land productivity is crucial. Microorganisms can provide essential nutrients to plants through both mutualistic and non-symbiotic symbiosis. Biotechnology, including bio-artificial and functional nanotechnology, will significantly enhance the success of integrated bio-cycle agriculture in the tropics.

Geo-eco-tourism offers investment efficiency, increased creative innovation, increased funding, job creation, development of social capital, social stimulation-entrepreneurship in society (Cahyanti and Agus 2017). The management of productive and conservative natural resources will become an exciting new object of geo-tourism. However, the management of ecotourism attractions is not developed in many tourist destinations. Its activities are still limited to some natural regions. Ecotourism is an industry that is based on the preservation of the natural environment and the success of promoting ecotourism programs related to the flora, fauna, and ecosystems. The presence of ecotourism in the era of the mission of sustainable development and tourism must be a minimal negative impact, both on environmental resources and on local socio-cultural values. Ecotourism activities are more oriented to the use of natural resources, natural ecosystems, and not yet polluted.

Agus et al. (2018) and Cahyanti and Agus (2017) developed gold agro-production, which intends to produce many products in a land entity, and these products represent real "gold" that has been neglected and given a lower value, namely "brown gold" (wood), "yellow gold" (grains rich in carbohydrates needed for human life), and "black gold" (organic fertilizer, compost) in addition to "blue gold" (biomass and biogas energy), "green gold" (green vegetables, fodder, environment, temperature, and humidity), "white gold" (milk, fish, food), "red gold" (animal protein from beef, pork, chicken, duck), "transparent gold" (water for life and oxygen), "colorful gold" from herbal medicines, and "magic gold" from spiritual activities and tourism, which play a significant role in maintaining human health and dignity of life human.

IBFS can provide additional yields and benefits for small, medium, and big capital farmers. By recycling organic waste into renewable resources to produce high-value production, such as organic fertilizers (liquid and solid), animal feed, and biological sources - energy gas (Agus et al. 2011). It will be a good prospect that organic agriculture can provide sustainable economic, environmental, and socio-cultural benefits (Cahyanti et al. 2019).

10.4 Life Cycle Assessment

Integrated Bio-cycle Management (IBM) is an alternative system, natural ecosystem-based development, that could manage our tropical natural resources (Agus et al. 2019a). As we know, the tropical natural resources, biotic and abiotic, are fundamental from both the ecological and socio-economic point of view, being at the basis of life-support. However, since the demand for finite resources continues to increase, the sustainability of current production and consumption patterns is questioned both in developed and developing countries (Crenna et al. 2018).

Life cycle assessment (LCA) is used to assess a product's environmental impact over an entire life cycle, from resource procurement to final disposition (Straka and Layton 2010). One ensures that IBM sustainability standards are being met, and the other measures the environmental impact of specific tropical natural resources products over a life cycle. Tropic natural resources have been barely considered within LCA, and specific improvements are needed to capture better impacts related to multifunctional and multi-product system use. Based on Straka and Layton (2010), LCA is a tool to evaluate multiple environmental impacts and some social impacts attributed to a product or process. Inputs and outputs are measured over the entire life process, to minimize adverse environmental impacts over the life cycle of a product or process.

Natural resources are defined as an area of protection and are part of the Life Cycle Impact Midpoint-Damage Framework (Oers and Guinée 2016). Tropical natural resources in the LCA are the category of "resource depletion" that must be conserved, whereas other management systems consider current and future resource use (Ludwig et al. 2015). IBM's tropical natural resource depletion is expected to be less than without IBM's management or with other management.

The depletion of abiotic and biotic resources is, therefore, a fundamental issue for sustainability assessment, entailing and affecting environmental and socio-economic aspects (Klinglmair et al. 2013). The depletion of a resource means that its presence on Earth is reduced. Other related terms are scarcity and criticality. The scarcity of a resource means that the amount available for use is, or will soon be insufficient ("demand higher than supply flow"). Meanwhile, the criticality of a resource means that it is scarce and, at the same time, essential for today's society (Van Oers and Guinée 2016). Therefore, resource scarcity is the rationale on which this category is commonly based on current practice, while different methodologies are used in the context (Ludwig et al. 2015).

Based on Van Oers and Guinée (2016), LCA should not strive to take into account all these different aspects of criticality assessment, i.e., environment, economy, and social aspects. They may be part of a broader life cycle sustainability assessment (LCSA), but even then, a general approach will be difficult, as many of the criticality aspects are highly time- and region-dependent and even differ for different stakeholders. LCSA is a framework for (cradle-to-grave) system analysis, which, besides environmental aspects, may also focus on economic and social issues. However, the impact categories for IBM's tropical natural resources

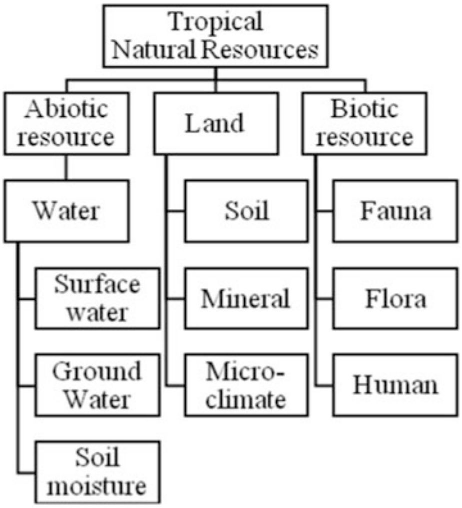

Fig. 10.2 A schematic of IBM's LCA based on the amount of tropical natural resources depletion (modified from Klinglmair et al. 2013)

depletion only deal with the environmental pillar of the sustainability assessment, and the indicator is based on the problem of depletion only.

A considerable range of methodologies for assessing resource depletion in LCA has been proposed, with different theoretical underpinnings. However, it is arguable whether resource availability is an environmental or economic issue and whether this should be subject to characterization models. Figure 10.2 gives an overview of the types of resource depletion looked at in the LCA context. No methodology provides full coverage of the resources in Fig. 10.2.

The LCA is focusing on the biotics part and in abiotic only assessed the water use. Based on Klinglmair et al. (2013), land use has been kept as its category, since it is neither as clearly to be characterized in mass or volumetric terms, nor as abiotic or biotic but in terms of area. There is no consensus on unambiguous land categorization in the stock/fund/flow scheme, and the land is not counted as a resource. However, further studies in several aspects are highly needed for the complete inclusion of IBM's tropical natural resources in LCA.

However, it should be noted that increasing the efficiency of resource use has become an essential strategy in the pursuit to limit the impacts of resource utilization on the environment as resource efficiency is considered an essential element for sustainable development (Ludwig et al. 2015). IBM has known for managing land resources (i.e., soil, water, mineral, air, and microclimate) and biological resources (i.e., fauna, flora, and human). IBM is an essential strategy that is able to increase land and water productivity in protective tropical ecosystems (Agus et al. 2019a); this management system successfully increases the yield of the product while using resources efficiently.

10.5 Biowastes Management

IBM is a smart tropical agroecosystem management system that could be implemented to solve a tropical environment problem (Agus 2018, 2019). Based on Vandermeer (2002), the tropical environment is unique in many ways, from the lack of a biological down season (winter) to generally poor soil conditions, to a reliance on traditional methods of agriculture in an undeveloped society. At a time when the sustainability of natural resource use in the tropics has become an important issue, tropical agroecosystems provide a critical scientific foundation for developing a sustainable agriculture component within this process.

In lowland tropics, the net annual primary productivity may be higher than anywhere else in the world (Janzen 1973). This productivity is the primary factor controlling litterfall production. If there is no appreciable consumption by direct grazing, organic substances return to the soil mainly as litterfall, timber fall, and dead roots (Wanner 1970). In tropical environments, the fine litterfall in the biowaste represents the primary process that determines the potential return of organic matter and nutrients to the soil, which supports plant development and soil biota. However, nutrient recycling is achieved when the litter is decomposed by soil biota (León and Osorio 2014).

Fine litter production and decomposition are two critical processes that provide the primary input to form soil organic matter and regulate nutrient cycling in forest ecosystems (León and Osorio 2014). Those are controlled by biological and physical processes such as the activity and composition of soil and litter macro- and micro-fauna and climate variations, in particular, rainfall and temperature (Sanches et al. 2008). The rates at which both processes occur determine the thickness of the litter layer on the forest soil. Thus, the role of litter in plant nutrition is determined by its turnover time (León and Osorio 2014).

The year-round warmth of the lowland tropics is a mixed blessing. High year-round soil temperatures lead to a very rapid breakdown of litter, with subsequent leaching of soil nutrients before they can be taken up by plants (Janzen 1973). León and Osorio (2014) stated that if the nutrients are quickly released, they could be lost by leaching or volatilization. If the decomposition occurs, the nutrient supply slowly to plant roots will be insufficient, thus limiting plant growth and development. For these reasons, the rates at which litter decomposition and subsequent nutrient release occur constitute key factors for ecosystem functioning.

Soils in the tropical lowlands are often a nutrient reservoir or deficient capacity. Plant ash from burning, ions from the very rapid litter breakdown, and chemical fertilizers are rapidly leached from the soil if not taken up by plants. There is generally a deep layer of nutrient-poor material over an unweathered rock (Janzen 1973). Therefore, the organic matter return is the best biowaste management in a tropical agroecosystem.

Regular addition of locally available biowaste and organic resources like litter, crop residues, green manures, green leaf manures, cover crops, vermicomposting, and tank silt improve soil organic matter (SOM) in agroecosystems. SOM plays an essential role in maintaining the productivity of tropical soils because it provides energy and substrates and promotes the biological diversity that helps to maintain soil quality and ecosystem functionality. Once the soil is continuously cultivated for agricultural production, especially in the tropical regions, SOM is rapidly decomposed due to modifications in soil physical properties such as aeration, soil temperature, and water content and productivity of soil decline due to a decrease in organic matter content and soil pH. This condition can affect many soil functions that are either directly or indirectly related to SOM, due to its capacity to retain water and nutrients. Although the breakdown rate of SOM can be faster in the tropics, regular inputs of organic amendments can promote a build-up of SOM. Regular additions of organic manures are considered to be an effective way to achieve soil organic carbon (SOC) sequestration and supplying micronutrients to crops in comparison with the use of chemical fertilizers alone in a tropical agroecosystem (Surendran et al. 2016).

10.6 Bioenergy and Biogas Management

From 1964 to 2015, global food consumption increased per person per day from about 2358 kcal/day in the 1960s to 2940 kcal/day in 2015. It is predicted to expand 3050 kcal/day in the 2030s (Vasileska and Rechkoska 2012). The growth in food consumption has also been accompanied by significant changes and shifts from grain foods to more livestock and vegetable oil products (Bruinsma 2003). Livestock products provide 17% global kilocalorie consumption and 33% of global protein consumption (Fonseca 2009). Moreover, the population is also predicted to increase steadily year by year. Food and Agriculture Organization (FAO) predicts the increase in the population of 9.7 billion in 2050 (FAO 2018). It means there is an increase in livestock and vegetable oil products consumption. In 2018, especially in Indonesia, meat consumption increased by 12.5%, egg consumption increased by 6.64%, chicken consumption increased by 11.22% as compared to 2016 data (Statistics Indonesia 2018). In recent years, livestock and poultry farming are overgrowing, but it is likely to be adversely affected by climate change, competition for land and water, and food security. The growth of livestock and poultry farming is not accompanied by good waste management. Manure becomes one of the biggest and most important waste in livestock and poultry farming. The impact of livestock and poultry farming is not only on the soil and water environment but also on the atmospheric environment. The effect on the air environment is from methane, carbon dioxide, and nitrous oxide emissions that cause global warming. The livestock farming contributes about 14.5% of total global emissions (Rojas-Downing et al. 2017). Further, about 27% of livestock emissions are in the form of carbon dioxide, 29% of livestock emissions as nitrous oxide, and 44% in the form of methane (Fig. 10.3).

Tubiello et al. (2014) reported that the most significant global warming emission comes from enteric fermentation, manure, and synthetic fertilizer (40%, 15%, and 13%, respectively). Greenhouse gases emissions from enteric fermentation consist of methane produced in the digestive system of ruminants and to a lesser extent of

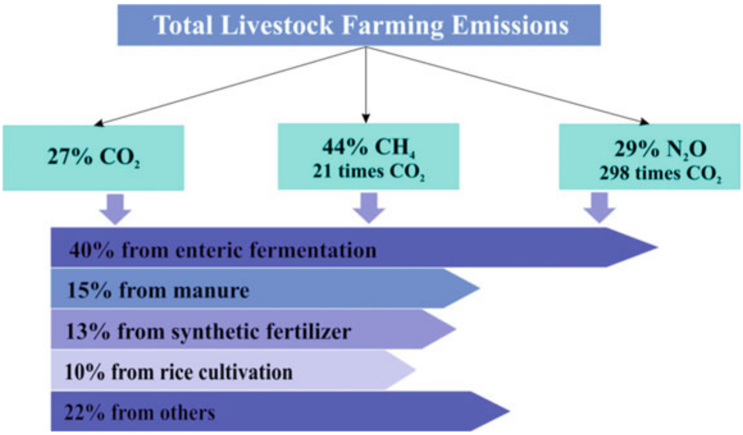

Fig. 10.3 Distribution of GHGs emissions from livestock farming (modified from Tubiello et al. 2014 and Rojas-Downing et al. 2017)

non-ruminants. At the same time, livestock manure releases methane and nitrous oxide from the decomposition of the organic materials in manure under anaerobic conditions. Liquid manure found in lagoon or tanks releases more methane than dry manure. These emissions also depend on temperature, moisture, pH, storage time, and animal diet. FAO (2018) reported that manure decomposition contributes 17.5 million tonnes of global methane per year. Of all gas emissions from livestock and poultry activities, methane is dominant and the Global Warming Potential of methane is 21 (Gerber et al. 2013).

The greenhouse gases emissions from livestock can be attributed to lower efficiency and productivity of livestock and due to excess loss of nutrients, energy, and organic matter (Gerber et al. 2013). The solution for this problem is developing an Integrated Bio-cycle System (IBS) in livestock and agriculture farming. Principles in IBFS are cycling of energy, organic matter, and carbon, water, nutrient, production, and money through the 9R method (reuse, recycle, refill, replace, repair, replant, rebuild, reward). This concept is offered to manage bioenergy and waste in livestock and poultry farming, and to mitigate the negative impacts on the environment. Integrated Bio-Cycle Farming System (IBFS) also leads to a circular economy as a business practice that gives benefit by utilizing waste and by-products. In other words, a circular economy is a generic term for an industrial economy that is producing no waste and pollution. EIP-AGRI Network defined circular economy as a principle in which resource efficiency is at the center of economic decision-making and practice, ensuring added value and making sure that resources are maintained as long as possible so that they can be re-applied by eliminating waste (EIP-AGRI Network 2015). The concept of a circular economy is presented in Fig. 10.4. This phenomenon is a contrast to a linear economy which involves "take, make, and dispose" model of production. The circular economy not only focuses on to decrease the waste by the 9R method but also arranges how to utilize

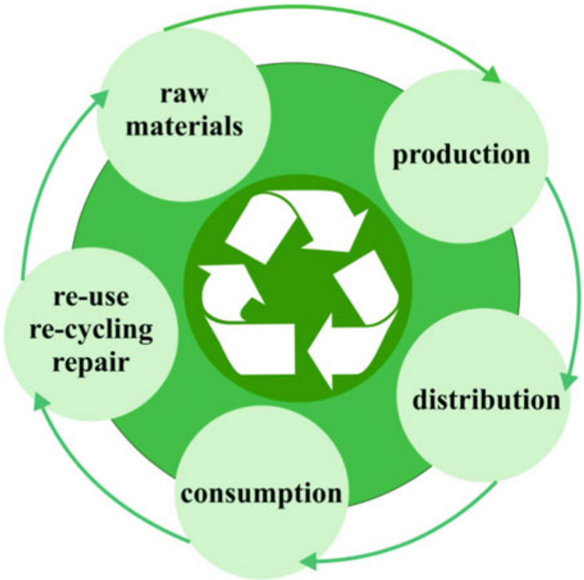

Fig. 10.4 The circular economy involves feedback loops (Modified from EIP-AGRI Network 2015)

waste and by-products so that economic value is added. Adoption of IBFS increases resource efficiency through use and reuse of resources and improvement in feedback loops. Implementation of IBFS and circular economy will make our business more economical and sustainable in the long term.

Implementation of IBFS and circular economy in agriculture and livestock farming is possible. Many agriculture and livestock waste are ideal raw materials for biological processes to create new products or existing products. Technologies that facilitate these processes are composting, anaerobic digestion, open-pond bioreactors, pyrolysis, and chemical extraction. These technologies have been spread and implemented in the agriculture and livestock sectors previously, but the integration of these technologies in an integrated area is rare. Biorefinery is also an important option in waste management. The biorefinery is a facility for processing bio-based feedstocks into valuable products addressing the needs of a diverse market like fuels, plastics, or other commodities (Murthy 2019). Biowastes can be treated through direct combustion, thermochemical conversion, biochemical conversion, and non-value-added treatment (Yu et al. 2018). The most common method is the first three types, waste to energy (WTE). Waste to energy is a transformation of biodegradable waste to energy by direct combustion, thermochemical conversion, or biochemical conversion. One of them is anaerobic digestion technology that produces biogas. Biogas becomes one of the products in IBFS and circular economy applications in biowaste management by biochemical conversion technology. The biochemical process involves microorganisms to convert biomass into environmentally friendly products. Today, biogas has been established all over the world and utilized to produce energy and heat in rural areas. If we assume that every cattle produces 0.32 m^3/day biogas (Bond and Templeton 2011), then Indonesia with

Fig. 10.5 Potential products from livestock manure

17 million cattle has potential to produce biogas of 545,600 m^3/day. Biogas plants in addition to producing biogas, provide sludge, which can be used as a value-added product (Pertiwiningrum et al. 2016, 2019; Stefaniuk and Oleszczuk 2015). Biogas sludge also can be combined with eggshells to grow oyster mushroom (Saputra et al. 2010; Pertiwiningrum et al. 2017, 2018).

Livestock manure has many potential economic benefits besides biogas. Manure contains nitrogen, phosphorus, and other nutrients that plants need to grow. Manure nutrients can also be used to grow worms, insect larvae, algae, or another living organisms. Through biochemical conversion, microorganisms transfer manure nutrients to their bodies, which can be harvested and used as fertilizer, animal feeds, or soil enrichments. People also use manure as fiber, mixed with undigested animal feed and agriculture waste. The biorefineries pathway of livestock manure is shown in Fig. 10.5. Utilization of livestock waste as fertilizer, soil enrichment, energy source, and even construction materials can protect water and air quality and reduce greenhouse gases. Livestock waste can harm the environment, but through circular conservation, it can be managed to be valuable resources.

All biorefinery products from livestock and agriculture waste can be integrated into an area through the IBFS system. The IBFS system applies integrally to the agrifood value chain, including livestock and crops, food processing, and the retail sector (Cahyanti et al. 2019). It also provides a mechanism to achieve increased

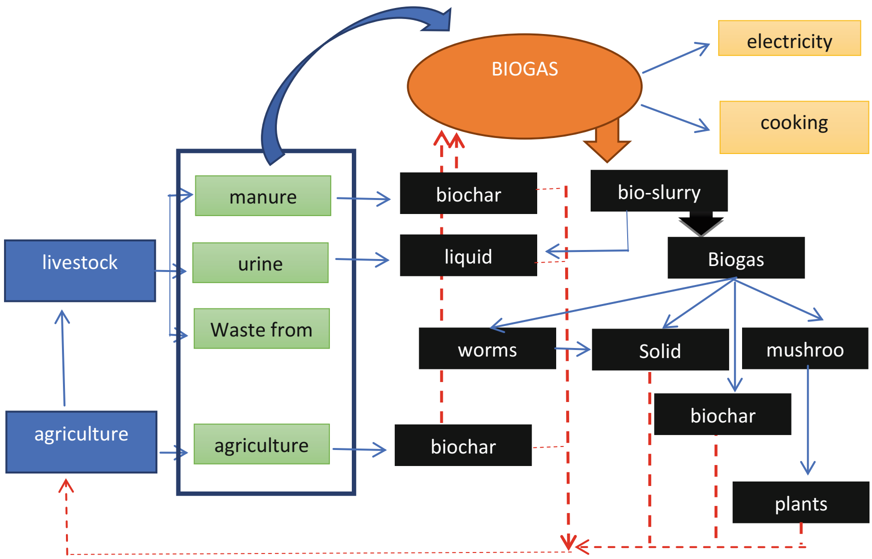

Fig. 10.6 Integrated bio-cycle farming system

recycling and valorization of agricultural or livestock waste by maximizing the use of byproducts by creating new sustainable value chains (Toop et al. 2017). One model in the IBFS system in livestock and agricultural sectors is presented in Fig. 10.6. Biogas contains methane and carbon dioxide, but the presence of carbon dioxide decreases calorific value because carbon dioxide is non-flammable gas. Biochar from biomass waste like agriculture waste, manure, and sludge can capture carbon dioxide by biogas upgrading process. Porous characteristic of biochar plays a crucial role in absorbing carbon dioxide. Utilization of biochar as an adsorbent in biogas upgrading leads to a sustainable biogas system. The concept of IBFS in biogas implementation cannot achieve success without intervention of human capital. Capacity building of human capital can be developed through community development. In community development, there is sharing of knowledge and experience between farmers practicing waste management and the IBFS system. Moreover, through community development, farmers also learn to be entrepreneur. Collaboration between stakeholders also plays an essential role in the sustainability of biogas management. Collaboration involves academics, financial partners, government, and industry. Collaboration between stakeholders is expected to create an innovation and sustainable agroprenuer atmosphere. The government is also expected to be a facility to create a business in a circular economy concept so that collaboration between stakeholders has a positive impact on developing local economies.

10.7 Agricultural Bioeconomy

In the twenty-first century, human kind is faced with several challenges such as energy instability and environmental pollution (Valenti et al. 2020). The most crucial environmental problem is related to greenhouses gases (GHG) caused by the continuous rising combustion of fossil fuels (Hosseini et al. 2013). Some countries seem to agree to reduce GHG emissions from fossil fuels by moving to renewable energy sources (Pätäri et al. 2016), produce cost-effective energy, and by increasing bioenergy efficiency (Wu et al. 1999; Garnier 2014; Ebner et al. 2015). The agreement is seen from the increasing number of countries that have decided to develop strategies and policies on "bioeconomy." These countries include Spain (Lainez et al. 2018), Ghana (Poku et al. 2018), Brazil (Scheiterle et al. 2018), and Poland (Woźniak and Twardowski 2018).

Aside from the urgency of the need for renewable energy sources, the presence of bioeconomy is also driven by rapid progress in life sciences and technologies which results in new opportunities in using biotechnological processes in industries and creating novel bio-based products (Global Bioeconomy Summit 2015; Woźniak and Twardowski 2018). The bioeconomy can be one of the fastest-growing sectors caused by the challenges faced by the world economy, such as managing natural resources sustainably and ensuring food security (European Commission 2012; Woźniak and Twardowski 2018).

Bioeconomy is a concept that has been around for the past 10 years (Egea et al. 2018) but with unclear definitions (Woźniak and Twardowski 2018). McCormick and Kautto (2013) defined bioeconomy as an economy in which the materials, chemicals, and energy used are derived from renewable biological resources. In the future, bioeconomy as sustainable economic system and lifestyle transformation is needed to face social challenges, such as increasing population, climate change, adverse effects of the human activities, uncertainties about food security, and sustainability issues, i.e., depending on the secure, sustainable, and safe availability of food, energy, water, and industrial raw materials (Egea et al. 2018; von Braun 2018).

In the European Union, bioeconomy comes as a spinoff of the sciences, especially biotechnology that aims to transfer research results efficiently into society and to the market as products and services (Egea et al. 2018). Bioeconomy provides goods and services to all economic sectors (Global Bioeconomy Summit 2015). Through products and services obtained by making efficient and sustainable use of biological resources, the bioeconomy can generate economic value (Lainez et al. 2018).

Bioeconomy or bio-based economy encompasses the sustainable production of renewable biological resources or biomass and conversion of the biomass and waste streams into several bio-products, ranging from a feed, food, health, fiber, and industrial products to high value-added products and bioenergy (Egea et al. 2018; European Commission 2012). Through bioeconomics, biomass resources are produced and converted into new economically competitive products, sustainable, and eco-efficient (Global Bioeconomy Summit 2015; OECD 2008). Biomass is an organic resource derived from plants and animals, and the rich source of biomass is crops and their residue (Poku et al. 2018).

Bioeconomy is part of the green economy concept (Scarlat et al. 2015). The model offered by bioeconomy for sustainability management places more emphasis on knowledge transfer (D'Amato et al. 2019). Bioeconomy faces a dilemma. On the one hand, bioeconomy would focus on new growth of traditional and emerging bio-based sector opportunities, but on the other hand, it is constrained by global challenges (e.g., raw material supply constraints) as well as resource and environmental constraints (IEEP 2014; European Commission 2014).

The duality problem shows that the development of bioeconomy is not without challenges (Scheiterle et al. 2018). The sustainability of raw material, efficiency in use, and economy of scales in biomass mobilization becomes the crucial problem faced by the modern bio-based economy (Scarlat et al. 2015). The increasing use of biomass will also threaten global food security because the production cost of biomass is not cheaper, and it will lead to higher food prices and affect food security in the coming years (Rosegrant et al. 2013; Scheiterle et al. 2018).

Most countries have launched their bioeconomy strategies. In the EU, a strategy on bioeconomy has launched in 2012 intending to drive the transition from a fossil fuel-based economy to a bio-based economy that is geared to obtain sustainable economic growth and create new jobs in all areas related to the sector (Egea et al. 2018). In the same year, 2012, Malaysia has launched Bioeconomy Transformation Programme (BTP) that is expected to be one of the strategies transforming Malaysia into a high-income nation with activities focusing on agriculture productivity and sustainable industrial processes (Arujanan and Singaram 2018).

The EU horizon 2020 program associated with the bioeconomy strategy was predicted to create €45 billion in added value and 130,000 jobs in the bioeconomy sectors by 2025 (Egea et al. 2018). Similar to the EU program, BTP in Malaysia is also expected to create 170,000 new job opportunities by the year 2020 (Arujanan and Singaram 2018). Agriculture and food and feed production play an essential role in the bioeconomy strategy of Poland, where the share of agriculture in generating gross value added was 41% in 2014 (Woźniak and Twardowski 2018). Poland has considerable potential in producing biomass to be produced into energy or conversion into biofuels and raw industrial materials (Woźniak and Twardowski 2018).

Sub-Saharan Africa agriculture has transformed from food supply to the biomass supply and processing sector to support other global and international bioeconomic products (Timilsina et al. 2012; Virchow et al. 2016). An increase in demand for food and agriculture indirectly shifts the sector activities towards more secure, higher quality, promote consumer health, and with differentiated added values (Lainez et al. 2018). Besides, to reduce dependence on imports of oil and intermediate inputs, bioeconomy strategy in Africa also sought to create employment, income, and economic growth, especially in rural areas, by diversifying the markets for agricultural commodities (Poku et al. 2018) and promoting rural and coastal development also became one of the goals of the bioeconomy strategy in Spain (Lainez et al. 2018). Cascade use of biomass is also used as a strategy to process cassava biomass or by-products in Ghana (Poku et al. 2018). This strategy is related to the complex systems of interlinked biomass value chains (Virchow et al. 2014; Poku et al. 2018). Still based on the same approach, Brazil uses sugarcane biomass as a raw material to produce bio-based products, ranging from food (sugar and related products), bioenergy (ethanol, bioelectricity), bio-based bulk materials (bio-plastic) to bio-based high-value products (e.g., flavors and fragrances) (Scheiterle et al. 2018).

Both Ghana and Brazil use biomass value webs to interlink value chains in which food, feed, fuel, and other biomass-based raw materials are produced, processed, traded, and consumed (Virchow et al. 2016). Potential bioeconomy products or new cassava value chains include biogas, biofuel, pharmaceuticals, cosmetics, bioplastics, detergents, etc. (Poku et al. 2018). Then, potential bioeconomy products of sugarcane are not too much different with cassava, such as bioplastics, colorants, organic acids, amino acids, lubricants, flavors and fragrances, cosmetics, detergents, etc. (Scheiterle et al. 2018). Ghana combines the concepts of the biomass value web with the Diamond model (Poku et al. 2018), while Brazil combines it with National Innovation System (NIS) (Scheiterle et al. 2018). The two concepts have the same basis, namely identifying the actors involved in the biomass value web and analyzing competitive advantage of value web (Poku et al. 2018; Scheiterle et al. 2018). Poku et al. (2018) found that the actors playing an important role in strengthening cassava value chains are out-grower or contract farming, an institution such as financial institutions and public extension services and government policies. The actors playing an essential role in sugarcane value chains are bureaucratic system, the exchange of qualified employees between research and industry, and the development of public–private partnership (Scheiterle et al. 2018).

The development of a sustainable bioeconomy for replacing non-renewable resources also depends on innovations in biomass transformation processes (Valenti et al. 2020). Valenti et al. (2020) investigated the effect of using feedstock mixture on methane production for bioenergy generation using anaerobic co-digestion (AcoD). They explained that AcoD has several benefits, such as improving the stabilization of the process, the dilution of inhibitory substances, the nutrient balance, and the reduction of GHG emissions. This study used 10 Mediterranean feedstocks highly available in the Mediterranean area, i.e., olive pomace, olive mill wastewater, citrus pulp, poultry litter, poultry, and cattle manure, whey, and cereal straw. They used the feedstocks highly available because there is a transport cost problem in this sector. So, this study was done to select the best biomasses producing methane optimally.

The other innovation that has been carried out towards sustainable bioeconomy transitions is using integrating pyrolysis in a winery waste biorefinery. This study was done by Zabaniotou et al. (2018). This study uses cascade waste biorefining approaches to ensure sustainable use of biomass for food, feed, energy, and bio-based products. Wastes produced by wineries are used as biorefinery feedstock because the wastes are suitable and fulfill the criteria of availability.

A sustainable bioeconomy is not the task of one or two people. Many actors are needed in this area to keep it sustainable. Arujanan and Singaram (2018) concluded that we need a strategy that focuses on many sectors, such as accessibility for funding, government policies, market needs, talent development, industry collaboration, and other relevant sectors. The Indonesian government set policy, the Go Organic Campaign in 2010, to foster the farmers' movement to grow organic paddy was initiated in 2001. Many farmers, among others in Sleman, Garut, Sragen, and Magelang have performed extensively since the early 2000s, while others have not been interested because they do not know the benefits, especially for the improvement of soil properties (Utami and Handayani 2003; Saepurrohman 2003; Sugiyanto et al. 2006, 2010). The positive impact of organic farming has been widely recognized, among other things viz. producing quality products, environmentally safe products, etc. However, farmers may face the risk of a decrease in production. Farmers need to diversify risk or a reduction in adoption fees as an incentive. Farmers need incentives so that they choose to adopt organic fertilizer for rice production, technical assistance from the extensionist, and favorable pricing policy. Overall, the Indonesian government underlines the bioeconomy strategy in its Master Plan for Agricultural Development 2015–2045 (Priono 2016). It includes sustainable agrobioindustry, the change of agricultural development paradigm, and comprehensive research (agronomy, biomass processing, and integrated agri-bioindustry). Further, the government implemented climate-smart agriculture, pilot model development of sustainable integrated agriculture bioindustry in 33 provinces, Science and technopark development program, promotion of integrated crop-livestock systems, and Organic Farming Village program.

10.8 Conclusion

The tropical ecosystems have biomass productivity more than10 times, but the economic value is only half compared to temperate ecosystems. The new paradigm from extraction to the empowerment of natural resources will provide new challenges to move from the red and green economic concept to the blue economic concept. The synergism between biological resources (flora, fauna, human) and land resources (land, minerals, water, air, microclimate) by the development of Integrated Bio-cycle Management (IBM) through empowerment of life cycle assessment as a closed-to-natural ecosystem would manage our tropical natural resources through multifunctional and multi-product system. Information about agroecosystem, life cycle assessment, biowastes, bioenergy, bioeconomy on tropical natural resources would give valuable concepts for sustainable development of smart tropical agroecosystem. This integrated farming system can produce food, feed, fiber, fertilizer, wood, energy, water, oxygen, medicine, mysticism, and tourism, so they have higher added values in environmental, economic, socio-cultural, and health aspects. This system is essential for the sustainable and productive management of tropical natural resources.

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Biopesticides for Pest Management

11

Meenatchi Rajamani and Aditi Negi

Abstract

Biopesticides are the biological agents used to control the pest population. It includes the use of botanicals, microbial pathogens such as fungi, bacteria, viruses and natural enemies of pests such as parasitoids and predators, nematodes and semiochemicals. Biopesticides play an important role in sustainability of agricultural bioeconomy. The ecosystem benefits rendered by the agriculturally important biological resources warrant inclusion of biopesticides in Integrated Pest Management Programmes. This chapter elaborates different types of biopesticides, their mode of action, formulations available, successful proven biological agents used in the suppression of pests, advantages and disadvantages of each method.

Keywords

Bioeconomy · Biological organisms · Biopesticides · Biological Pest Management

11.1 Introduction

Biopesticides are the biological agents or plant-based products used to control the population of injurious organisms to the ecosystem. They are naturally occurring substances from living organisms (natural enemies) or their products (microbial products, phytochemicals) and their by-products (semiochemicals) that can control pests by non-toxic mechanisms (Salma and Jogen 2011). They are considered as

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minimal risk products safe to human and his environment. It includes the use of botanicals, microbial pathogens such as fungi, bacteria, viruses and natural enemies of pests such as parasitoids and predators, nematodes and semiochemicals. Indiscriminate use of synthetic pesticides resulted in the development of resistance, resurgence and outbreak of secondary pests. Stringent regulation in the use of synthetic pesticides and the demand for organics promote the use of biopesticides. Management of pests without using harmful chemicals to human health and the environment is possible only by using biopesticides (Chandler et al. 2011; Bastiaans et al. 2008). Biopesticides play an important role in sustainable agriculture (Prasad et al. 2014, 2017). It causes mortality by substantially reducing arthropod populations before it reaches the economic threshold level (Betz et al. 2000). There is an urgent requirement to include biopesticides in Integrated Pest Management Programmes (IPM) to make it more sustainable since it lacks phytotoxicity, leaves no residues and is eco-friendly (Bhattacharyya et al. 2016).

11.2 Biopesticides: Global and Indian Perspective

The contribution of biopesticides to insecticide sector accounts for 15% of the total insecticide market. The estimated share of biopesticides in the world market is around $3 billion accounting for 5% of the total crop protection (Marrone 2014). The growth rate of a biopesticides is increased to 15%. In a successful natural control program, only 15% of biocontrol agents for control of insect pests have been identified. Commercially more than 125 species of natural enemies are available as biopesticides. Almost 90% of the microbial biopesticides currently available in the market are derived from only one entomopathogenic bacteria, i.e., *Bacillus thuringiensis* (*Bt*). Major producers and users of biopesticides in the world are the United States (US), European Union (EU) and India. In the US market, more than 200 *Bt* products and in EU 60 *Bt-based* products and 60 analogous products are commercially available (Kumar and Singh 2015). According to the report of India Biopesticides Market Insights, the Indian biopesticides market is expected to reach INR 316 Billion by 2024 from INR 197 billion during 2018. Biopesticides market potential in India is remarkably huge as the crop losses due to pest is about USD 9259 million per annum. However, presently, the biopesticides market accounts for only 5% of the pesticide industry. The Central Insecticides Board and Registration Committee (CIBRC) in India have registered about 970 microbial formulations. Further, about 200 entomopathogenic fungi-based products are available for commercial use. Among them, *Beauveria bassiana*, *B. brongniartii*, *Metarhizium anisopliae*, *Lecanicillium lecanii* and *Hirsutella thompsonii* are widely used against arthropods. A total of 45 products of *Bt* are commercially available. *B. thuringiensis* subspecies *kurstaki* is widely used against bollworms, loopers and other lepidopterans. *B. thuringiensis* subspecies *israelensis* and *sphaericus* are used against the mosquito. Among viruses, nuclear polyhedrosis viruses (NPV) are used against bollworms and armyworms. Rao and Manjunath (1966) demonstrated the use of first entomopathogenic nematodes *Steinernema carpocapsae* (DD-136 strain) for the control of lepidopteran pests of rice, sugarcane and apple in India. Several other indigenous strains of entomopathogenic nematode such as *Heterorhabditis indica*, *Steinernema carpocapsae*, *S. abbasi*, *S. thermophilum*, *S. riobrave* were also exploited for the management of field pests. The development of wettable formulation from *H. indica* with an extended shelf life of 12 months is commercially available in India (Kumar et al. 2019).

11.3 Categories of Biopesticides

Based on the classification by Environmental Protection Agency on the type of ingredient used, biopesticides are categorized into three major classes (1) microbial, (2) biochemical and (3) plant-incorporated protectants (Olson 2015).

Microbial Pesticides Microbial pesticides are the largest group of pest-specific, broad-spectrum biopesticides. Microbial pesticides include use of microbes such as bacteria, viruses, fungi and protozoans as active ingredients for the management of insect pests. They are relatively precise for their target species. Microbial biopesticides are self-perpetuating, host-specific and environment-friendly. Among the most widely used microorganisms against insect pests is *Bt*. It is used to control a wide array of pests including lepidopterans, coleopterans and dipterans (Gill et al. 1992).

Plant-Incorporated Protectants (PIPs) They are also called as genetically modified crops. Plant-incorporated protectants are pesticidal substances produced by plants and the genetic material required to produce such substances are introduced into the plants to offer resistance against pests. Pesticidal proteins separated from the bacteria or fungi are introduced into the plant and the genetically modified plants resist against specific pests. A typical example of this is use of *Bt* protein to develop PIP thorough the process of genetic engineering. *Bt* toxin is host-specific, achieves quick mortality of the pests usually within 48 h (Siegel 2001). No harmful effect on the ecosystem and it does not harm vertebrates (Lacey et al. 2015).

Biochemical Pesticides They are also known as herbal pesticides (Pal et al. 2013). They are naturally occurring substances and secondary metabolites that control or inactivate pests. Most widely used biochemical pesticide is from neem and neem-based formulations such as neem oil, neem seed kernel extract, neem extract concentrates from bark and leaves which are available in India. Also, essential oils from canola, tea tree, lemongrass (*Cymbopogon citrates*) and pyrethrin from *Chrysanthemum cinerariaefolium* are used as biochemical pesticides. Diatomaceous earth (DE) derived from fossilized sediments of numerous marine and freshwater siliceous organisms especially diatoms and other algae are used against an array of field pests. It has high absorption potential cause abrasion and desiccation in insect cuticle and finally results in death of insect.

Semiochemicals come under biochemical pesticides which include insect attractants, repellents, sex pheromones and kairomones. Semiochemicals are chemical signals produced by one organism usually by insects which results in behavioural change in an individual of the same or different species. The most widely used commercially available semiochemicals are insect sex pheromones. Sex pheromones are very successful to control adults by causing mating disruption. Mass trapping using sex pheromones to manage flying insects especially lepidopterans and coleopterans are very useful in IPM programs.

11.4 Biopesticides Derived from Bacteria

Bacterial pesticides are broadly classified into three categories

1. *Obligate pathogens*: These pathogens require special conditions and media for growth reproduction and sporulation. They have a very narrow host and most of them are spore formers. They are ideal for biological pest control programs. They have good stability. For example: *Bacillus papillae* and *B. lentimorbus* cause milky disease in white grub populations.
2. *Facultative pathogens*: Facultative pathogens do not require special conditions for growth, reproduction and sporulation. They are less virulent than obligate pathogens. Two categories of facultative pathogens are crystalliferous and non-crystalliferous. Crystalliferous bacteria produce proteinaceous crystals responsible for its toxicity. These are mostly spore formers. They have a wide host range. The bacterium *B. thuringiensis berliner* is a crystalliferous spore former commercially exploited as the biocontrol agent.
3. *Potential pathogens*: Potential pathogens can easily be cultured on artificial media and have a wide host range. It can infect insects even at small doses (<10,000 cells) and has a broad host range, e.g. *Pseudomonas aeruginosa* and *Serratia marcescens* used against root-knot nematodes and *Phyllophaga blanchardi* used against coleopteran pests. The non-invasive and non-spore forming nature of these pathogens limits them as promising biocontrol agents.

Microbial biopesticides from bacteria successfully used in mass multiplication are *Bacillus popilliae*, *B. thuringiensis*, *Clostridium bifermentans*, *Pseudomonas alcaligenes*, *Pseudomonas aureofaciens*, *Saccharopolyspora spinosa*, *Serratia entomophila* and *Streptomyces avermitilis. B. thuringiensis* and *Bacillus sphaericus* are harmful to lepidopterans, dipterans, coleopterans and hymenopteran pests. The insecticidal properties of this bacterium lie during the spore formation phase. During sporulation, *Bt* produces specific crystal protein (Cry I-IV and Cyt) which is harmful to the target pests. Table 11.1 enlists the *B. thuringiensis* subspecies and its toxin used against various pests. The *B. thuringiensis* based pesticides commercially available to control various pests (Gelernter and Schwab 1993) are presented in Table 11.2.

Table 11.1 List of *Bacillus thuringiensis* subspecies and its toxin used against various pests

Bacillus thuringiensis subspecies	Toxin class	Prototoxin size (K Da)	Target insect
Bt subsp. *Berliner*	Cry I	130–140	Lepidoptera
Bt subsp. *Kurstaki*	Cry I	130–140	Lepidoptera
Bt subsp. *kurstaki*	Cry II	71	Lepidoptera, Diptera
Bt subsp. *aizawai*	Cry I	135	Lepidoptera
Bt subsp. *tenebrionis*	Cry III	66-73	Coleoptera
Bt subsp. *israelensis*	Cry IV	68	Diptera

Table 11.2 List of *Bacillus thuringiensis* based pesticides commercially available to control various pests

Bacteria used	Target pests	Trade name
Bacillus popilliae	Japanese beetle grubs	Doom, Japidemic, Milky Spore Disease, Grub Attack
B. sphaericus	Mosquito larvae	Sphericide, VectoLex
B. thuringiensis subsp. *aizawai*	Lepidopterans	Certan
B. thuringiensis subsp. *israelensis*	Mosquito, blackflies and fungus gnats	Bacticide, Summit Bactimos, Bacto Power-Bti, Biodart M, Larvect50, Deltafix, Biovectra Spicbiob, VectoBac, Vectocid
B. thuringiensis subsp. *kurstaki*	Lepidopteran larvae	Abtec Btk, Agni, Bioasp, BioDart, Bactur, Biobit, Bioworm, Biolep, B.T.Killer, Caterpilin, Cezar, CID, Deflin, DiPel, Dipole, Gold Btk, Halt, JasBT, KavachBt, KrishiBio, Prasar, Lipel, Mahastra, Minchu, Neelstaki
B. thuringiensis subsp. *tenebrionis*	Colorado potato beetle, stored pests, coleopteran adults and larvae	Foil, M-one, M-track, Novardo, Trident
B. thuringiensis subsp. *Galleriae*	Lepidopteran larvae, bollworms, Diamondback moth	Spicturin

Source: Usta (2013)

11.4.1 Mode of Action of *Bacillus thuringiensis*

B. thuringiensis produces protein crystals during spore formation, which is responsible for lysis of gut cells when consumed by susceptible insects (Chandler et al. 2011). *B. thuringiensis* produces crystalline protein (cry and cyt). When cry protein is ingested by the larva, delta-endotoxins are activated in the gut of the insects which has alkaline pH (9.0 to 11.0). The proteins are attached to the gut receptor site, create pores in the midgut cells (Kumar 2012). *Bt* toxin causes paralysis of the midgut, cell lysis results in the release of gut contents into the hemocoel of the insect, disrupting the pH balance and finally death of specific target pest (Betz et al. 2000; Zhu et al. 2000; Darboux et al. 2001) (Fig. 11.1).

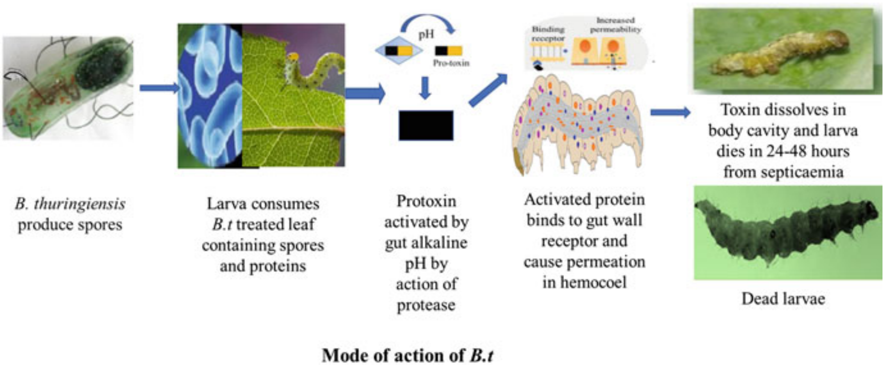

Fig. 11.1 Mode of action of bacterial pesticide

In contrast to Cry proteins, Cyt toxins are inserted directly into the lipid membrane of insects. Recent evidence shows that Cyt synergizes or suppresses resistance to mosquitocidal-Cry proteins by functioning as a membrane bound receptor for Cry toxin. Both Cry and Cyt toxins are pore-forming toxins (Aronson and Shai 2001; Bravo et al. 2007).

11.4.2 Advantages of Bacterial Biopesticides

- *Safe to use*: Bacterial biopesticides are safe to wildlife, humans and other organisms.
- *Specific*: The bacterial biopesticides are specific against their target organisms. They do not affect the beneficial insects.
- *Compatible with other methods*: Most of the bacterial insecticides are compatible with synthetic chemical biopesticides.
- *Non-hazardous*: It leaves no residues. So it can be applied even during the harvesting stage of the crop.
- *Natural establishment*: Bacterial biopesticides are self-perpetuating. Hence it is effective even during the subsequent crop growth seasons.

11.4.3 Disadvantages of Microbial Insecticides

- Microbial insecticides are toxic to only a specific species or group of insects. It may control only specific pests and the others will survive and continue to cause damage.
- When predators and parasitoids are used in pest management programs use of synthetic pesticides may harm the beneficial organisms. The selection of appropriate chemical pesticides is essential.
- The effectiveness of microbial insecticides is affected by factors like ultraviolet radiation, heat, etc. Hence, it should be applied in the morning hours only.

- Special formulation and storage procedures are necessary for microbial pesticides. Storage of microbial insecticides according to label directions is mandatory to maintain the virulence of pathogens.
- Mass multiplication of natural enemies throughout the year is difficult thus limit the availability in the market. The product registration process and less availability limit the use of biopesticides compared to chemical pesticides.
- Effectiveness of biopesticides is mainly depending upon the external environmental conditions such as temperature, relative humidity and rainfall. Weather conditions should be suitable for the multiplication and survival of biocontrol agents in the field.

11.5 Viruses as Biopesticides

Baculoviruses (BV) are widely used as viral biopesticides. They are highly pathogenic for insects and other arthropods. BV are tiny double-stranded DNA viruses and parasitically replicating microscopic elements. The genus baculoviruses contain three subgroups (1) nuclear polyhedrosis viruses (NPVs), (2) cytoplasmic polyhedrosis viruses (CPVs) and (3) granulosis viruses (GVs). They are considered as inclusion viruses which differ in the number of occlusion body and structure of the protective protein coat. NPV and CPV produce polyhedral bodies which are comprised of numerous virus particles. GV produces granular occlusion bodies which contain just one virus particle. The distinct mechanisms of NPV, CPV and GV virus uncoating occur among the baculoviruses. NPVs uncoat within the nucleus, CPVs uncoat in the cytoplasm and GVs uncoat within the nuclear pore complex to establish infection in the host. The occlusion bodies help the virus to survive outside the host (Cory 2000).

11.5.1 Mode of Action of Viruses

The mode of action of the viruses is like bacteria and needs to be ingested by the insect larvae to initiate infection. Immediately after the ingestion, virus enters the insect body through the intestinal epithelium and causes systemic infection in the host cell. NPV passes through intestinal epithelium to hemocoel, fat body and other tissue cells, disintegrates the integrity of the tissues and liquefies the cadavers. In case of GV, the infection is limited to insect midgut (Fig. 11.2).

11.5.2 Steps Involved in the Preparation of NPV and CPV

Usually third to fourth-instar larvae of *Helicoverpa armigera* are infected with viral food. The definitive phase of viral disease occurs over 5–10 days. Once the complete infection of the virus in the larvae is completed, before death, putrefying infected larvae climb higher in the plant canopy and start releasing billions of polyhedra which aid in the dissemination of virus particles from the cadavers to the lower parts of the

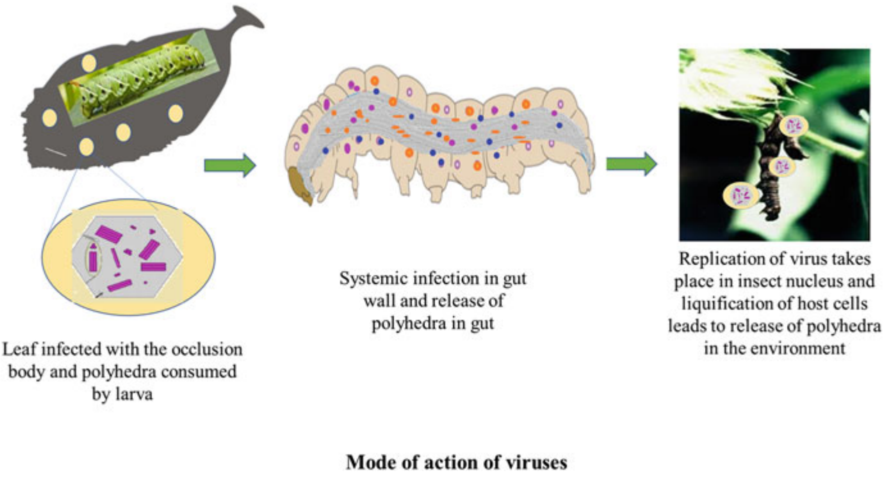

Fig. 11.2 Mode of action of virus

canopy. This behaviour helps in the spread of the virus to cause infection in healthy larvae. In commercial production, larvae are being harvested from the field or reared in the laboratory and allowed to feed on the contaminated diet. Before the inoculation of the virus, larvae are kept hungry for 24 h. Within three to four days larvae get infected with the virus and hang upside down in tubes. Infected larvae are collected and kept in water for purification. Purified larvae are crushed using mortar and pestle with sterile chilled distilled water in a ratio of 1:2.5 (w/v). Homogenate filtered with double layer muslin cloth and repeatedly washed with sterile distilled water in the ratio of 1:7.5 to 12.5 (w/v) for the original weight of cadaver larva. The filtrate is centrifuged to separate polyhedra from the debris. The pellets are repeatedly washed and centrifuged three times with sterile distilled water and finally collected purified polyhedra in the suspension are counted through haemocytometer. The dose of virus is fixed as one larval equivalent (LE) that is 6×10^9. The effective lethal concentration (LC_{50}) of NPV is 1×10^9/mL for *H. armigera* larvae. For gram, pigeon pea and cotton HNPV at 250–300 LE, 500 LE and 250 LE/ha should be used. Viruses are very host-specific and can cause significant reduction in host populations. Examples of some commercially available viruses include *Helicoverpa zea* single-enveloped Nuclear polyhedrosis virus (HzSNVP), *Spodoptera exigua* multi-enveloped nuclear polyhedrosis virus (SeMNPV) and *Cydia pomonella* granulovirus (CpGV). Table 11.3 shows the list of commercially available viral biopesticides.

11.5.3 Advantages of Viral Biopesticides

- Viruses are safe to humans and other non-target organisms.
- The target organisms will not develop resistance against viral biopesticides.
- Viruses can be integrated with other methods of insect control including chemical pesticides.

Table 11.3 List of commercially available viral biopesticides

Target pest	Host	Products available
NPV of *H. armigera* (HaNPV)	*Helicoverpa zea* *H. armigera*	Biokill-H, BioVirus-H, Heli-Cide, Heliokill, Helimar-NPV, Helivax, Jas Viro–H, Helicop, Heligard, Somstar-Ha
NPV of *S. litura* (SlNPV)	*Spodoptera lituraS. exigua*	BioVirus-S, Jas Viro–S, Spodo-Cide, Spodopterin, Somsta-SL
Nuclear polyhedrosis for Gypsy moth	Gypsy moth caterpillars	Gypchek virus
Tussock moth NPV	Tussock moth caterpillars	TM Biocontrol-1
Pine sawfly NPV	Larvae of pine sawfly	Neochek-S
Granulosis virus for Codling moth (GV)	Codling moth caterpillars	Madex, Carpovirusine, CYD-X

(Source: Usta (2013))

- They are self-perpetuating and keep the pest population under check.
- No secondary pest outbreaks.
- No pesticide residues.
- No pre-harvest interval is required.

11.5.4 Disadvantages of Viral Biopesticides

- It can be used for the management of multiple pests as that of chemical pesticides.
- A long period of lethal infection is required for successful control of target pests.
- Viruses get inactivated by environmental factors like ultraviolet light, extreme temperature, etc.

11.6 Fungi as Biopesticides

Fungi-based biopesticides are most versatile since it has a wide host range to the field and stored pests. They are safe and highly specific. Fungal products are developed using saprophytic or parasitic fungi, which grows inside an insect's body and feed on its internal tissues. The most common commercial fungal biopesticides available in the market are from *Beauveria bassiana*, *Metarhizium anisopliae*, *Nomuraea rileyi*, *Trichoderma viride*, *Paecilomyces farinosus* and *Verticillium lecanii*. These fungi are either obligate or facultative, has symbiotic or antagonestic relationship with insects for their survival. The pathogenic action of fungi depends on the contact and subsequent infection to the target pests. Commercial formulations of *B. bassiana* and*M. anisopliae* are effective against aphids, beetles and their grubs, grasshoppers, leaf and plant hoppers, pod borer, cutworms and other lepidopteran and coleopteran pests (Table 11.4).

Table 11.4 List of commercially available fungi-based biopesticides

Fungi	Host range	Products
Beauveria Bassiana	Effective against a variety of insects such as rickets, white grubs, fire ants, flea beetles, plant bugs, grasshoppers, thrips, mites, mosquito larvae and aphids, fungus gnats, whiteflies and to stored pest	BotaniGard, Mycotrol, Naturalis, Racer BB, Ostrinil, Brocari l, Mycotrol, Mycotrol-0 BotaniGard, Boverin, Naturalis-L, Naturalis-H&G Naturalis-T&O
Metarhizium anisopliae	Effective against a wide range of pests. Black vine weevil, locusts and grasshoppers	Bio-Blast, Bio-Path, Green Muscle, Met52 Metaquino Pacer MA Tick-Ex
Trichoderma viride	Effective against Rot disease	EcosomTV, Tricon, Trieco
Trichoderma harzianum	Effective against a variety of soil pathogens	Rootshield, BioTrek, Supresivit

Source: Usta (2013)

11.6.1 Mode of Action of Fungi-Based Biopesticides

Fungi act by penetration of the mycelium into the cuticle of the insects into the hemocoel causing the death of the attacked individuals.

- The fungal spore called conidia get adhere to the host cuticle by hydrophobic attachment.
- Spore germination will take place through the filamentous growth of conidia called germ tube or by appressorium.
- It penetrates the cuticle through hydrolytic enzymes produced by them. Also, organic acids, secondary metabolites, toxins and detoxifying antimicrobial compounds are secreted by fungi.
- Fungal spores penetrates from the cuticle of the insects into the hemocoel leads to the death of insects.
- Further, the internal mycelium grows outward sporulate and emerges on the outer surfaces of cadavers of insects (Pedrini et al. 2007; Gabarty et al. 2014) (Fig. 11.3).

11.6.2 Advantages of Fungi-Based Biopesticides

- *Wide host range*: As compared to bacteria and viruses, fungi have a wide host range and can infect field, stored and soil pests.
- *Ease of production*: Commercially important fungi such as *Beauveria*, *Metarhizium*, *Lecanicillium* and *Isaria* are relatively easy to mass produce with low substrate requirements.
- Effective and highly specific.
- Eco-friendly.

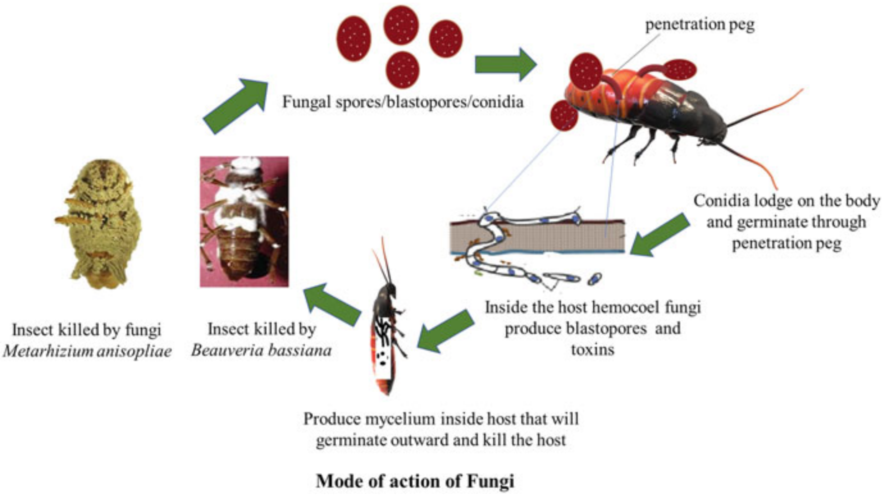

Fig. 11.3 Mode of action of fungi-based biopesticides

11.6.3 Disadvantages of Fungi-Based Biopesticides

- Ideal environmental conditions**:** Fungi are highly sensitive to environmental conditions. Humidity over 80% and above is required for spore germination and penetration on the surface of arthropods cuticle.
- Temperature and exposure to UV radiation affect the survival of fungi.
- Production and stabilization of fragile conidia or durable resting phase are difficult.
- It is costlier than other microbial methods.

11.7 Entomopathogenic Nematodes (EPN) as Biopesticides

Entomopathogenic nematodes are soil-dwelling, soft-bodied, un-segmented roundworms that are naturally present in water film near soil particles. Nematodes are obligate or sometimes facultative parasites that locate the host insects in response to carbon dioxide, vibration and other chemical indications. Commercially two families, namely *Steinernematidae* and *Heterorhabditidae*, have been effectively identified and used as bionematicides in pest control programs (Kachhawa 2017). *S. carpocapsae*, *S. thermophilum*, *H. bacteriophora*, *H. indica* products are registered and sold in India.

11.7.1 Mode of Action of EPN

- The non feeding infective third stage juveniles (0.4–1.5 mm in length) enter into an insect through natural openings, such as mouth, anus or breathing holes.
- Nematodes enter insect body cavity and release their symbiotic bacteria into the intestine of the host. Toxins produced by the bacteria kill the insect in a week.
- It feeds on the cadaver and liquefies its host. Nematodes reproduce and generate to three-generation descendants on host cadaver.
- Infective juvenile nematodes leave the dead insect and seek for a new host. Under optimal conditions, nematode-infected pest stages should be present 5–7 days after application. Insects killed by Steinernematidae become brown or tan; ones killed by Heterorhabditidae turn red. Dead insects, however, are not always visible (Fig.11.4). Table 11.5 represents the list of commercially available EPN based biopesticides.

11.7.2 Advantages of EPN

- They are considered safe to humans, plants and animals and relatively safe to the environment. It does not require personal protective equipment, safety masks and re-entry intervals. It leaves no residues.
- It is effective against field pests such as cranberry girdler, root weevil, black vine weevil, webworms, cutworms, armyworms and wood-borers.

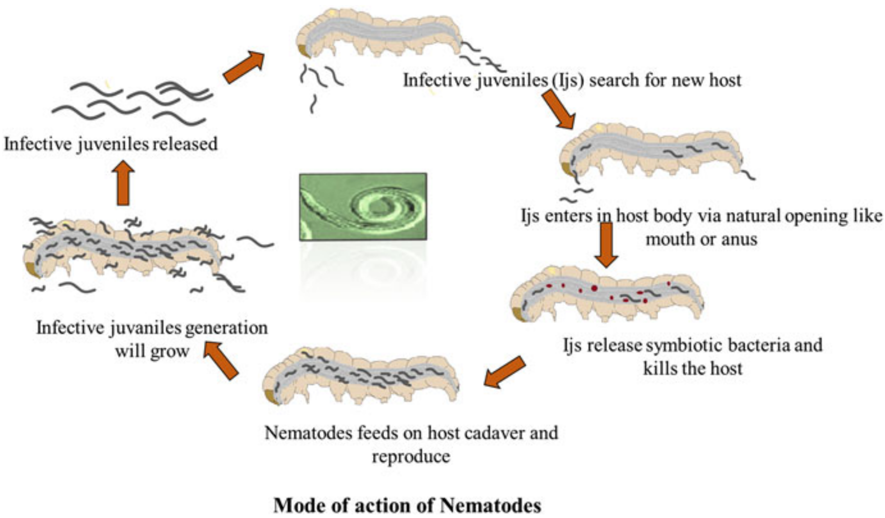

Fig. 11.4 Mode of action of nematodes

Table 11.5 List of commercially available EPN based biopesticides

Entomopathogenic nematodes	Host range	Commercial products
H. bacteriophora	Effective against root weevils, cutworms, fleas, borers and fungal gnats. Effective against black vine weevil populations by 56–100%	BioSafe, Larvanem, Nemaplant, NemaShield-HB, Nematop, Nematech-H NemaTrident-H, NemaTrident-C, Nema-green, Optinem-H
H. indica	*H. armigera*, *Conogethes punctiferalis*, *Athalia proxima*	Soldier, Nema power, GrubTerminator, Grubcure, Calterm, Aarmour
H. downesi	*Black vine weevil*	*NemaTrident-CT*
Steinernema feltiae, *S. riobravis*	Effective against black vine weevils, strawberry root weevils, cutworms, cranberry girdler and termites	Biosafe, Ecomask, Hortscan, Guardian, Millenium, Nematac C, NoFlea, Savior WG, Scanmask, Termask, Vector
S. carpocapsae	Borer beetles, caterpillars, crane fly, moth larvae, coconut rhinoceros beetle	Capsanem, Carpocapsae-system, Exhibitline SC, Optinem-C, NemaGard, Nemastar, NemaTrident-T, NemaRed, Nemasys-C, Palma-life

Source: Koul (2011), Gupta et al. (2010), Ruiu (2018)

- The soil around the roots of cranberries should be moist and humid, protection from harmful UV light and temperatures is often suitable for the survival of nematodes.
- Nematodes can withstand short-term exposure of (2–24 h) to many chemical and biological insecticides, fungicides, herbicides, fertilizers and growth regulators.

11.7.3 Disadvantages of EPN

- Nematodes are sensitive to environmental conditions such as UV and high temperatures; conditions that may be hard to control.
- Compared to traditional chemical insecticides, nematodes are generally very expensive. In a natural system, the number of insect hosts and nematodes is in balance. If the natural balance is overloaded with nematodes, they will kill the insects but will then die off themselves until insect populations start to build again. Hence re-application of nematode is essential.
- Since nematodes cannot live above the soil, they cannot infect insects that live above soil such as foliar-inhabiting insects. Nematode formulations have a short shelf life.
- It should be applied early in the morning or in the evening to protect from UV radiation.
- Pre- and post-irrigation is required for moistening the soil and washing the nematodes into the soil.

11.8 Protozoans as Biopesticides

Protozoans are also referred to as microsporidians. Microsporidia are ubiquitous, obligate intracellular parasites have the potential to attack lepidopteran and orthopteran insects hence can be used as a component of integrated pest management program, e.g. *Nosema* sp. and *Vairimorpha* sp. Although, they are pest-specific, slow-acting, induce chronic and debilitating effects on targets, the use of protozoa as biopesticides is not very successful compared to other organisms such as bacteria, viruses and fungi. Table 11.6 shows the protozoa based successful commercial biopesticides.

11.8.1 Mode of Action of Protozoans

- Microsporidia must be eaten by insects to get infected.
- Microsporidian infects European corn borer, *Ostrinia nubilalis*.
- The spores germinate in the midgut region and the sporoplasm is injected into the midgut cells.
- The spores spread to different tissues and organs, where they multiply resulting in tissue breakdown and septicaemia (Senthil-Nathan 2015).

11.9 Natural Enemies of Pests as Biocontrol Agents

Natural enemies of pests such as parasitoids and predators are widely used against the field and stored pests. Insect parasitoids have an immature stage of life that develops on or within a single insect host and finally kills the host. Parasitoids lay their egg on or in the body of insect host and the developing larvae utilize host body fluids and organs as food, kill the host as it pupates or emerges as an adult. Most important insect parasitoids are from the families of Ichneumonidae and branconidae. Wasps or a fly, which attacks the caterpillar, has a wide host range including aphids. Tachinid flies parasitize a wide range of pests such as caterpillars, larvae and adults of lepidopteran pests and beetles. For successful biocontrol program, parasitoids used should be host-specific, reproductive and should adapt to wide environmental conditions. Predators are free-living, large in size, feed on the host and destroy them during their life period. Predators such as *Brumoides* sp., *Chrysoperla* sp., dragonflies and damselflies are effective against various crop pests (Strand and Obrycki 1996) (Figs. 11.5 and 11.6). Table 11.7 shows the list of promising biocontrol agents used against crop pests.

Table 11.6 Protozoa based successful commercial biopesticides

Protozoan	Host Range	Products
Nosema locustae	European corn borer caterpillars, grasshoppers and Mormon crickets	NOLO Bait, Grasshopper attack

Source: Usta (2013)

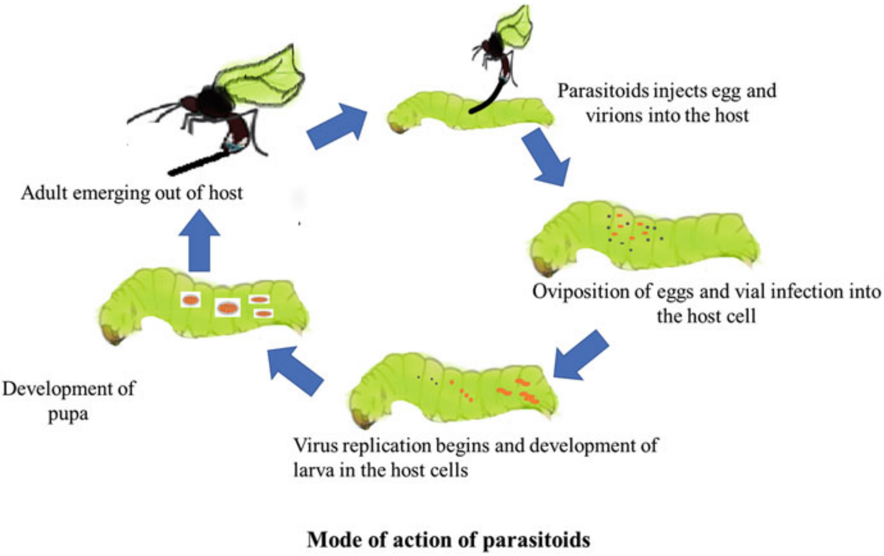

Fig. 11.5 Mode of action of parasitoids

Fig. 11.6 Natural predators

11.9.1 Advantages of Parasitoids in Biological Pest Management

- Specialized and host-specific.
- Parasitoids are efficient host searchers, can find their hosts even at low pest densities and bring infestation level below economic thresholds.
- Parasitoids reduce the number of pests surviving to the next generation.
- They are compatible with other biological control agents (predators).
- Some parasitoids affect feeding behaviour, e.g. parasitized larvae eat less than healthy ones, and are smaller than the host.

Table 11.7 List of promising biocontrol agents used against crop pests

Crop	Pest	Promising bioagent	Stage of pest	Kind of biocontrol agent
Sugarcane	Leafhopper, *Pyrilla perpusilla Walker*	*Epiricania melanoleuca*	Nymph and adult	Parasitoid
		Ooencyrtus pyrillae Mani	Eggs	Parasitoid
	Internode borer, *Chilo sacchariphagus indicus*	*Cotesia flavipes*	Larva	Parasitoid
		Rhaconotus scirpophagae Wilk	Larva	Fungal pathogen parasitoid
		Trichogramma chilonis Ishii	Larva	Parasitoid
	Gurdaspur borer, *Acigona steniellus*	*Cotesia flavipes*	Larva	Parasitoid
		Xanthopimpla stemmator Thunberg	Pupa	Parasitoid
	Maize borer, *Chilo partellus*	*Allorhogas pyralophagus Marsh*	Larva	Parasitoid
	Root borer, *Emmalocera Depressella swinhoe*	*Goniozus indicus Ashmead*	Larva	Parasitoid
		Elasmus Zentri ferriere	Larva	Parasitoid
	Shoot borer, *Chilo infuscatellus Snellen*	*Telenomus beneficiens Zhnt.*	Egg	Parasitoid
		Tetrastichus schoenobii Ferr.	Egg	Parasitoid
	Stalk borer, *Chilo auricillus, Dudgeon*	*Beauveria bassiana*	Larva	Fungal pathogen
		Goniozus indicus ashmead	Larva	Parasitoid
		Sturmiopsis inferens Tns.	Larva	Parasitoid
		Trichogramma chilonis	Egg	Parasitoid
	Top borer *Scirpophaga excerptalis Walker*	*Cotesia flavipes*	Larva	Parasitoid
		Fusarium subglutinans	Larva	Fungal pathogen
		Goniozus indicus Ashmead	Larva	Parasitoid
		Isotima javensis	Larva	Parasitoid
		Sturmiopsis inferens Tns.	Larva	Parasitoid
	White grub, *Holotrichia consanguinea*	*Bacillus papillae Dutky*	Grub	Bacterial pathogen

(continued)

Table 11.7 (continued)

Crop	Pest	Promising bioagent	Stage of pest	Kind of biocontrol agent
		Beauveria bassiana	Grub	Fungal pathogen
		Chilocorus cacti	Nymph and adult	Predator
		Fusarium subglutinans	Nymph and adult	Fungal pathogen
	Mealybug, *Saccharicoccus sacchari (cockerell)*	*Brumoides suturalis Fabr.*	Egg nymph and adult	Predator
Cotton	Spotted bollworm, *Earias insulana boisdual*	*Chelonus blackburni Cameron*	Egg	Parasitoid
		Trichogramma brasiliensis Ashmead	Egg	Parasitoid
		Trichogramma pretiosum Riley	Egg	Parasitoid
	Gram pod borer *Helicoverpa (Heliothis) armigera*	*Trichogramma chilonis Ishii*	Egg	Parasitoid
		Granulosis virus	Larva	Viral pathogen
		Nuclear polyhedrosis virus (HaNPV)	Larva	Viral pathogen
	Pink bollworm, *Pectinophora gossypiella Saunders*	*Apanteles angaleti Muse.*	Larva	Parasitoid
		Bracon bravicornis Weise	Larva	Parasitoid
		Bracon hebetor Say	Larva	Parasitoid
		Trichogramma pretiosum Riley	Egg	Parasitoid
	Spodoptera litura (fabricius)	*Chrysoperla carnea* (*St*)	Egg and neonate larva	Predator
		Nuclear polyhedrosis virus (NPV)	Larva	Virus pathogen
	Jassid, *Amrasca biguttula, biguttula Ishida*, *Aphis gossypii* Glover and whitefly, *Bemisia tabaci*	*Chrysoperla carnea (St.)*	Nymph and adult	Predator

(continued)

Table 11.7 (continued)

Crop	Pest	Promising bioagent	Stage of pest	Kind of biocontrol agent
		Coccinella septempunctuata Linn.	Nymph and adult	Predator
Rice	Stem borer, *Scirpophaga incertules* (Walk.)	*Trichogramma chilonis Ishii*	Egg	Parasitoid
		Tetrastichus Schoenobii Ferr.	Egg	Parasitoid
	Leaf folder, *Cnaphalocrocis medinalis* (Guen.)	*Trichogramma japonicum Ashmead*	Egg	Parasitoid
	Planthopper *Nilaparvata lugens* and leafhopper	*Cyrtorhinus lividipennis Rent*	Egg	Predator
	Gall midge, *Orseolia oryzae (wood mason)*	*Platygaster oryzae Cam.*	Egg	Parasitoid
Maize and jowar	Stem borer, *Chilo partellus* (swinhoe)	*Cotesia flavipes Cam.*	Egg	Parasitoid
		Trichogramma exiguum	Egg	Parasitoid
		Trichogramma chilonis Ishii	Egg	Parasitoid
	Aphid, *Rhopalosiphum maidis*	*Coccinella septempunctuata Linn.*	Nymph and adult	Predator
		Chrysoperla carnea (Stephens)	Nymph and adult	Predator
		Menochilus sexmaculata (Fabr.)	Nymph and adult	Predator
Groundnut	Hairy caterpillar, *Amsacta albistriga* (*Wlk.*) mustard aphid, *Lipaphis erysimi* (*Kalt.*)	*Telenomus manolus Nixon*	Egg	Viral pathogen
		Brumoides suturalis (Fabr.)	Nymph and adult	Predator
		Chrysoperla carnea (St.)	Nymph and adult	Predator

Source: Gautam (2008)

11.9.2 Disadvantages of Parasitoids in Biological Pest Management

- Highly susceptible to insecticides, especially adults.
- Adults require an alternative food source such as pollen or nectar.

- Immature parasitoids, especially if protected within the egg of their host or in their own cocoon, may tolerate pesticides better than adults, but immature parasitoids will usually die if their host is killed.
- To improve the abundance and diversity of beneficial insects especially parasitoids and predators it is necessary to consider native vegetation on the farm as a part of a pest management strategy.
- Sometimes multiple parasitoids may emerge from one pest.

11.9.3 Advantages of Predators in Biological Pest Management

- Bigger in size, prey many hosts, can reduce the pest population potentially.
- Not much affected by external environmental conditions and pesticides compared to parasitoids.

11.9.4 Disadvantages of Predators in Biological Pest Management

- Non-host specificity.
- Mass multiplication is difficult.
- Cannibalism is common in many predators.

11.10 Biochemical Pesticides

Phytochemicals or herbal pesticides are chemicals derived from plant origin. Each phytochemical possesses specific structure, performs various functions such as protection, growth acceleration and reproduction in plants (Huang et al. 2014). Phytochemicals are found in various parts of the plants like fruits, vegetables, grains, pulses, nuts, seeds, bark, etc. Since it has several bioactive compounds that contain antiparasitic, bactericidal, fungicidal, viricidal and insecticidal properties, it can be considered as a potential alternative for inorganic pesticides. These are secondary metabolites produced by plants by nature such as (1) terpenes contain phyto-volatiles, glycosides, (2) sterols contain phenolic compounds such as phenolic acids, lignin, tannins and alkaloids. Secondary metabolites play an important role in the plant defence system against insects. It acts as a toxicant, insect growth regulator, repellents and antifeedant (Mossa 2016). Phytochemicals from the plants can be extracted using solvent extraction, microwave-assisted extraction, ultrasonic-assisted extraction based on the presence of a group of phytochemicals present in it (Altemimi et al. 2017). At present only a few phytochemicals are used as biopesticides and most of them are neem-based (Table 11.8). These are mainly 3% neem oil or 5% neem seed kernel extract concentrates which can be applied at 25 kg/ha against major field pests.

Table 11.8 List of commercially available biochemical pesticides

Plant source	Target pest	Commercial name/compounds
Azadirachta spp., *Nicotiana* spp.	*Aphis craccivora*, Bollworms, Aphids, Jassids, Thrips, Whitefly, Leaf folder, Pod borer, Fruit borer, Leafhopper, Diamondback moth	Essential oils, nicotine, azadirachtin, salanin, nimbin, (leaf, seed, kernel) nimbecidin, bionimbecidin
Chrysanthemum cinerariaefolium *Lonchocarpus* spp. *Ryania* spp.	Crawling and flying insects such as cockroaches, ants, mosquitoes, termites	Pyrethrium, Rotenone Ryanodine
Artemisia annua	*Helicoverpa armigera*	Essential oils from leaf and seed
Vinca rosea	*Helicoverpa armigera*	Essential oils from leaf and seed
Ocimum basilicum *Salvia Officinalis*	*Aphis craccivora* Koch, *Agrotis ipsilon*	Essential oils form aerial parts leaves
Citrus sp.	Fleas, aphids, mites, paper wasp, house cricket	D-limonene linalool
Schoenocaulonofficinale	Bugs, blister beetles fly, caterpillars, potato leafhopper	Sabadilla dust
Adenium obesum	Cotton pests	Chacals Baobab (Senegal)

11.10.1 Mode of Action

The mechanism of action of herbal pesticides is either by absorption by insect cuticle, inhalation or by ingestion thus affects the physiology, biochemical pathway or nervous system of the insects. It affects the respiration of insects by blocking spiracles leading to suffocation. At the cellular level, it will interfere with the signal transduction, disturbing ion channel and ion pump of insect membrane. It also affects the neuroendocrine system of insects and juvenile hormonal imbalance resulting in malformation of insects. The decrease in adult mating time, reduction in ovulation, reduced fecundity and egg fertility are other effects. Monoterpenes present in the essential oil act as neurotoxicant which acts on the acetylcholinesterase enzyme involved in nerve impulse transmission in insects causing paralysis and death of the insects. It also interferes with DNA, RNA and protein synthesis (Fig. 11.7).

11.10.2 Semiochemicals

Semiochemicals are chemical substances produced by the organisms that enable and mediate communication between the organisms. Basically there are two types of semiochemicals, namely intraspecific semiochemicals (pheromones) and interspecific semiochemicals (allelochemicals). Pheromones are volatile chemical substances produced by an organism so as to elicit a reaction or response from the receiving individual (of same species). The releaser pheromones cause behaviour change in the recipient. The releaser pheromones include sex pheromones,

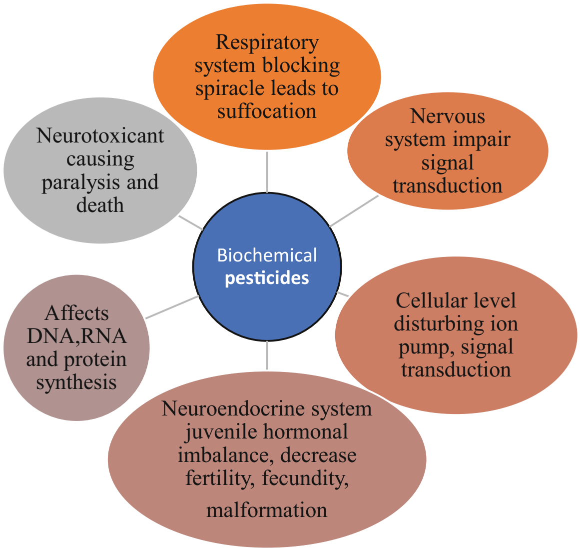

Fig. 11.7 Mode of action of biochemical pesticides

aggregation pheromones, alarm pheromones and trail pheromones. Aggregation pheromones are released by insects as an indication of food source available. Alarm pheromones are secreted by insects to show the presence of a predator and cause movement of insects away from the source. Sex pheromones are released normally by one sex only and they elicit responses in the other sex. These pheromones facilitate in mating. Synthetic analogues of sex pheromones are used in pest management. In fact, sex pheromones are used for pest monitoring, mating disruption and mass trapping.

11.10.3 Advantages of Biochemical Pesticides

- Safe for natural enemies, environment and human beings.
- Lesser chance to develop resistance to these pesticides.
- Economical, biodegradable, renewable and user friendly.
- Active component degrade rapidly thus it is more acceptable.
- They are stable and can be stored for extended period.
- They are insect specific especially in case of semiochemicals.

11.10.4 Disadvantages of Biochemical Pesticides

- More quantity of pesticide required due to its crude formulations.
- Mode of action is slow.
- Higher specificity and require an exact identification of the pest/pathogen.
- Variable efficacy.

11.11 Plant-Incorporated Protectants

Plants with the toxin-producing genes to fight against the pest are called plant-incorporated protectants or genetically modified or genetically engineered plants. These PIPs help the plants to resist bacteria, viruses or fungi. When PIPs are used against target insect, it is known as insect-resistant crops. Some of the examples for PIPs are soybean, brinjal, cotton, corn, potato and tomato. Transgenic plants are developed by transferring the target gene either by Agrobacterium-mediated transfer or by gene gun or ballistic methods (Fig. 11.8). These methods were used in wheat, maize, rice and corn (Table 11.9).

Plant-incorporated protectant have several advantages like it will give more yield with lesser amount of pesticide use. Thus, they are cost effective and protect neighbouring non-Bt crop also. Some potential risks are also associated with the plant-incorporated protectants, such as it affects non-target pest, risk to human health and environment, possibility of PIP gene to spread to the other plants and chances for development of pesticide or insect resistance.

11.12 Biopesticides Formulations

In most cases, biopesticides are formulated in the same way as that of synthetic pesticides. They are more convenient to use by the farmer and same equipment can be used for an application. Since it is made from living organisms, it is a prerequisite to maintain its viability during formulation and storage. Biopesticide formulations are available as active ingredients (AI) and inert or inactive ingredients. The active

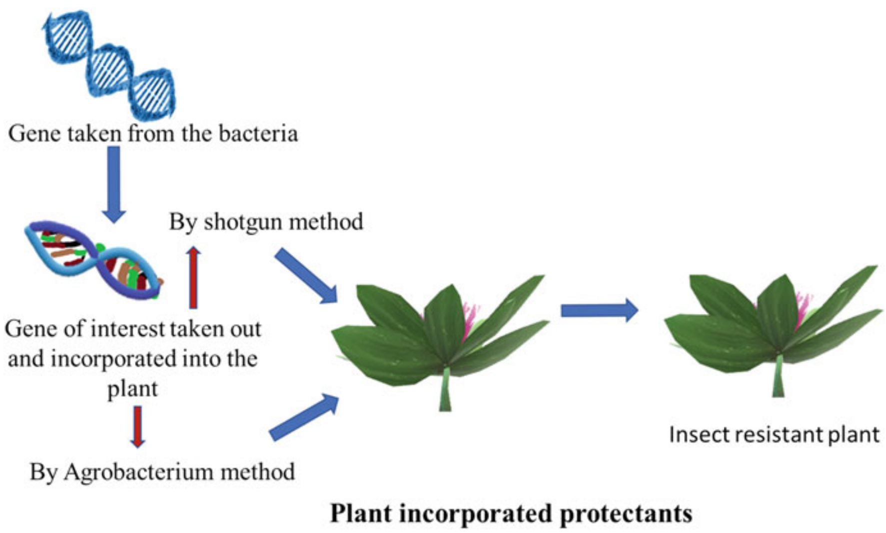

Fig. 11.8 Technique producing plant-incorporated protectants

Table 11.9 List of plant-incorporated protectants against crop pests

Plant	Gene incorporated	Resistance to insect	Commercial name
Cotton	Cry 1Ac toxins from *Bacillus thuringiensis*	Cotton and tobacco bollworm	Bollgard
Maize	Cry 1Ab,1F,9c toxins from *Bacillus thuringiensis*	European corn borer	Yieldgard, Knockout, Herculex I, Starlink, Maximizer
Rice	Cry1C from *Bacillus thuringiensis*	Leaf folders (*Cnaphalocrocis medinalis*) and stem borers	
Tobacco	QB protein of photosystem II from mutant Amaranthus	Atrazine resistant	–
Brinjal	Cry1Ac from the soil	Shoot and fruit borer, *Leucinodes orbonalis*	*Bt* Brinjal
Tomato	Cry1Ab gene of *Bacillus thuringiensis*	Second instar larvae of *H. armigera* and *S. litura*	*Bt* tomato

ingredient(s) is part of the formulation designed to control the target pest. The function of inert ingredients is to enhance application and effectiveness of the active ingredient(s). A pesticide formulation is nothing but a combination of active and inactive ingredients. The organism used in the biopesticides formulation must revive from their dormant state to be active during application and post-application phase (Boyetchko et al. 1999). Biopesticides are divided into two categories based on formulations.

- Dry (dust powders, granules, seed dressers, wettable powders and wettable dispersible powder)
- Liquid (Emulsion, suspension, emulsifiable concentrate, ultra-low volume liquids)

11.12.1 Dry Powders

Dry formulation is used for direct application as dustable powders in which only 10 % of active ingredients are mixed with a finely ground mineral powder such as clay or talc. The inactive ingredients act as UV protectants and they increase the adsorption of biopesticides. The active ingredient in granule formulation ranges from the 2–20% which is coated or absorbed into granules made up of silica, starch, clay, groundnut plant residues, etc. These formulations are applied near to soil. When sufficient soil moisture is attained, it releases its active component. It can control insects, weeds and nematodes. In India, *Bt var. israelensis* Serotype H-14, Strain VCRC B-17 is available in the form of slow-release granules. Seed dressing/coating formulations are also available in powder form. They are mixed with seed before planting. Wettable powders (WP) are finely ground powders obtained by mixing active ingredients with dispersing agents, surfactants, melting agents, etc. and can be applied after mixing with water. Wettable powders have good storage, stability and miscibility with water. In India, *Bt* var. *kurstaki* and *Bt* var. *israelensis* (5 and 2.5% WP); *Trichoderma viride* 1% and 1.5% WP; *Pseudomonas fluorescens* 1.25% WP; Entomogenous fungi *Beauveria bassiana* are available in wettable powder formulations. Water dispersible granules (WDG) are dust-free formulations that can be suspended with water to enhance storage stability.

11.12.2 Liquid Formulations

Active ingredients of liquid formulations are mixed with water/aqueous suspension (AS) or with oil, kerosene or petroleum-based solvents as a carrier. *B. thuringiensis* var. *kurstaki* is available in 2.5 and 3.5% AS. NPV of *H. armigera* is used in 0.43% (AS), and NPV of *S. litura* in 0.50% (AS). Various types of liquid formulations are available in the market including emulsifiable concentrate. An emulsion is a mixture of homogenous emulsion with active ingredient particles suspended into it. In emulsion, active ingredient is in liquid form and is dissolved in the petroleum-based solvents. To improve the stability of the emulsion, it is necessary to choose an appropriate emulsifier. In suspension concentrate (SC), which is also known as a flowable concentrate, the active solid ingredient is dissolved in water. Agitation during formulation is being done for the even distribution. It is safer for the environment and user. *B. thuringiensis* var. *galleriae* 1.3%, *B. thuringiensis* var. *sphaericus B-101* and *Bacillus subtilis* are available in *2%* suspension concentrate. Entomopathogenic fungi-based SC formulation of *Beauveria bassiana* is available as 1.15%, 10% SC. Ultra-low volume formulation (ULV) contains 100% active ingredient. It is used for mosquito control and has agriculture and forestry application. Newer formulation, capsule suspension is developed in which active ingredients are encapsulated in starch/cellulose or other polymers that can be dissolved in water before use. This type of formulation is used to protect the bioagents from harsh unfavourable conditions. Liquid aerosol is also used against field pests where the active ingredients are kept in the form of liquid or the gaseous phase (in case of fumigants) in a pressurized container. Thus, by pushing nozzle, very fine-droplets of liquid or gas can be applied to the target surface (Tijjani et al. 2016).

11.12.3 Compatibility of Biopesticides

It is the ability to mix various pesticides without affecting physical and chemical nature that results in increased effectiveness and reduced phytotoxicity. Compatibility is an important aspect to be considered while using combination of biopesticides. One of the limitations with biological pesticides is that it has a very narrow host range and is effective at controlled environmental conditions. The sole use of biopesticides is not sufficient to control plant-feeding insect or mite populations. Thus, to increase the effectiveness of biopesticides, appropriate compatible conventional pesticides can be mixed to increase the synergism. Also “biorational” or "reduced risk" agents such as essential oil, diatomaceous earth, insect growth regulator and related compounds can be used to enhance the toxicity.

Microbial pesticide formulation based on *Bt* subspecies *kurstaki* and *Bt* subspecies *aizawai* were found to be effective against a wide range of lepidopteran pests. *Bt* subspecies *kurstaki* (0.2%) in combination with 5% neem oil or citronella oil is effective against *H. armigera*. Use of HaNPV 250 LE/ha in combination with endosulfan 0.035 % and Fenvalerate (0.005%) +NPV; monocrotophos (0.035%) + NPV; NPV + *B.t* and HNPV + NSKE (2.5%) were found to be effective against larvae of *H. armigera*, *S. litura and L. trifolii. B. bassiana* and *M. anisopliae* fungi-based pesticides in combination with deltamethrin or dimethoate 0.015% and acetamiprid 0.004% were effective on various field pests. Combination of *B. bassiana* and *M. anisopliae* + insecticides was successful in controlling yellow fever mosquito, *Aedes aegypti*, coleopterans and stored pests. Synergistic effect of fungal biopesticides and diatomaceous earth in the management of several crops and stored pests (Kavallieratos et al. 2006; Sabbour et al. 2014) and *B. bassiana* + imidacloprid and DE were effective against soil insects such as the southern mole cricket, *Scapteriscus borellii* (Sirvi et al. 2013).

11.13 Factors Influencing the Success of Biocontrol Agent

There are several factors both extrinsic and intrinsic factors that challenge the effectiveness of biopesticides on a large scale. Since they are from biological agents, they are affected by external factors such as sunlight and UV radiation. Ultraviolet light is extremely destructive and results in the photodecomposition of biopesticides. Temperature plays a significant role and extreme temperature results in reduced efficacy. Maintaining the optimal temperature in the field is difficult. However, for its survival and multiplication, the environmental conditions must be favourable to them. Most of the fungi-based formulations are temperature and humidity sensitive and conidia will not grow above or below 80% relative humidity. In case of NPV and other viruses, the suspension sprayed when adhere to the soil surface or leaf which is not consumed by the larvae does not have any effect on the pests. Hydrolysis in combination with photodecomposition is often involved in the breakdown of various pesticide active ingredients. The faster the hydrolysis, the less time the pesticide is available in the environment. Leaching also affects the biopesticides. If an acidic pesticide is applied to an alkaline surface or vice versa it may breakdown very rapidly. Thus, the soil pH and soil biota are important which influence the effectiveness of biopesticides. Rain during the application of biopesticides wash off from the plant and reduces its effectiveness. Some biopesticides are incompatible with chemical pesticides and thus reduce the activity of biopesticides. The compatibility of biopesticides with predators and parasitoids is also to be considered while releasing biocontrol agents. Antagonistic effects of phytochemicals on biopesticides are also to be considered.

11.14 Conclusion

There have been growing interests in sustainable and organic agriculture in developing countries because of the availability of natural inputs, human resources and agro-climatic conditions. Disadvantages of the use of chemical insecticides and demand for organics pushed biopesticides forefront in pest management. Microbes provide certain distinct advantages over other control agents and methods. The major advantage of exploiting microorganisms for pest control is their environmental safety primarily due to the host specificity of these pathogens. Microorganisms have natural capability of causing disease at epizootic levels due to their persistence in soil and efficient transmission. Many insect pathogens are compatible with other control methods including chemical insecticides and parasitoids. The cost of development and registration of microbial insecticides are much lesser than chemical insecticides. The self-perpetuating nature of most of the pathogens in both space and time are major advantages of biopesticides. There is a long-term regulation of a pest population in nature by beneficial organisms to keep pest populations below the threshold level. Though biopesticides possess several benefits, it is not well popularized due to lack of awareness among the farmers. It is necessary to convince farmers and government agencies to adopt biopesticides as a prime component of IPM.

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Renewable Energy for a Low-Carbon Future: Policy Perspectives

12

Shiv Prasad, V. Venkatramanan, and Anoop Singh

Abstract

To mitigate the consequences of global warming and climate change, concerted efforts are being undertaken, across the world to switch over from the fossil fuels to renewable energy sources. The potential of biological resources to meet the growing energy demand is significant. Low carbon and decarburization are viewed as an effective way to mitigate enhanced CO_2 emissions and an integral part of the energy transition. Currently, low carbon and decarburization is an international policy priority towards search in eco-friendly energy supply options with enhanced energy efficiency. In the low-carbon economy, bioenergy is essentially important for the benefits it renders to the bioeconomy, socio-economic benefits and it is in fact a valuable substitute to fossil fuels. Indeed, the bioenergy is essential component of "low-carbon energy mix". Further, technological developments in the bioenergy sector coupled with dynamic initiatives in energy policy provide a sustainable low-carbon pathway.

Keywords

Low-carbon future · Energy mix · Climate change · Renewable energy · Bioeconomy

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12.1 Introduction

The world's energy requirement is mostly satisfied through the use of fossil fuels. The use of *fossil fuels* (coal, oil, and natural gas) is a *problem* because the burning of these *fuels* in industry, transport, and the generation of electricity release *carbon dioxide (CO_2)*, an important greenhouse gas. Fossil fuel combustion releases about 21.3 billion tons of carbon dioxide per annum into the atmosphere. Nevertheless, only about half of the carbon dioxide emissions is absorbed by the natural sequestration processes leaving behind 10.65 billion tonnes of atmospheric carbon dioxide, which is indeed a cause of concern (USDoE 2007). CO_2 is one of the principal GHG responsible for the rise in global warming and thus an increase in average surface temperatures of the earth (Prasad et al. 2014). The unrestricted use of these fossil fuels is unsustainable due to the determinate supply and unequal distribution of reserves, coupled with anthropogenic global warming resulting from increasing greenhouse gas (GHG) emissions (Tan et al. 2013). Besides this, non-renewable energy resource use also lead to adverse effects, especially climate change, which makes it questionable for further usage (Prasad et al. 2014). Growing concerns with regard to climate change, finite energy resources, and dire need for low-carbon growth drive the transition from non-renewable fossil fuel-based energy to renewable bioenergy (Sadik et al. 2010; Prasad et al. 2019a, b).

Climate change and global warming associated with the anthropogenic activity are recognized as one of the most considerable threats to the long-term future of the human being (IPCC 2014; Prasad et al. 2014). The global average atmospheric carbon dioxide (CO_2) in 2018 was 407.4 ppm by volume, having risen from pre-industrial levels of 280 ppm (Lindsey 2018). In the 1960s, atmospheric CO_2 global growth rate was roughly 0.6 ± 0.1 ppm/year. Over the past few decades, the CO_2 growth rate has been closer to 2.3 ppm/year. As a greenhouse gas (GHG), CO_2 in the atmosphere traps the sun's heat, and as a consequence, global average temperatures continue to rise, otherwise known as global warming. According to the National Oceanic and Atmospheric Administration (NOAA), the average global temperature has been increased by about 1.4 °F (0.8 °C) over the past 100 years. One of the most significant immediate and visible impacts of global warming is the increase in temperatures, rapid melting of glaciers, permafrost, and sea ice around the world.

Since record-keeping began in 1895, the hottest year on record worldwide was 2016, according to NOAA and NASA data. The reduction of CO_2 emissions would be the most effective way to address climate change. However, figuring out an alternative to deal with climate change threat is an herculean task. An alternative to fossil fuel use demands a holistic approach which integrates "scientific, technical, economic, social, and political elements" (Royal Society 2009). In this context, renewable energy resources particularly the biomass energy and wind energy are considered as an important long-term solution. Also the technological developments across the world provide ample scope for tapping the renewable resources. In the present day, the focus is to maintain the reliability of energy supply, to make ardent effort to reduce the carbon emissions from energy sector, built environment, and construction sector, and to upscale the technological interventions so as to pursue low-carbon growth (RICS 2009).

In this regard, decarburization is also viewed as an effective way to mitigate enhanced CO_2 emissions. It has made decarburization an international policy priority (IPCC 2007). Economy and society have grown around carbon-based fuels over decades and centuries so that CO_2 emissions are embedded into set patterns of work, leisure, travel, and heating. That also means that there are multiple possible ways to decarbonize, such as changing lifestyles, improving energy efficiency, and finding various ways to produce energy. Assessing and comparing these multiple opportunities, and taking account of how they might change over time means dealing with many uncertainties, and no firm forecasts of the best routes for decarburization can be offered (Winskel et al. 2009).

The Member States of the UN Framework Convention on Climate Change (UNFCCC) concluded the Paris Agreement to mitigate climate change and to strengthen the actions desired for a sustainable transition towards a low-carbon future (Busu 2019). Low-carbon solutions refer to all measures and methods designed to reduce the use of fossil fuels such as oil, coal, and gas (which give off a lot of CO_2 when burned) by replacing them with renewables. Low-carbon solutions are an integral part of the energy transition. It is a way of thinking, behaving, and operating that minimizes carbon emissions while enabling sustainable use of resources, economic growth, and improvements in quality life. The transition to a low-carbon economy heralds an appealing but challenging economic and social transformation.

Indeed a low-carbon economy provide impetus for sustainable growth and also resilience against energy crisis. The whole world has a role to play in creating the transition to a low-carbon economy. Low-carbon technology development is essential. Its application can make a difference by changing the collective behaviour of businesses, individuals, communities, and the public sector. A practical policy framework must serve as the backbone for a low-carbon development path. The programme needs its own set of supporting laws, making it necessary to revise national legislation, including regulations, rules, and standards backed up by a series of policies and strong political support.

12.2 World Energy Transition

The world has undergone various energy transitions between different energy sources since the beginning of the Industrial Revolution. These so-called Kondratieff long-waves are depicted in terms of world primary energy shares in Fig. 12.1 (Hammond and Waldron 2008), alongside future pathways out to 2050, as suggested by the Shell "Dynamics as Usual" Scenario (Davis 2001). "Traditional" energy sources include animal manure, fuelwood, water wheels, and windmills. In the coming decades, there could be significant growth in energy demand resulting from population growth and economic development (Hammond and Waldron 2008; Allen and Hammond 2019). Dynamics, as usual, scenario emphasizes choices

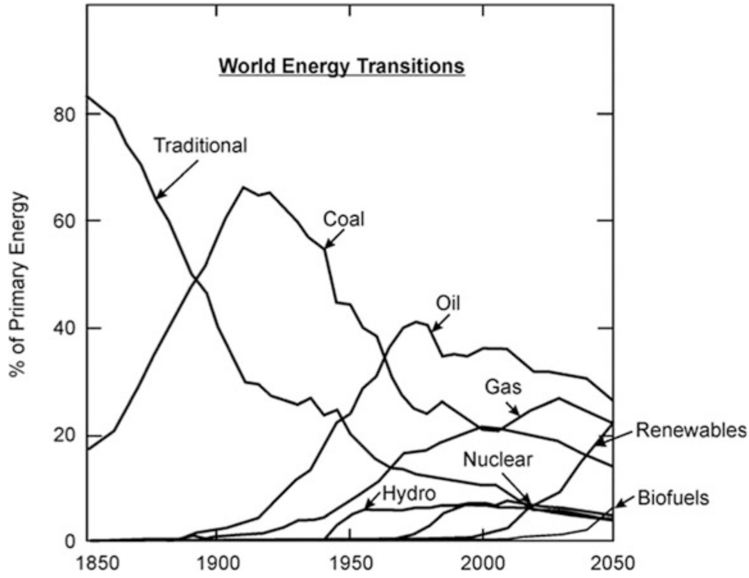

Fig. 12.1 World primary energy shares from 1850 to 2050. Future projections based on the Shell Dynamics as Usual Scenario. Source: Allen and Hammond (2019)

by peoples for clean, secure, sustainable energy. As natural fossil resources become increasingly scarce, these choices lead to reliance on renewable fuels (Allen and Hammond 2019).

12.3 Need for a Strategic Technological Approach Towards Low and Zero-Carbon Growth

Strategies to achieve a low-carbon energy mix vary in each country or region depending on the particular needs. However, three key areas where systemic changes must focus are: (a) reducing energy demand through efficiencies and lifestyle changes; (c) shifting to new technologies; and (c) promoting carbon capture and storage. According to Dodd (2008), energy planning at a town and city-scale needs another strategic approach, supported by robust planning policies and complementary facilitating mechanisms.

Energy strategies must be driven by a collective purpose to reduce CO_2 emissions and enhance the energy security of societies. They should be based on a clear and rational relationship between (1) the benefits of low-carbon energy production technologies; (2) Access to renewable resources in the local environment; (3) The forms and grades of energy required for various end-uses; (4) Parameters for cost-effective and efficient deployment; (5) The scale and type of development opportunities (Dodd 2008).

In fact, there are quite a number of technological interventions available for energy transitions towards a sustainable, low-carbon economy. Nevertheless, it must be categorically stated that no single technological interventions can provide pragmatic solution for all the sectors. So there is a need for energy mix, disruptive innovative technologies, and proactive policy. Clean power technologies are essential for developing a low-carbon development path. Below are examples of widely used clean power technology:

12.3.1 Small Hydropower

Small hydropower technology is very mature and used extensively, mainly in mountainous countries, such as Nepal, India, and China. In India, hydropower projects with a station capacity of up to 25 megawatts (MW) each fall under the category of small hydropower potential (SHP). India has an estimated SHP potential of about 15,000 MW. As of November 2017, small hydro projects totalling 4399.35 MW have been installed in the country. By 2009, small hydropower generation was deployed widely in China with a capacity of 33 GW, while in Japan, the size reached 4 GW. The capacity deployed among the three countries accounted for close to 70% of the world total in 2009. In addition to the environmental benefit, hydropower could be used to provide electricity to rural and remote areas. This results in a higher national electrification rate, an increase in local agricultural production, and more income.

12.3.2 Wind Power

Wind power has been utilized in various forms for thousands of years. Wind power is the use of wind to provide mechanical energy through wind turbines to turn electric generators and traditionally to do other work, like milling or pumping. A modern wind turbine uses an aerodynamic lift to power a rotor attached to an electrical generator. Wind power enabling technologies has long-term prospects, which facilitate a gradual transition to renewables-based power systems. As of the end of 2018, the global total cumulative installed electricity production capacity from wind power amounted to 591 GW (WWEA 2019).

Several nations have realized relatively high levels of wind power electricity penetration, such as Denmark 39%, Portugal 18%, Spain 16%, Ireland 14%, and Germany 9% in 2010. With regard to India, the wind energy production capacity greatly increased during the last decade. The total wind energy installed capacity is about 36.6 GW. The dominant *wind* energy-producing states in India are Tamil Nadu, Gujarat, Karnataka, Maharashtra, and Rajasthan.

12.3.3 Ocean Energy

The ocean energy production comprises diverse technologies, namely tidal, wave, ocean thermal energy conversion (OTEC), and salinity gradient, designed to harness power contained in our seas and oceans and convert it to renewable low-carbon electricity (Mofor et al. 2014). *It is* expected to become commercially viable with considerable promise over the medium and longer terms. It represents a significant opportunity to address the growing need for power and the problems associated with fossil fuel burning. However, there is continuous challenge in consenting for wave or tidal devices due to concerns over environmental effects. This needs to be making a stride in a better understanding of potential impacts on marine animals, and reduce certain risks in the near future (OES, Annual Report 2017).

The assessments of the *global* potential of tidal *energy* production vary, but it is widely agreed that tidal stream *energy capacity* could exceed 120 GW globally. Worldwide installed ocean power has more than doubled from less than 12 MW in 2016 to over 25 MW in 2017 (OES, Annual Report 2017). *Ocean energy* has been included in renewable *energy* to give a further boost to *ocean energy in India*. According to the estimates of the Indian government, the country has a potential of 8000 MW of tidal power. This includes about 7000 MW in the Gulf of Cambay in Gujarat, 1200 MW in the Gulf of Kutch, and 100 MW in the Gangetic delta in the Sunderbans region of West Bengal.

12.3.4 Solar Photovoltaic (PV) Technology

Sun is the prime source of energy driving all the processes in the biosphere. Solar photovoltaic (PV) technology enables direct conversion of sunlight into electricity. It widely provides a significant part of the world's future energy supply. According to the IRENA latest statistics report, total solar PV power-generating capacity reached 480.3 GW by the end of 2018. In the IRENA annual report, it is stated that new global capacity additions hit 94.2 GW, up slightly from 93.7 GW a year earlier and considerably more than the 71.4 GW deployed in 2016 (IRENA 2019).

Asia has the largest share in cumulative installations, at around 274.6 GW. Most of that capacity is installed in China (175.0 GW), Japan (55.5 GW), India (26.8 GW), South Korea (7.8 GW), Thailand (2.7 GW), and Taiwan (2.6 GW) (IRENA 2019). In the past few years, India has become a leading player in the world's PV technology. India's total capacity is anticipated to grow 116 GW by 2023, which means the country will be installing almost 90 GW from 2019 to 2023, or nearly 18 GW annually, on average. Europe was the second-largest region with a combined capacity of 119.3 GW. The biggest markets by total installations are Germany (45.9 GW), Italy (20.12 GW), the UK (13.4 GW), France (9.4 GW), Turkey (5 GW), Spain (4.7 GW), the Netherlands (4.1 GW), and Belgium (4.0 GW) (IRENA 2019).

12.3.5 Bioenergy

Sustainable bioenergy is a versatile source of low-carbon energy, which plays a crucial role in meeting carbon budgets. Bioenergy that comes from the conversion of biological resources is a highly flexible option for decarbonizing the economy, spanning a wide range of fuel feedstocks, conversion technologies, and end-use applications. There are several large-scale commercial deployments already in progress, including bioethanol production and the use of biomass in co-firing and dedicated combustion. A mixed portfolio of bioenergy supply must be maintained at this time, ensuring the development of competitive and secure bioenergy and a firm research base for future large-scale deployments (Winskel et al. 2009).

Bioenergy is often considered carbon neutral, as the carbon dioxide released in combustion is assumed to be compensated by the CO_2 absorbed during the growth of trees or other plants. Global sustainable bioenergy potential has been estimated to be between 200 and 500 EJ/year in 2050. Currently, agricultural crop residues and municipal wastes are the primary feedstocks for the electricity generation and heat energy production. Further, "a small share of sugar, grain, and vegetable oil crops" are used as feedstocks for the production of liquid biofuels (Prasad et al. 2012). Ethanol production from biomass such as sugar-containing materials like sugarcane or sweet sorghum syrup/juice is the most straightforward route for producing biofuels (Prasad et al. 2006, 2009, 2013).

The biochemical conversion of biomass into ethanol happens in three steps: pretreatment, enzymatic hydrolysis, and fermentation (Prasad et al. 2019a, b). Pretreatment weakens the plant wall, then acid or enzymatic hydrolysis separates the cellulose into sugars, and lastly, fermentation converts the sugars into ethanol (Prasad et al. 2007, 2018). Globally, about 50 EJ of energy per annum is contributed by biomass resources and it accounts for about 10% of annual global primary energy consumption. The traditional biomass is mainly used for heating and cooking purposes (Fig. 12.2). In 2017, electricity generation from biomass-based sources was the third largest renewable electricity source after hydropower and wind.

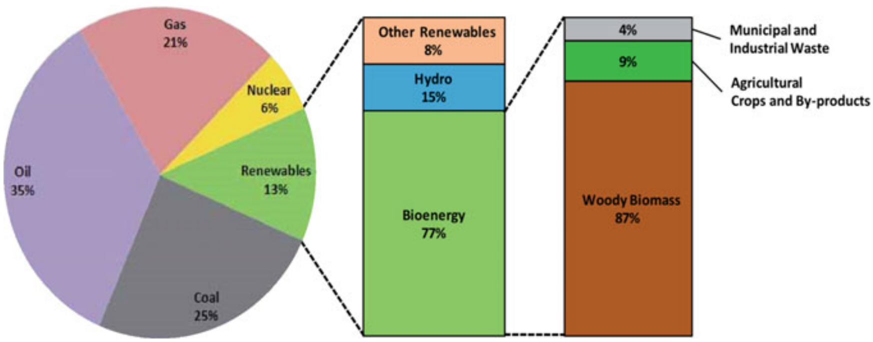

Fig. 12.2 Share of bioenergy in the world's primary energy mix. Source: (Winskel et al. 2009). Note: EJ = 10^{18} Joules (J) = 10^{15} kilojoules (kJ) = 24 million tonnes of oil equivalent (Mtoe)

Biomass-based fuels, especially ethanol and biodiesel, are one of the best options for replacing fossil oil in the transport sector. However, the share of biofuels in the transport sector in 2017 was only 3%, with a total contribution of 3.5 EJ. World Bioenergy Association (WBA) estimation data shows that the utilization of all major crop residues can generate approximately 4.3 billion tonnes of energy (low estimate) to 9.4 billion tonnes of energy (high estimate) annually around the world (WBA 2019). Globally, 11 million individuals were working in the renewable energy industry by the end of 2018. Bioenergy was the second largest employer globally with approximately 3.2 million individuals employed in the bioenergy supply chain.

12.3.6 Nuclear Power

Nuclear power seeks to harness the power of the atom, either by splitting heavy elements apart in fission reactions or by merging light elements in fusion reactions. Nuclear technology is a primary base-load power-generating source and accounted for 10.5% of global power generation in 2017. The countries like the USA, France, Japan, China, Russia, South Korea, Canada, and Ukraine are known to possess significant amount of nuclear power capacity. In fact, these countries account for about 84% of the world's total installed nuclear power capacity. Nevertheless, the USA and France are leading in the nuclear power market in terms of nuclear power generation. However, the world nuclear electrical generating capacity is projected to increase to 554 GW(e) by 2030 and to 874 GW(e) by 2050 in the high case. This represents a 42% increase over current levels by 2030 and a doubling of capacity by 2050 (IAEA 2018).

12.3.7 Carbon Capture and Storage (CCS)

Many forecasts predict a continued significant role for fossil fuels in meeting global energy demand to 2020 or even 2050 and beyond. In this context, CCS is potentially a key technology for mitigating emissions of CO_2 from these fuel sources. CCS has only recently emerged as a low-carbon supply-side perspective technology. CCS involves abating the emissions from power plants and other industries by chemically capturing or separating the CO_2, transporting it to a storage site, and injecting it for long-term storage in sealed geological formations. Depending on capture technology, CO_2 is captured from flue gases, from the fuel before combustion, or directly from the combustion process. *CCS* technology can *capture* up to 90% of CO_2 emissions from the fossil fuels used in electricity production and industrial operations, preventing the *carbon dioxide* from entering the atmosphere. The global CCS market size was 61,150-kt in 2015. The national governments of various countries, primarily in North America and the European Union, are promoting their drive to mitigate climate change with a keen focus on the power sector source of around 40% of CO_2 emissions.

It is interesting to note that the CCS technology with biomass is construed as one of the important carbon abatements technologies, aiming to remove carbon dioxide from the atmosphere. Functionally, the CCS technology involves three steps viz. "capturing of CO_2, transporting the CO_2, and subsequently storing the CO_2 underground safely and securely in the depleted oil and gas fields and deep saline aquifer formations". As regards the separation of CO_2 from gases that are produced from industrial production establishments and electricity production plants, the carbon capture technology endeavours to capture CO_2 by pre-combustion capture, post-combustion capture, and oxyfuel combustion. The CO_2 so captured is transported by road, tankers, ships, and pipelines to safe storage sites (CCSA 2019). The CO_2 is stored deep inside the earth in selected "geological rock formation" or "depleted oil and gas fields". CO_2 is also used to enhance the oil recovery in the oil and gas fields. Nevertheless, the commercial adoption of CCS technology involves well qualified CCS techniques, monitoring techniques, safety regulations, and Government regulations as well (CCSA 2019).

12.3.8 Hydrogen and Fuel Cells

Hydrogen energy is one of the cleanest energy sources produced in many countries around the world as a substitute for fossils fuels. Currently, the primary process of producing hydrogen (H_2) is by cracking natural gas, steam reforming of naphtha, which is dependent on fossil fuels. H_2 can also be produced from biomass, which is similar to H_2 production from fossil fuels. Gasification of biomass is performed to produce gas, consisting of H_2, CO, and CH_4. From the produced gas, CH_4 is converted into H_2 and CO by being reformed with steam. Also, the efficiency of H_2 is increased by the conversion of CO into H_2 by the water-gas shift reaction. The gas byproduct of the process is CO_2, but the CO_2 released from the biomass is neutral, that is, it does not increase the CO_2 concentration in the atmosphere (Kayfeci et al. 2019). Besides, the $H_2 + CO_2$ gas mixture can also be used to generate electricity in fuel cells.

Fuel cells (FC) are electrochemical devices that generate electricity and heat using hydrogen and hydrogen-rich fuels, together with oxygen from the air. Today, fuel cells are considered to be an essential option for improving the sustainability of energy use, reducing greenhouse gas emissions, and reducing other emissions related to transportation energy use. Fuel cells can be used for large and small-scale electricity generation, combined heat and power (CHP), transport of all types, and as a battery replacement for portable power applications such as laptop computers and mobile phones. Fuel cell vehicles (FCVs) have the potential to reduce greenhouse gases emissions significantly. Further, FCVs have been encouraged in Europe, America, and Asia. For instance, in the state of California, it was reported that transportation sector alone contributes about 40% of GHG emissions. Further, switching over to hydrogen-fuel vehicles from gasoline powered vehicles reduce GHG emissions to the extent of 30–60%. Additionally, toxic air pollutants are not released from hydrogen-fuel vehicles (CEC 2019). The production volume of these fuel cell vehicles inevitably grows, and it seems that it will occupy a part of mainstream automobiles in the future.

12.4 Intended Nationally Determined Contributions and Low and Zero-Carbon Initiative

The Intended Nationally Determined Contributions (INDCs) are the climate actions that the countries propose to undertake to limit the GHG emissions. So the INDCs communicated to the UN body provide a picture of intentions that the countries contemplate to achieve the goals of Paris Agreement. The countries determine their contributions on the basis of their national policy and priorities, their responsibilities and capabilities, and their socio-economic and other prevailing circumstances. Further, INDCs pair national policy setting with a global UNFCCC framework which drives collective and concerted action towards a climate resilient society and climate resilient future with net zero carbon emissions. INDCs create constructive feedback between nations and decision making on climate change. INDCs reflect each country's ambition for decreasing GHG emissions, taking into account its domestic circumstances and capabilities. Some governments also address how they will adapt mitigation strategies to climate change consequences, and what help they require from, or will contribute to other nations to adopt low-carbon plans and to build climate resilience nations.

Policy targets are also being established for the expansion of renewable energy. More recently, growing concerns about climate change and energy security have prompted increased spending on energy research and development and total global investment in sustainable energy technologies rose by over 50% in 2007 (UNEP 2008). The UK Government placed "Energy White Paper" for action on climate change in their focused energy policy. That shows the government's international commitment to the reduction of CO_2 emissions. The UK's energy policies plead long-term strategic goals: placing the UK on a path to cut CO_2 emissions by 60% by 2050, with substantial advancement by 2020. In their core policy, they are maintaining reliable energy supplies, promoting competitive markets in UK and increase the rate of sustainable economic growth and to improve products and to assure that every house is adequately and affordably heated (Dodd 2008).

European Commission's environmental policy report confirms Europe's commitment to achieving net-zero GHG emissions by 2050. In 2018, the EU adopted legislation striving to reduce its GHG emissions by 40% by 2030, as compared to the 1990 level. It is estimated that when the EU legislation is completely implemented, it can reduce EU emissions to reach about 45% by 2030 (Busu 2019). Like many other countries, Germany has defined goals to reduce its CO_2-emissions following the Paris Agreement on climate change. Aside from the European targets, Germany has set itself targets for 2030 and 2050, based on the reference year of 1990. These targets are also subject to the Paris Agreement ratified by Germany. The main goal is to provide a reduction of GHG emissions of at least 55% until 2030 and 80–95% in 2050 compared to the 1990-levels. Additionally, renewable energy sources are prescribed to account for at least 60% of the energy consumption in 2050, while efficiency rates should increase by 50% (BMUB 2016).

China has submitted INDC to the UNFCCC, affirming its intention to peak its CO_2 emissions around 2030 and lower CO_2 per unit of GDP by 60–65% based on the reference year of 2005 levels by 2030. The China INDC also included the goal of raising the share of non-fossil fuels in primary energy consumption to 20% by 2030. China also adopted environment-friendly industrial production, to build a low-carbon society, and effective carbon emissions control to combat against climate change. China is also developing a carbon emissions trading market (Wu 2017).

Japan submitted its INDC, which includes an emissions reduction target of 26% below 2013 emission levels by 2030, equivalent to 18% below 1990 levels by 2030. Japan's INDC is based on a problematic accounting method that excludes land use, land-use change, and forestry (LULUCF) from the base year emissions, but includes it in the target year emissions. This type of asymmetric emissions accounting needs to be scrutinized under the Paris Agreement. When accounting for LULUCF credits in the base year, this target is reduced to 23% below 2013 (15% below 1990) levels of greenhouse gases (GHGs). The Japanese Government also proposes using the Joint Crediting Mechanism (JCM), which could potentially further reduce the level of domestic reductions, depending on how Japan intends to account for the cumulative credits in the post-2020 period (Government of Japan 2015).

12.4.1 India's Intended Nationally Determined Contribution (INDC)

The INDC begins with India's existing environmental policy. Rooted in India's constitution (Article 48-A), the policy states that all States (of India) shall endeavour to protect and improve the environment and to safeguard the forests and wildlife in the country. More specifically, India's overarching framework on the environment and climate change is enshrined in the National Environmental Policy of 2006, which promotes sustainable development along with ecological constraints and the imperatives of social justice (MoEF 2006).

India started National Action Plan on Climate Change (NAPCC) in 2007, which reiterates the centrality of sustainable development as a policy goal but argues that there are benefits of addressing climate change concerns while promoting economic growth. The NAPCC is supported through eight "National Missions" that highlight priorities for mitigation and adaptation to fight climate change (NAPCC 2008). These broad policies are supplemented by the policies of state governments, NGOs, other stakeholders, and the private sector.

The INDC highlights that 32 states and union territories have inaugurated State Action Plans on Climate Change that attempt to make sure that climate change issues are integrated into the planning process. The INDC notes that these policies are supplemented by other legislation and guidelines such as the Energy Conservation Act, the National Policy for Farmers, the National Electricity Policy, and the Integrated Energy Policy.

12.4.2 Highlights of India's INDC

Fuel Mix

- Share of non-fossil resources in installed power capacity to 40% by 2030.
- Increase the percentage of renewables, i.e., wind, solar, and bioenergy installed capacity cumulatively from current 30 GW to 175 GW by 2022.
- Raise nuclear energy capacity from its current 5.8 GW to 63 GW by 2032.
- Upgrade the efficiency of 144 thermal coal plants.
- All the new coal plants should employ supercritical technology.

Infrastructure

- Under the National Smart Grid Mission, an investment of $6 billion is proposed in Green Energy Corridor projects to evacuate power generated by renewable energy sources.
- Enhance the share of railways in total land transportation from 36% to 45%.
- Creating two Dedicated Freight Corridor (DFCs) over a period of 30 years will reduce CO_2 emissions by 57 million tons.
- Under Smart Cities Mission and Atal Mission for Rejuvenation and Urban Transformation projects, infrastructural improvements are targeted in 600 cities.

Energy efficiency

- The National Mission for Enhanced Energy Efficiency (NMEEE) as part of National Action Plan on Climate Change (NAPCC) endeavours to strengthen the market for upscaling energy efficiency through policy and business models. The mission aims to obviate the need for 20 GW of capacity additions, which corresponds to 23 million tons of fuel savings per annum and 98 million tons of GHG emission reduction.

Finance

- Implement a carbon tax on the coal of $3.20 per ton to contribute to the National Clean Environment Fund.
- National Adaptation Fund for climate change was established to cater to the needs of States and Union Territories in the domain of climate change adaptation.
- Subsidies given by the government are to be disbursed through direct cash transfers.

12.4.3 India's Clean Energy Targets

To achieve the aims of Paris Agreement on Climate Change, India by itself proposed to create a "cumulative carbon sink" of 2.5–3.0 billion tons of CO_{2e} by the year

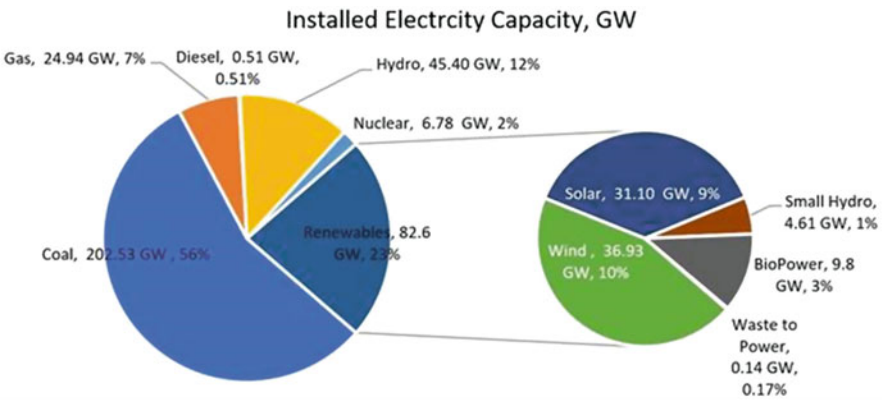

Fig. 12.3 All India Installed electrical capacity for coal, natural gas, diesel, hydro, and nuclear. Source: CEA (2019), Central Electricity Authority, Ministry of New and Renewable Energy

2030. It is perhaps an ambitious target. The national policy on climate change is also tuned towards the use of clean energy sources. In the INDC, India has committed to generate 40% of its total electricity consumption from non-fossil fuel sources by 2030. However, Central Electricity Authority's strategy blueprint reveals a much more ambitious goal of India. By the year 2027, the country aims to achieve about 60% of the total electricity generation from renewable sources. Towards this end, by the year 2027, India aims to establish "275 GW from renewable energy, 72 GW of hydroelectricity, 15 GW of nuclear power, and nearly 100 GW from other zero emission sources" (Safi 2016). According to CEA (2019), all India installed electric capacity for coal, natural gas, diesel, hydro, and nuclear is presented in Fig. 12.3.

12.4.4 Biofuel Policy in India

Biofuel policy in India was formulated with the basic purpose of reducing oil imports from foreign countries and to promote biofuel production and achieve energy security. The Government of India through various interventions and programmes focused on research and development, sustainable bioeconomy, and "waste-to-energy" strategies. The policy also focused on augmenting biofuel production, production of value-added products from wastes like agricultural wastes, industrial waste, and also setting up of industrial units for biofuel production. Way back in 2003, the National Biofuel Mission was started with the objectives like increasing biofuel production, adoption of innovative technologies to increase biofuel production, and reducing the dependency on the imported fossil fuels. The "Ethanol Blended Petrol programme" was also highlight of Government of India policy on biofuels (Prasad et al. 2020). Consequently, the National Biofuel Policy of 2009 set a target of "20% blending of both ethanol and biodiesel by 2017" (Prasad et al. 2020). Further, the policy advocated for second generation biofuels. In other words, biofuel production from non-food crops and materials like lignocellulosic waste material, molasses, non-edible oils, etc. (Aradhey 2010). The policy provided broad guidelines on financial support and incentives to promote biofuel production in India (Aradhey 2018). The National Biodiesel Policy emphasizes the need for energy security, energy access and efficiency, and the pivotal role played by the energy sector in the socio-economic development of India (Aradhey 2018). The recent National Policy on Biofuels 2018 focusses in addition to the objectives set in the previous biofuel policy, on raw materials for biofuel production, farmers' welfare, and pathway to upscale biofuel production. In effect, the National Policy on Biofuels 2018 aims to reduce dependency on imported fossil fuels, to switch over to clean renewable energy, and to mitigate climate change through reduction of GHG emissions. The policy targets to generate 10 GW of power from biofuels by 2022. As regards the transport fuel blending, the policy aims to achieve by 2030, 20% ethanol blending (with gasoline) and 5% biodiesel blending (with diesel). The benefits from the implementation of Biofuel policy include reduction in import dependency, clean atmospheric environment and health benefits, municipal waste management, agricultural crop residue management, increase in farmers' income and employment opportunities. The salient features of the National Policy on Biofuels (Prasad et al. 2020):

- "The policy increases the scope of raw material for ethanol production by allowing the use of sugarcane juice; sugar-containing feedstocks like sugar beet and sweet sorghum; starch-containing feedstocks like corn and cassava; damaged food grains like wheat, rice and rotten potatoes unfit for human consumption for ethanol production.
- The new biofuel policy allows the use of surplus food grains for ethanol production for blending with petrol/gasoline with the approval of the National Biofuel Coordination Committee.
- With a thrust on advanced biofuels, the policy indicates a viability gap funding scheme for 2G ethanol biorefineries of Rs. 5000 crores in 6 years in addition to additional tax incentives, a higher purchase price as compared to 1G biofuels.
- The policy supports setting up of supply chain mechanisms for biodiesel making from non-edible oilseeds, waste cooking oil and short gestation crops".

12.5 Potential GHG Emissions Reductions by Renewable Resources

Renewable energy sources are primary energy resources that are inexhaustible, clean, and low-risk category (Amponsah et al. 2014). "Renewable energy (RE) has the potential to play an important and increasing role in achieving ambitious climate mitigation targets" (IPCC 2012). Not like the fossil fuel combustion which releases greenhouse gases (carbon dioxide), the renewable energy resources like solar, hydroelectric energy, and wind release no greenhouse gases. However, biomass energy on combustion produces carbon dioxide emissions. But they are considered

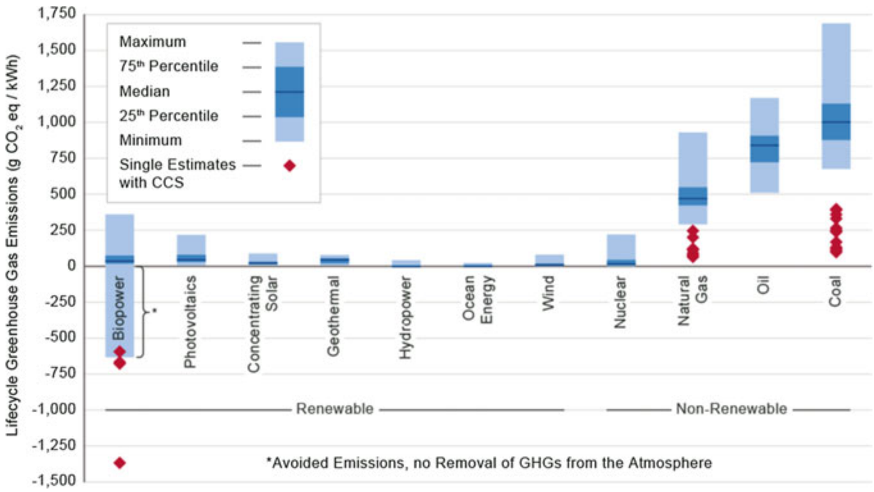

Fig. 12.4 A comparison of the life cycle GHG emissions from diverse electricity- generation technologies. Source: IPCC (2012)

as "carbon neutral", because the CO_2 released are not construed to increase atmospheric CO_2 concentration due to the fact that in the recent past, the plants have removed atmospheric CO_2 through the photosynthesis process. Renewable energy resources such as biopower, solar and photovoltaics, *wind*, and *hydropower* offer potential GHG (gCO_2eq/kWh) emissions reductions compared to fossil fuels such as coal or petroleum (IPCC 2012). A comparison of the life cycle analysis of GHG emissions from diverse energy-generation technologies, both renewable and non-renewable, is shown in the Fig. 12.4.

12.6 Conclusion

Climate change concerns and reduction of carbon emissions through low-carbon growth are driving forces in renewable energy production. Renewable energy provides a diverse source of energy, potentially improving energy security through the substitution of oil and natural gas. The use of domestic bioenergy resources would generally contribute to the diversification of the energy mix. Ambitious targets for economy-wide decarburization and low-carbon technology deployment are being established worldwide. Already, the recent resurgence in energy-related innovation activity globally has encouraged the emergence of a large number of prospective low-carbon energy supply technologies, supported by policy initiatives, investment programmes, developer firms, and research institutions.

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TNAU Energy Soft 2016: An Efficient Energy Audit Tool to Identify Energy Saving Technologies for Sustainable Agriculture

13

Ga. Dheebakaran, D. Jegadeeswari, SP. Ramanathan, and S. Kokilavani

Abstract

The face of the earth surface has been changed by the human activities particularly land use changes. World agriculture occupies about 38% of Earth's terrestrial surface. The modern day agricultural economy has become more energy-intensive. Sustainability in agriculture should ensure both agricultural productivity and environmental safety. Agriculture being one of the important consumer of energy, particularly fossil fuels, generates greenhouse gas emissions. It is very important to curtail the use of high energy and non-renewable energy sources in farming activity. Further, reducing the use of non-renewable energy sources and increasing the efficiency of energy use, would reduce the greenhouse gas emissions from the agriculture sector. Energy auditing is a method to understand which component of the technology involves high energy and inefficient in generating outputs. TNAU Energy Soft 2016 is an energy audit tool, which helps the scientists working on agricultural technologies to identify the better input energy source combination (renewable/non-renewable/commercial/non-commercial) of technology without doing repeated and expensive field trials. This is a simple, user-friendly windows based desktop application which facilitates easy selection of input sources; adds new energy source, crop and field operations; compares six treatments at a stretch. The resulting output includes detailed analysis and abstract of energy use of a single treatment, individual field operation-wise energy use within a treatment, net energy benefit, energy efficiency and category-wise energy use. The TNAU Energy Soft 2016 helps scientist to ensure sustainability in agricultural productivity, environmental safety and sustainable bioeconomy through finding the ways and means of reducing non-renewable fossil fuel based inputs and increasing the use of renewable and biological resources.

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Keywords

Energy audit · Sustainable agriculture · TNAU Energy Soft 2016 · Sustainable agricultural bioeconomy · Climate change · Mitigation

13.1 Introduction

The face of the earth surface has been changed by the human activities particularly land use changes (Foley et al. 2005). World agriculture occupies about 38% of Earth's terrestrial surface (Foley et al. 2005; Ramankutty et al. 2008). Indeed, the global agricultural landscape is one of the largest terrestrial biomes on our planet (Venkatramanan and Shah 2019). However, the increase in agricultural area and technological interventions aided in increasing the global food grain production. The developments in Indian agriculture are no exception. Indian economy is mainly agrarian in nature. The modern agriculture in India and elsewhere is based on "(1) the varietal improvements in targeted crops, achieved through either conventional plant breeding or through genetic engineering and (2) increased utilization of purchased inputs, such as inorganic fertilizers, agrochemical crop protection and usually petroleum-derived energy to support larger-scale production with extensive mechanization" (Uphoff 2015; Venkatramanan and Shah 2019). The bottom line is that the agricultural activity has become more energy-intensive and it is a source of greenhouse gas (GHG) emissions. Agriculture is both a contributor and a victim of climate change. However, the industrial revolution, population growth and unsustainable consumption pattern are the globally accepted reasons for the increased GHG emissions. Increasing GHG emissions is a cause of concern. Anthropogenic actions are responsible for the total GHG emissions of about 49 gigatonnes of CO_2-equivalent per year ($GtCO_2$-eq/year) (Fig. 13.1) (IPCC 2014). CO_2, CH_4 and N_2O together account for 80% of the total radiative forcing and their concentration is reportedly increasing since the industrial revolution (Venkatramanan and Shah 2019). Human activities like "combustion of fossil fuel", "land use changes" and "agricultural activities" are responsible for the increasing concentration of these three important GHGs. It is reported that "CO_2 increased by 40% from 278 ppm about 1750 to 390.5 ppm in 2011. During the same time interval, CH_4 increased by 150% from 722 ppb to 1803 ppb, and N_2O by 20% from 271 ppb to 324.2 ppb in 2011" (Ciais et al. 2013). While the causes for increase in methane were "natural wetlands emissions, agriculture, waste management, biomass and biofuel burning" (Venkatramanan and Shah 2019), the nitrous oxide emissions increased due to "nitrification and de-nitrification reactions occurring in soils and in the ocean" (Ciais et al. 2013). Indiscriminate use of agricultural chemicals and fertilizers is also equally contributing to climate change through GHG emissions. In effect, the agriculture, forestry and other land use (AFOLU) sectors contribute about 10–12 Gt of CO_2-equivalent per year. As regard the AFOLU sector, the driving factors for GHG emissions are land use changes, enteric fermentation, rice cultivation, crop

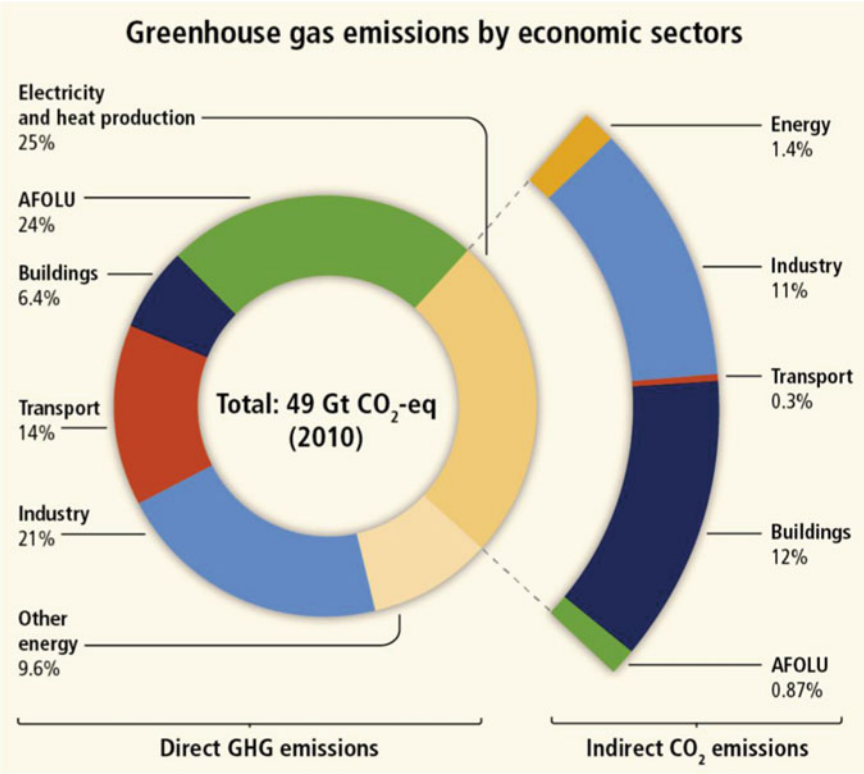

Fig. 13.1 Total anthropogenic greenhouse gas (GHG) emissions (gigatonne of CO_2 equivalent per year, GtCO_2-eq/year) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in % of total anthropogenic GHG emissions) from five economic sectors in 2010. The emission data on agriculture, forestry and other land use (AFOLU) include land-based CO_2 emissions from forest fires, peat fires and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU). Source: IPCC (2014)

residue burning, biofuel burning and application of nitrogenous fertilizers (Lipper et al. 2014; Smith et al. 2014; Venkatramanan and Shah 2019). The NOAA and American Meteorological Society's report on "State of Climate in 2018" stated that the global atmospheric CO_2 was 407.4 ± 0.1 ppm in 2018, a new record high. It is estimated that the increase was 2.2 ± 0.1 ppm (2016), 2.5 ± 0.1 ppm (2017) and 2.4 ± 0.1 ppm (2018), whereas the global growth rate of atmospheric carbon dioxide was roughly 0.6 ± 0.1 ppm per year during 1960 (Blunden and Arndt 2019).

13.2 Influence of Energy Demand on Climate Change Factors

Among the top ten Global GHG emitters, India now stands fourth, trailing behind China, the USA and European Union. Among the different economic activities, the agriculture, forestry and other land use sectors contribute one-fourth of the total GHG emissions. India's GHG emissions in 2014 were 2607.48 million metric tons without land use, land-use change and forestry (LULUCF). The net national GHG emissions including the LULUCF sector were 2306.29 million metric tons of CO2e, as the LULUCF sector is a net sink. The LULUCF sectors were able to remove about 12% of India's GHG emissions. India's GHG emissions source includes sectors like energy, "Industrial Processes and Product Use", agriculture and waste sector. 73% of the total GHG emissions for the year 2014 were contributed by the energy sector. While the "Industrial Processes and Product Use" (IPPU) is responsible for 8% of the total GHG emissions, the agriculture sector accounted for 16% of the GHG emissions in 2014. It must be noted here that the two important GHGs methane and nitrous oxide are released mainly from the agriculture activity. The contribution of the waste sector to the national GHG emissions is to an extent of 3% for the year 2014. Within the waste sector, emissions are mainly from the handling of wastewater and solid waste disposal. In terms of the gas-wise distribution of India's GHG emissions for the year 2014, carbon dioxide accounts for 76.6%, methane for 16.1% and nitrous oxide for 5.7% (MoEFCC 2018).

India is the second largest energy consumer of Asia, since 2008 and 3rd at the Global level, trailing the USA and China. India's energy consumption during 2010–2011 and 2017–2018 by different sectors in India is charted in Figs. 13.2 and 13.3 (Energy Statistics 2019). Among the six different sectors, higher energy was consumed by the industrial sector (42%) followed by domestic (24%) and agriculture sector (18%). There is no much difference in the energy consumption trends by different sectors during the recent years. According to the Indian Energy Statistics report for 2019, currently India is meeting its energy demand shortage from imported fossil fuels (Energy Statistics 2019).

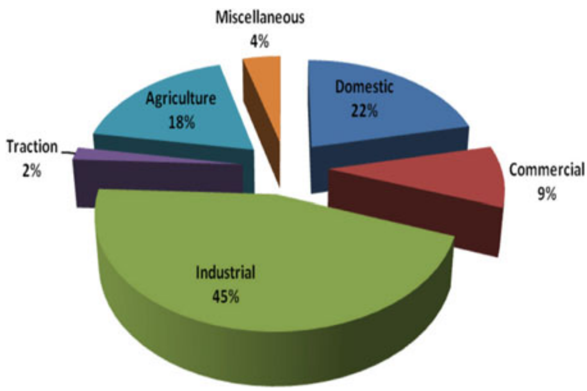

Fig. 13.2 Energy consumption by different sectors in India during 2010–2011. Source: Energy Statistics (2012)

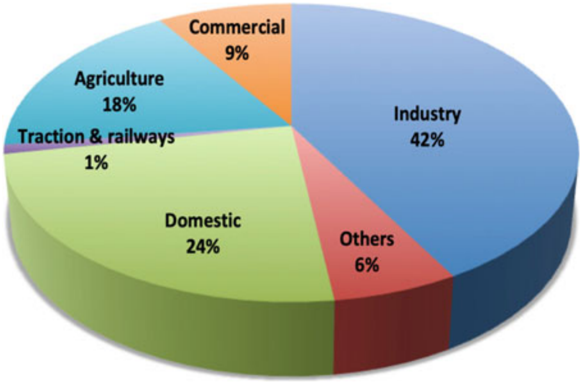

Fig. 13.3 Energy consumption by different sectors during 2017–2018. Source: Energy Statistics (2018)

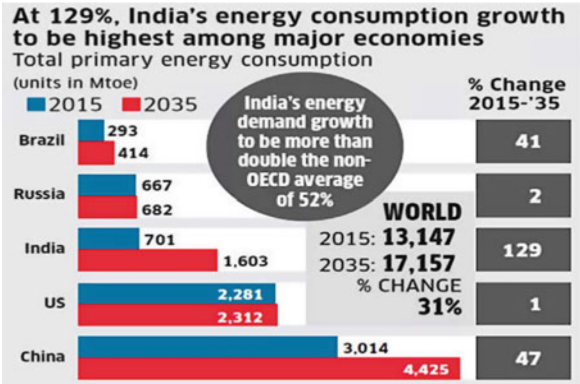

Fig. 13.4 Total primary energy consumption growth in India and other countries between 2015 and 2035. Source: Economic Times Bureau (2017)

According to the Economic Times Bureau (2017), the energy consumption growth in India between 2015 and 2035 would be around 129%, which is highest among all the other developing countries. Likewise, our share of global energy consumption would grow at 9%, in which, coal will remain the dominant fuel produced in India with a 65% share of total production in 2035. Renewables overtake oil as the second largest by increasing from 4 to 14% in 2035 as oil drops from 10 to 3%. India's gas demand will reach to 162%, followed by that of oil (121%) and coal (105%) (Figs. 13.4 and 13.5). The renewable energy rise by 712%, nuclear energy by 317% and hydropower by 97% showed some positive sign towards the reduced GHG by 2035. Gupta (2018) had warned based on the International Energy Agency's latest World Energy Overview that the energy demand is growing fastest in India and it would be more than double (1880 million tonnes of oil equivalent) by the year 2040 than the current year 2017 (898 Mtoe) if there is no policy to improve the energy efficiencies. If the government policies comply with sustainable development goals, India's renewable energy consumption could grow almost five times from 57 Mtoe in 2017 to touch 277 Mtoe by 2040, surely reduce the demand and ensures environmental safety by reducing the GHG emissions.

Fig. 13.5 Global level shift projected in types of energy consumption between 2015 and 2035. Source: Economic Times Bureau (2017)

Change in consumption in the next 20 years
Change (%), 2015-2035

	Brazil	Russia	India	US	China	World
Oil*	15	15	121	-17	61	15
Gas*	43	-2	162	25	186	38
Coal	-16	-22	105	-50	-2	5
Nuclear	149	17	317	-2	644	59
Hydro	37	14	97	15	38	42
Renewables^	157	>1000	712	182	673	291

*Data for oil is reported in Mb/day and for gas in Bcf/day; ^ including biofuels

13.3 Influence of Agricultural Technologies on Climate Change Factors

Agriculture crops and forest trees are the important sinks of atmospheric CO_2 in the terrestrial ecosystem, though it contributes equally to climate change through GHC emissions. Also, the climate change impact on agriculture reflects directly on food security and indirectly on the standard of living of farmers. The study by Cline (2007) alarmed that the primary agricultural production sector would greatly suffer from projected climate change and the Indian region would get a decline in food production of 15–25% in southern parts and 25–50% in northern parts of India by 2080. A lot of interventions are being made globally in different sectors to contain greenhouse gas emissions by reducing the use of energy, in particular non-renewable fossil fuel. At present, agricultural researchers are aiming for sustainability in productivity and economic development without affecting environmental safety. The following studies are clearly indicating how the alternate technologies reduce the GHG emissions and Global Warming Potential (GWP) of Agricultural systems.

A study conducted in collaboration of International Maize and Wheat Improvement Center (CIMMYT), the University of Aberdeen and the Indian Council of Agricultural Research (ICAR), with support from the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS) inferred that 18% of GHG emissions from Indian agriculture could be reduced through the adoption of mitigation measures such as efficient use of fertilizer (17.5 $MtCO_2e$ per year), zero tillage (17 $MtCO_2e$ per year) and better water management (12 MtCo2e per year) in rice farming (Sapkota et al. 2019). The study also estimated that by 2030, GHG emissions from the agricultural sector in India would be 515 $MtCO_2e$ per year, with a technical mitigation potential of 85.5 $MtCO_2e$ per year through adoption of various mitigation practices.

The cultivated soils are the major sources of methane and nitrous oxide, both having significant global warming potential. The GWP ranged from 240 kg CO_2eq. per ha in pulses to 3700 kg CO_2eq. per ha in continuously flooded rice. Agriculture has the potential to mitigate GHGs cost-effectively through the adoption of low carbon in agricultural technologies and management practices. Another study by Pathak et al. (2013) and Jain et al. (2013) inferred that the Direct Seeding of Rice (DSR) and System of Rice Intensification (SRI) reduce or totally eliminate methane emission, as they do not require continuous soil submergence. These DSR and SRI have reduced the GWP by about 35–75% as compared to the conventional puddled transplanted rice.

There are so many new technologies that are constantly emerging to improve food production by increasing the productivity of inputs. Such technologies should also be environmentally sustainable in view of climate change adaptation and mitigation strategies, but not adequately tested for their environmental friendliness due to lack of adequate methodologies and basic tools. Proper understanding of the energy consumed in the input–output chain of agriculture and more emphasis on renewable inputs rather than non-renewable sources will help to achieve sustainability in food production and environmental protection. In agriculture, the energy is being used as direct inputs for the production and as indirect input such as manufacturing of fertilizers, chemicals, machineries, electric motors and implements. The energy consumptions of each technology are varying with each other in type, viz. direct or indirect, renewable or non-renewable, commercial or non-commercial and quantity.

Energy is needed at every level of the food value chain *viz*., production of agricultural inputs, crop production in the field, food processing, transportation, marketing and consumption. Primary agricultural operations consume about 20% of total energy involved in agriculture, whereas food processing including transport uses around 40% of energy. The processes along the value chain to the right (Fig. 13.6) are heavily dependent on the use of fossil fuels. These energy demands can be reduced in all agricultural processes where energy is used, by appropriate technology changes, as well as by improved management and operations (Energypedia 2019). It is also noted that GHG emissions would continue at a significant level from the agricultural sector unless the energy efficiency of that sector increased. The major knowledge gaps mentioned by Energypedia (2019) are (1) subsidy measures which often hide energy costs, (2) the long period of relatively cheap supplies of fossil energy, (3) the assumption that measures to increase agricultural production cannot be reconciled with the reduction of fossil energy inputs, (4) the hypothesis that energy inputs in agricultural production are either low or cannot be reduced in an economic manner, (5) lack of funding for interventions to reduce greenhouse gas emissions from the agricultural and food industry and (6) the lack of advisory and consulting services constitutes another major obstacle for the successful implementation of improvement measures in the field of sustainable energy in the agricultural and food economy. Hence, it is appropriate and need of the hour to use energy consumption or energy efficiency as a factor in identifying the climate smart agriculture.

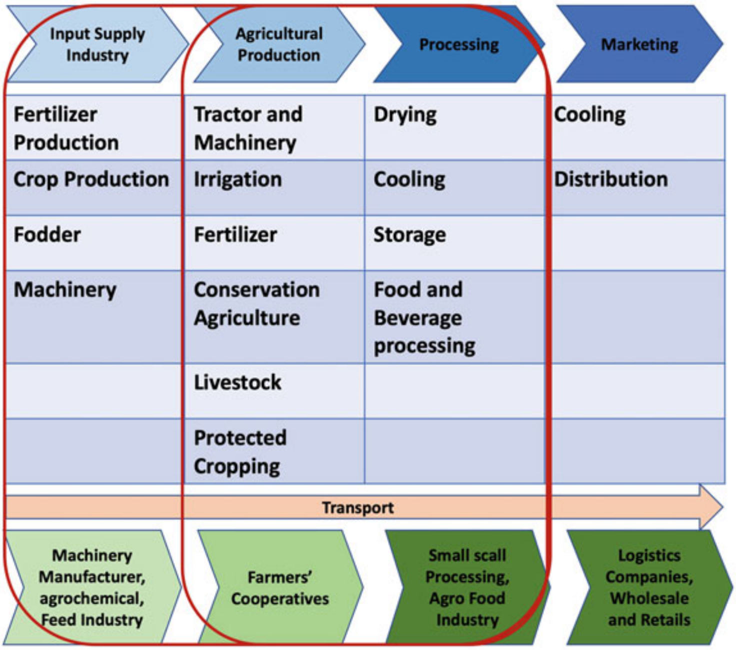

Fig. 13.6 Energy consumption within different steps of the value chain. Source: Energypedia (2019)

13.4 Energy Auditing for Identifying Climate Smart Agricultural Technologies

Identifying environmentally efficient technology by auditing the energy consumed and energy output from the technology and selection of climate and environment smart technology from different options will help us to reach our climate change mitigation goal.

13.4.1 Energy Auditing

Energy auditing is defined as understanding of "how energy is used within the system or process, and where it is wasted". It helps to find the alternatives, in order to reduce the energy losses and to increase the energy efficiency for overall better performance. By reviewing the energy load patterns and measuring process, energy demands could be identified along with suitable energy efficiency measures. Thus, energy auditing is helpful for economic and environmental betterment, becoming a very important tool in the energy sector. It is well known that the technology that uses more renewable and non-commercial energy (organic resources) would be good technology from a climate change point of view. But there is a belief in agricultural production systems that altering or reducing the energy sources by means of new technologies may affect productivity. Hence, it is necessary to identify energy efficient agricultural technologies without affecting the productivity through energy auditing methods. Like benefit–cost ratio and input use efficiency, we could calculate energy-output ratio, energy efficient ratio and net energy benefit.

13.4.2 TNAU Energy Soft

Energy auditing in agriculture needs the calculation of energy used in particular technology, information such as category, type and their equivalent energy of each input and output. There are so many inputs and outputs in agriculture and hence, it has become very difficult to calculate the energy efficiency of these technologies. A simplified energy calculation tool will help them to calculate the energy efficiency with minimum effort. In this context, TNAU Energy Soft 2016 has been developed at Tamil Nadu Agricultural University, Coimbatore, India to integrate energy databases with simplified energy efficient calculation methodology. The software was developed in the VB. Net programme with Microsoft Access database. It is a desktop application and user-friendly. This software facilitates easy creation of new treatment and options to create new by altering old treatment. It calculates and reports the total energy utilized, source wise, category wise, type wise energy utilized and could compare six treatments at a stretch. Similar to that of economic analysis, *viz.,* benefit–cost ratio and net profit, we could calculate energy efficiency and net energy benefit with this TNAU energy soft. This will be helpful to identify the energy efficient agricultural technologies and climate change mitigation technologies.

13.4.3 Methodology Used in TNAU Energy Software for Energy Analysis

Energy analysis is a significant tool for judging treatment efficiency and the respective treatment is considered more efficient when it produces higher output energy and requires less input energy. Energy ratio or energy efficiency ratio is the ratio between energy produced and the amount of energy consumed (energy output/energy input). It is generally used in the analysis of food production systems. Energy intensity is the amount of energy required to create a unit of output energy (energy input/energy output). It is the reciprocal of energy ratio and is equal to GER expressed in tons of output energy.

$$\text{Energy efficiency} = \frac{\text{Total Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}}$$

$$\text{Energy intensity} = \frac{\text{Energy input (MJ/ha)}}{\text{Total Energy output (MJ/ha)}}$$

$$\text{Energy Profitability} = \frac{\text{Net Energy Ouput (MJ/ha)}}{\text{Energy input (MJ/ha)}}$$

$$\text{Energy Productivity} = \frac{\text{Crop Economic Yield (kg/ha)}}{\text{Energy input (MJ/ha)}}$$

Classification of Energy

- Direct source: Human, bullocks, mechanical or electric power units and tractors.
- Renewable direct sources: Human, animals, solar and wind energy, agricultural wastes, etc.
- Non-renewable direct sources: Coal and fossil fuels
- Indirect source: Seeds, manures, chemicals, fertilizers and machinery
- Renewable indirect sources: Seeds and manures
- Non-renewable indirect source: Chemicals, fertilizers and machinery manufacturing
- Commercial energy: petroleum products and electricity
- Non-commercial energy: Human labour and bullocks

The energy equivalents of various agriculture related inputs and outputs are collected from many literature (Slesser 1988; Mittal and Dhawan 1988; Devasenapathy et al. 2009) and are given in Table 13.1.

Inputs Needed for Energy Calculations

- Information on energy sources: Direct/indirect, commercial/non-commercial, renewable/non-renewable
- Information on type of energy: Human/animal/chemical/machine/bio-products
- Equivalent energy value per unit source
- Quantity of energy source used in each operation

The energy values of different inputs related to agriculture (Table 13.1), sample energy calculation (Table 13.2) and energy calculation for nutrients (Table 13.3) are detailed below.

Opportunities and Modules in the TNAU Energy Soft 2016

- Easy selection of input items
- Compare six treatments at a stretch

Table 13.1 Equivalents for direct and indirect sources of energy

Particulars	Units	Equivalent energy (MJ)	Remarks
Inputs			
I Human labour			
a. Man	Hours	1.96	Adult
b. Woman	Hours	1.57	1 woman = 0.8 man
II Animals			
a1. Bullocks—large	Pair—hour	14.05	Bodyweight >450 kg
a2. Bullocks—medium	Pair—hour	10.10	Bodyweight 352–450 kg
a3. Bullocks—small	Pair—hour	8.07	Bodyweight <350 kg
b. He—buffalo	Pair—hour	15.15	1.5 medium bullock pair
c. Camel or horse	Hours	10.10	Medium bullock pair
d. Mules and small animals	Hours	4.04	0.4 medium bullock pair
III Power sources			
Diesel	Litre	56.31	Incl. cost of lubricants
Petrol	Litre	48.23	
Electricity	KWh	11.93	
IV Machinery			
a. Electric motor	kg	64.80	Distribute the weight of machinery equally over the total life span of machinery (hours)
b. Prime movers other than electric motors (including self-propelled machines)	kg	64.80	
c. Farm machinery	kg	62.70	
V. Manures and fertilizers			
i. N	kg	60.60	Estimate NPK in the fertilizer. Then compute the amount of energy input from chemical fertilizer
ii. P_2O_5	kg	11.10	
iii. K_2O	kg	6.70	
iv. Farmyard manure	kg (dry mass)	0.30	
VI Chemicals			
i. Superior chemicals	kg	120.00	Chemicals requiring dilution at application
ii. Zinc sulphate	kg	20.90	
iii. Inferior chemicals	kg	10.00	DDT, gypsum or any other chemicals not requiring dilution at application
VII Seeds			
a. Output of crop production system and not processed			Same as that of output of crop production system
b. Output of crop production system and is processed before using it for seed (e.g. potato, groundnut, cotton)			Add 1.5, 1.0 and 0.5 MJ/kg for potato, groundnut and other seeds, respectively, to the equivalent energy of the crop product

(continued)

Table 13.1 (continued)

Particulars	Units	Equivalent energy (MJ)	Remarks
Output			
VIII Main product			
a. Cereals (wheat, maize, sorghum, bajra, barley, oats, paddy (not shelled rice)) Pulses (mash, green gram, lentil, red gram, soybean, peas)	kg (dry mass)	14.70	The main output is grains
b. Oilseeds (cottonseed, groundnut, sesame, mustard, rapeseed, linseed, sunflower)	kg (dry mass)	25.00	The main output is seed except for groundnut (where it is pod)
c. Sugarcane	kg (at harvest)	5.30	
d. Vegetables			
i. Root or tuber vegetables			
Higher food value: sweet potato, tapioca	kg	5.60	
Medium food value: potato, beetroot, colocasia	kg	3.60	
Low food value: carrot, radish, onion, beetroot	kg	1.60	
e. Fruit or seed vegetables			
i. Broad beans, cluster beans, ladyfingers	kg	1.90	
ii. Gourd vegetables, cucumber, drumstick, green papaya, pumpkin, tomato, chillies	kg	0.80	
f. Leafy vegetables			
Cabbage, spinach, green mustard leaves	kg	0.80	
g. Fruits			
i. High value: tamarind, grapes	kg	11.80	
ii. Low food value: guava, mango, amla, apple peach, pears, pineapples, ber, sapota, cashew, citrus	kg	1.90	
h. Fibre crops (cotton, sunn hemp, jute)	kg (dry mass)	11.80	Main product is fibre
i. Fodder crops (berseem, lucerne, senji, oats, maize, bajra, sorghum, cowpea, guava, napier)	kg (dry mass)	18.00	The main product is dry or green fodder
j. Green manure crops (dhaincha, cowpea, sunn hemp)			Energy equivalent to the amount of nutrients added to the soil as green manure

(continued)

Table 13.1 (continued)

Particulars	Units	Equivalent energy (MJ)	Remarks
IX Byproducts			
a. Straw, vines	kg (dry mass)	12.50	
b. Stalks, cobs, wood, fruit		12.50	
c. Vines, plant wood	kg (dry mass)	18.00	
d. Leaves, vines and straw	kg (dry mass)	10.00	
e. Cotton seed	kg (dry mass)	25.00	
f. Fibre crop seed other than cotton and fuel crop seed	kg (dry mass)	10.00	
g. Sugarcane leaves and tops	kg (dry mass)	16.10	

Table 13.2 Sample energy calculations for cotton

Particulars	Energy source	
Field preparation Tractor ploughing	Mechanical-tractor	$\frac{\text{Wt.of the tractor (kg)}}{\text{Life span (hours)}} \times \text{MJ} \times \text{hours of operation}$ $= \frac{2000}{12000} \times 64.80 \times (5+3+4+8) = 216\text{MJ}$
Disc (5 h/ha) × 1 times 9 tyne tiller (3 h/ha × 1 time) Rotavator (4 h/ha × 1 time) Ridges & Furrow (8 h/ha × 1 time)	Implement used—cultivator	$\frac{\text{Wt.of the cultivator(kg)}}{\text{Life span (hours)}} \times \text{MJ} \times \text{hours of operation}$ $Disc = \frac{300}{6000} \times 64.80 \times 10 = 32.04\text{MJ}$ $9\ tyne\ tiller = \frac{200}{6000} \times 64.80 \times 10 = 21.36$ MJ $Rotavator = \frac{300}{6000} \times 64.80 \times 10 = 32.04$ MJ Ridges & Furrow (R&F) 8 h/ha × 1 time R&F $= \frac{150}{6000} \times 64.80 \times 10 = 16.02$ MJ
	Diesel consumption	For 5 + 3 + 4 + 8 = 20 h = 20 × 3.5 L/h =70 L × 56.31 MJ = 3941.7 MJ
	Driver (human)	=20 h × 1.96 MJ = 39.20 MJ
Ridges and furrows rectification	Human	=10 men × 6 h × 1.96 MJ = 117.6 MJ

Table 13.3 Energy calculation for fertilizer

10 kg of urea	=10 × 46/100 × 60.60	=278.8 MJ
10 kg of super phosphate	=10 × 16/100 × 11.10	=17.76 MJ
10 kg of MOP	=10 × 60/100 × 6.70	=40.20 MJ
10 kg of DAP	=(10 × 18/100 × 60.60) + (10 × 45/100 × 11.10)	=159.75 MJ
1 ton FYM	=1000 × 0.30	=300.00 MJ

- Create new treatment on your own or altering old treatments and save as new
- Edit, delete and modify the treatment
- Add new energy, crop, field operations

- Detailed energy use of single treatment
- Individual treatment abstract
- Field operation-wise energy use
- Net energy benefit, energy efficiency
- Energy use will be categorized as source
- Output will be directly exported to excel

13.5 A Case Study Using TNAU Energy Soft 2016

Using the TNAU Energy software, energy efficiency was calculated for the field experiment on "identifying the best nutrient management for maize" conducted at Maize Research Station, Vagarai, Palani, Dindigul district of Tamil Nadu (Tables 13.4 and 13.5). The treatments for this experiment are as follows:

- T1 Treatment—Farmer's method: 150–50–50 NPK kg/ha
- T2 Treatment—TNAU-RDF: 250–75–75 NPK kg/ha
- T3 Treatment—IPNI-SSNM: 150–47–29 NPK kg/ha
- T4 Treatment—IPNI-nutrient expert: 180–115–160 NPK kg/ha
- T5 Treatment—Control—No fertilizer

Among the five treatments, the TNAU-RDF method had produced higher yield and used lesser energy followed by IPNI-nutrient expert method. Though the IPNI-nutrient expert method had recorded a higher BC ratio than TNAU-RDF method, the energy efficient method was TNAU–-RDF as it had higher energy output, net energy benefit and energy efficiency ratio. The difference in energy use between TNAU-RDF and IPNI-nutrient expert (3314 MJ) was much lesser than the difference of net energy benefit (23825) between the treatments. Hence, the TNAU-RDF is better in both energy efficient and economic method of fertilizer application than IPNI-nutrient expert and IPNI-SSNM method. TNAU Energy soft 2016 aids in identifying the energy efficient agricultural technologies. Further, it helps to determine the best mix of input sources without repeated and expensive field trials. So by identifying and promoting energy-efficient technologies, it would be possible to reduce expenditure and hence cost of cultivation. The energy-efficient technologies aid in cutting down the GHG emissions from agricultural activity.

13.6 Conclusion

Development of technology in every area, including agriculture, is a continuous process to maintain and increase productivity to feed the large population. The reliability of these technologies, especially energy efficiency should be ensured for their input usage, so that the technologies can provide necessary impetus for climate action. TNAU Energy soft 2016 helps scientists to identify the energy efficient agricultural technologies as climate change mitigation and adaptation. It assists to

Table 13.4 Energy used by farmer's method of fertilizer application

Major activity	Direct and commercial		Indirect and commercial		Direct and non-commercial		Indirect and non-commercial		Total		Grand Total
	RN	NR	RN	NR	RN	NR	RN	NR	RN	NR	
Initial land preparation	0	0	0	119	118	0	0	0	118	119	237
Seeds and sowing	0	0	328	0	236	0	0	0	564	0	564
Manure and fertilizer	0	0	0	10,225	141	37,500	0	0	141	47,725	47,866
Plant protection and weed management	0	241	0	481	104	0	0	0	104	722	826
Irrigation	0	0	0	6032	251	0	0	0	251	6032	6282
Harvest and post harvest	0	563	0	17	565	0	0	0	565	580	1145
Yield and by products	0	0	193,451	0	0	0	0	0	193,451	0	193,451
Total output	0	563	193,451	17	565	0	0	0	194,016	580	194,596
Total input	0	804	328	16,874	1414	37,500	0	0	1742	55,179	56,920
Energy efficiency	3.40										
Net energy benefit	136,530										

Table 13.5 Yield, economics and energy comparison for different methods of fertilizer application

Treatment	Yield (kg ha^{-1})	Net benefit (Rs.)	B:C ratio	Energy input (MJ)			Energy output (MJ)	Net energy benefit (MJ)	Energy efficiency
				Renewable	Non-renewable	Total			
T1-Farmer method: 150–50–50 NPK kg/ha	7424	44,544	2.50	1742	55,179	56,920	193,451	136,530	3.40
T2-TNAU RDF: 250–75–75 NPK kg/ha	8542	51,572	2.52	1742	61,684	63,556	24,3112	179,556	3.83
T3-IPNI-SSNM: 150–47–29 NPK kg/ha	6436	35,816	2.25	1742	55,003	56,745	185,379	128,633	3.27
T4-IPNI-Nutrient Expert 180–115–160 NPK kg/ha	8136	49,796	2.58	1742	58,500	60,242	215,973	155,731	3.59
T5-Control-No fertilizer	3240	11,188	1.52	1601	45,003	46,604	97,070	50,466	2.08

determine the best mix of input sources (renewable/non-renewable/commercial/non-commercial) of technology without repeated and expensive field trials. By identifying and promoting energy-efficient technologies, it would be possible to reduce expenditure on controlling climate change factors, particularly GHG emissions. TNAU Energy Soft 2016 assists to find the ways and means to reduce the non-renewable fossil fuel based inputs and to increase the use of renewable and biological resources and ensures sustainable bioeconomy.

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Mechanism for Improving the Sustainability of Homestead Food Gardens in the Gauteng Province, South Africa

14

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Abstract

Homestead food garden (HFG) projects are supported by government which attempts to alleviate poverty in food insecure households. Despite the fact that homestead food gardens are seen as a solution to food security in the Gauteng Province and other parts of the world, the issue of unsustainability and failure of these programmes after government support ceases cannot be ignored. A household survey was conducted in the Gauteng Province by the Agricultural Research Council (ARC) and the Gauteng Department of Agriculture and Rural Development (GDARD) to establish a sustainable mechanism for homestead food gardens. The following objectives were addressed: to identify socio-economic factors that influence sustainability of homestead gardens; to identify factors influencing garden availability; and to recommend the mechanism for improving the sustainability of homestead gardens. A total of 1150 households participated and were spread as follows: City of Johannesburg (319); City of Tshwane (270); Ekurhuleni Metropolitan (141); Sedibeng (216); and the West Rand (204). Quantitative and qualitative designs were used as a questionnaire, and stakeholder discussions and field observations were part of the data collection. A purposive sampling technique was used and data was coded, captured, and analysed using the Statistical Package for the Social Sciences (SPSS). Food security status was also in line with the fact that South Africa is food insecure at a household level in contradiction to the national level. A whopping number of households interviewed were food insecure (860), as compared to households that were food secure (290). This food security situation is worrying because

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695 households go to sleep at night hungry because there was not enough food and about 395 households could go the whole day and night without eating anything. It was also established that in terms of sustainability, not all household gardens are economically viable, or socially and environmentally sustainable. Nine hundred and seventy-one households agreed that gardens do not generate income, and very few households (179) emphasised that gardens were generating income. There was an almost equal response in terms of gardens supporting social initiatives. In terms of environmental sustainability, 933 households were not aware about the environmental issues. In conclusion, the majority of households felt that the HFG Programme is very good (371), good (490), and fair (191). Only a few households felt that the initiative is poor (70) and very poor (28). The majority of households felt that the support received is very good (443), good (341), and fair (166). Quite a number of households felt that the support received was poor (105) and very poor (95). Hence, some of the recommended activities to be included in the mechanism include stakeholder and community mobilisation, situational analysis, food garden inputs, nutrition education, participation of the community in homestead programme design and implementation, training, and monitoring.

Keywords

Households · Homestead Gardens · Gauteng Province · South Africa · Food Security and Sustainability

14.1 Introduction

According to Stats SA (2019), the Gauteng Province is a home for over 15.2 million people, which contribute to 25.8% of the total national population. Studies have shown that almost 20% of households in the Gauteng Province go to bed hungry due to food insecurity and unsustainable income. The South African government has committed itself to halving poverty between 2004 and 2014, and one of the critical components in meeting that objective was household food security (Stats SA 2017). Various studies (Musotsi et al. 2008; Shrestha et al. 2001; Maponya and Moja 2012) confirmed food gardening as a means for addressing food security and supplementing the means of income in the household. According to the Gauteng Provincial Government's programme of action of 2009–2014, which addressed strategic priority four, which is stimulating rural development and ensuring food security, the Gauteng Department of Agriculture and Rural Development is the main custodian in ensuring that strategic priority four is addressed. Various past and current food security programmes offered by the Gauteng Province, e.g. Homestead Food Garden Project, Growing Own Food, and the Siyazondla campaign, have to be appreciated as they have made a significant improvement in the livelihoods of many rural Gauteng residents. Although various interventions are made in the province in addressing the issue of food security through food gardening, the Gauteng Province Department of Agriculture and Rural Development is faced with a challenge of ensuring that the programme remains active and sustainable, even after the support from government has ceased. The problem is also highlighted in the study by Mwale et al. (2012) that despite the fact that the government has initiated the establishment of agricultural community projects as part of interventions for creating jobs and improving income levels, the lack of monitoring mechanisms in the established projects leads to the non-sustainability of these projects. The essence of the problem lies in identifying those factors affecting sustainability of homestead food gardens in the Gauteng Province.

The Homestead Food Garden Projects are one of the programmes supported by government which attempts to alleviate poverty in food insecure households. The basic aim of the initiative is to teach people to grow vegetables and fruit trees on their homesteads in order to supplement daily food requirements and secure extra income. Despite the fact that the homestead food gardens are seen as a solution to food security in the Gauteng Province and other parts of the world, the issue of unsustainability and failure of these programmes after government support ceases cannot be ignored. The Gauteng Province Department of Agriculture and Rural Development has adopted the National Outcome-Based approach to enable effective efficient implementation, monitoring, and evaluation of performance of its mandate. In delivering to its mandate of addressing outcome seven of its strategic plan, i.e. vibrant, equitable, sustainable rural communities contributing towards food security for all, the department is compelled to align its programmes to the stipulated outcome seven of the strategic plan. The outcome of the research would help establish sustainable mechanisms of ensuring that homestead food garden projects remain active and sustainable beyond the support period of the government. In doing so, the research would help the department to address outcome seven of its strategic plan, as well as the outcome statement of the Gauteng Provincial Government's programmes of action which is to develop a food secure Gauteng Province that is sustainable in the region.

14.2 Aim and Objectives

The general aim of the study is to establish a sustainable mechanism for homestead food gardens in the Gauteng Province, South Africa. The following are the objectives of this study.

- To identify socio-economic factors that influence sustainability of homestead food gardens in the Gauteng Province.
- To recommend a sustainable mechanism for homestead food gardens in the Gauteng Province.

14.3 Methodology

The project followed a participatory action approach since the researcher, collaborators, extension officers, farmers, and funder are actively involved in all phases of the project to ensure that the deliverables are achieved. According to Backeberg and Sanewe (2010), the method of participatory action research is most appropriate, since people, especially farmers, benefit while the research is ongoing. The participatory action approach was also recommended by various researchers who emphasised that the participatory action approach is a good alternative to the traditional "transfer of technology" or "top–down approach" to agricultural research and extension. It is against this background that the approach will be used to achieve the research aims and deliverables, and that all phases have been successfully completed. The research used quantitative and qualitative methods and purposive sampling from an existing sample frame from the GDARD database of the homestead food garden project. The sample size of the research was agreed on with GDARD officials, but the sample size should be statistically significant, which is normally obtained at 10% of the total population. A detailed questionnaire was developed as a quantitative data collection method and data was collected from 1150 households as follows: City of Tshwane Metropolitan (270), City of Johannesburg Metropolitan (319), Ekurhuleni Metropolitan (141), and the West Rand District (204). The questionnaire used both open and closed ended questions. Qualitative data collection methods included focus group discussions and field observations. The focus group discussions were conducted among 56 GDARD officials as follows: City of Tshwane Metropolitan (24), City of Johannesburg Metropolitan and the West Rand District combined (18), Ekurhuleni Metropolitan (7), and the Sedibeng District (7). Data collected was analysed quantitatively using the Statistical Package for Social Sciences (SPSS) windows version.

The following approach was used to determine correlations among variables:

Correlation is a bivariate analysis that measures the strengths of association between two variables and the direction of the relationship. In terms of the strength of relationship, the value of the correlation coefficient varies between +1 and −1. When the value of the correlation coefficient lies around ± 1, it is said to be a perfect degree of association between the two variables. As the correlation coefficient value goes towards 0, the relationship between the two variables will be weaker. The direction of the relationship is simply the + (indicating a positive relationship between the variables) or—(indicating a negative relationship between the variables) sign of the correlation. Usually, in statistics, four types of correlations are measured: Pearson correlation, Kendall rank correlation, Spearman correlation, and the Point-Biserial correlation. In this example, Pearson and Spearman correlations were used and the following variables were found to be significant: garden availability, age, gender, household members, and household income.

The following econometric model was used to determine the association of variables (Greene 1993):

Table 14.1 Description of variables used in the study

Variables	Description of variables	Unit (s)
Dependant variable		
Garden still available	1 if household has a garden , 0 otherwise	Dummy
Independent variables		
Age	Age of a household	Years
Sex	1 for a male household, 0 otherwise	Dummy
Education level	The highest qualification the household possesses	Number
Household income	Household incomes	Rands
Household members	Household members	Number
Household expenditure	Household expenditure	Rands
Irrigation access; garden tool; homestead initiative	1 if household has irrigation access, 0 otherwise	Dummy
	1 if household has a garden tool, 0 otherwise	Dummy
	1 if home garden initiative is working, 0 otherwise	Dummy

$$Wi = \_ + \_Xi + \_i \qquad (14.1)$$

where, *Wi* is the dependent variable value for person *i*. *Xi* is the independent variable value for person *i*. _ and _ are parameter values. *i* is the random error term. The parameter _ is called the intercept or the value of W when $X = 0$. The parameter _ is called the slope or the change in *W* when *X* increases by one.

The sample data variables predicted an 87% for Cox and Snell (measure for binary logistics regression); 91% for McFadden (measure for multinomial and ordered logit) variation in the dependent variable was explained by the independent variables. Prediction accuracy was assessed based on the coefficient of determination (R^2). The coefficient of determination R^2 was used to explain the total proportion of variance in the dependent variable explained by the independent variable. The R^2 removes the influence of the independent variable not accounted for in the constructs. R^2 is always between 0 and 100%. In general, the higher the R^2 value, the better the model fits the data, and Table 14.1 indicates the variables used.

The following approach was used to explain the odds ratio (Greenfield et al. 2008):

An odds ratio (OR) is a measure of association between an exposure and an outcome. The odds ratio can also be used to determine whether a particular exposure is a risk factor for a particular outcome, and to compare the magnitude of various risk factors for that outcome (Odds Ratio = 1 if the exposure does not affect the odds of the outcome; Odds Ratio >1 if the exposure is associated with higher odds of the outcome; and Odds Ratio <1 if the exposure is associated with lower odds of the outcome).

When the logistic regression is calculated, the regression coefficient ($b1$) is the estimated increase in the log odds of the *outcome per unit increase* in the value of the *exposure*. In other words, the exponential function of the regression coefficient (e^{b1}) is the odds ratio associated with a one-unit increase in the exposure. The 95% confidence interval (CI) is used to estimate the precision of the odds ratio. A large CI value indicates a low level of precision of the odds ratio, whereas a small CI value indicates a higher precision of the odds ratio.

The following approach was used during focus group discussions:

Focus group discussions allowed researchers to obtain a wealth of in-depth qualitative information, which was combined with the information obtained with the quantitative method, to help explain the "why" or the "how" of observed statistical trends. The results of the focus group interviews were combined with the quantitative results in a way that is coherent and that supports the overall findings, conclusions, and recommendations of the study. Three regional managers and 52 Homestead Food Garden (HFG) advisors took part in the focus group discussions. The presence of the HFG advisors made it possible to discuss issues of operations and management of the food gardens, as well as their relationship with households and the local councillors. The focus group method was chosen because the HFG advisors knew the households very well and therefore it was envisaged that they would be comfortable to share information about their relationship with these households and issues that affect them as the department. The focus groups also enabled the researcher to observe how government officials interact with one another, how they perceived issues of food security and sustainable livelihoods, and how these issues affect them as a department.

14.4 Results and Discussion

14.4.1 Study Area

As indicated in Table 14.2, a total of 1150 households in three metropolitans and two districts were identified and visited in the Gauteng Province: City of Johannesburg Metropolitan (319); City of Tshwane Metropolitan (270); Ekurhuleni Metropolitan (141); Sedibeng District (216); and West Rand District (204).

As further indicated in Figs. 14.1, 14.2, 14.3, 14.4, and 14.5, different locations/townships/suburbs/informal settlements were visited within each metropolitan and district as follows: City of Johannesburg Metropolitan (37); City of Tshwane

Table 14.2 Gauteng Province households visited and interviewed

Province	Metropolitan or district	Number of households
Gauteng	City of Johannesburg	319
Gauteng	City of Tshwane	270
Gauteng	Ekurhuleni	141
Gauteng	Sedibeng	216
Gauteng	West Rand	204
Total		1150

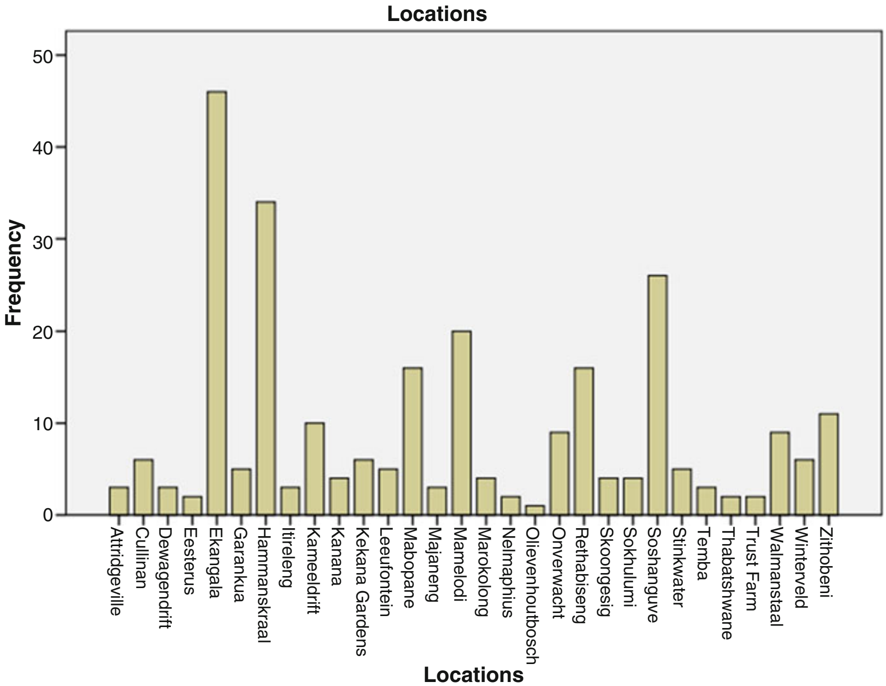


Fig. 14.1 Locations/townships/suburbs/informal settlements visited in the metropolitan City of Tshwane

Metropolitan (30); Ekurhuleni Metropolitan (11); Sedibeng District (13); and the West Rand District (10).

14.4.2 Descriptive Analysis

The majority of households interviewed were females (915) and the same trend is seen in the metropolitans and districts. The results are also in line with the Maponya and Moja (2012) study in the Limpopo Province which indicated that female households constitute a significant number of the economically active population and that the female-headed households usually fall within the vulnerable, marginal, and food insecure categories. Most households fall in the age category >56 years of age (454) and very few households fall in the age category <35 years of age (128) (Table 14.3). This shows an ageing population of households which could be critical to household food security. The same age categories trend is seen in metropolitans and districts. This indicates the need for youth involvement in the Homestead Garden Programme, as any future agricultural development in the districts and metropolitans should be tailor made to attract youth. In terms of educational attainment (Table 14.3), most households received secondary education (574), with a few

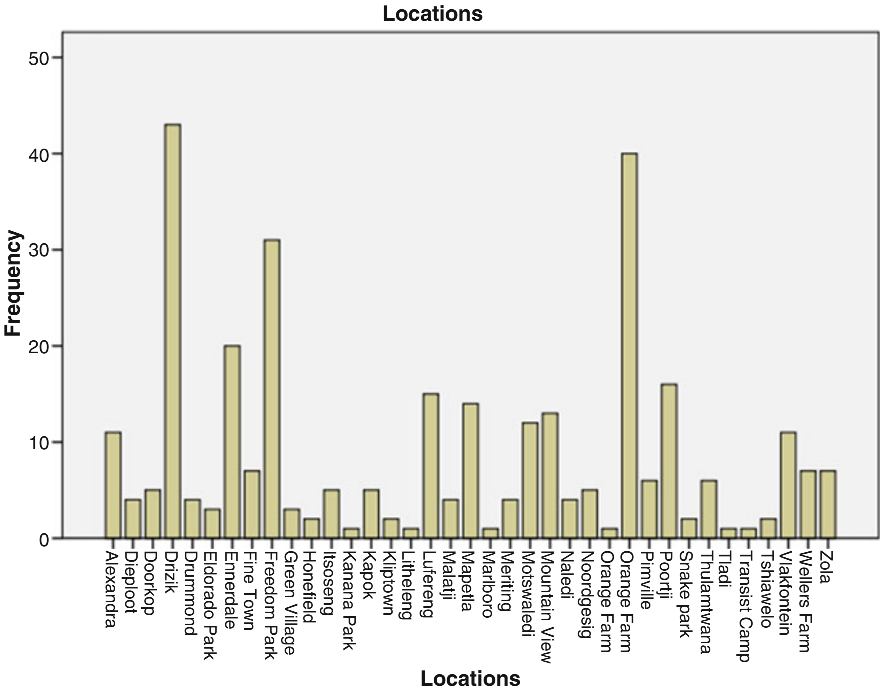


Fig. 14.2 Locations/townships/suburbs/informal settlements visited in the City of Johannesburg Metropolitan

receiving tertiary education (34). The level of education is consistent in all districts and metropolitans across the Gauteng Province. According to Heckman (1999), education is key to poverty reduction, improve household food security, and to improve the livelihoods of the poor. This is due to the ability of an education to increase knowledge and skills, which is supportive to a household's employability and the fulfilment of the household's basic necessities. Most households fall in the income level of R1001–R2500 per month and quite a number of households had no income (248) (Table 14.3). Most of the households were spending >R601 of their monthly expenditure on food. There was not much difference in the number of household members in the Gauteng Province. Most of the household's size ranged between 1 and 5 members, and the same trend was seen across districts and metropolitans. According to Amaza et al. (2009), the importance of household size as a major contributing factor to household agricultural production and hence food security, through labour supply, has been well documented globally.

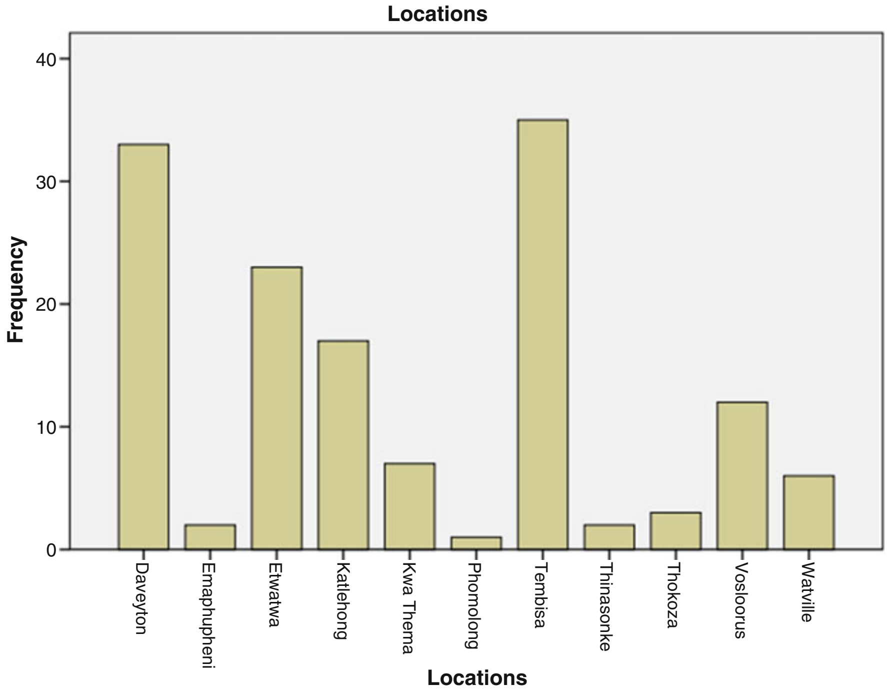


Fig. 14.3 Locations/townships/suburbs/informal settlements visited in the Ekurhuleni Metropolitan

14.4.3 Households Gardens Status

As indicated in Fig. 14.6, not all households in the provided list are still gardening. Out of 1150 households visited, 386 were found not involved in gardening. Some of the reasons are lack of skills and knowledge and loss of interest. As indicated in Fig. 14.7, various tools were supplied to households across the Gauteng Province. It was indicated by officials that after training has been concluded, agricultural advisors collect materials from the departmental warehouse and arrange delivery to a central location (e.g. community centre, police station, church, or school) where they can create an order, lay out tools, and check records for volunteer services. The starter pack delivered consisted of a standard set of items, including a spade, fork, rake, hand hoe, hose pipe, watering can; 21 m^2 shade net; six poles; two bags of compost; spray bottles; and irrigation fittings, including a mist sprayer, tailpiece, tap connector, and clamp. Figure 14.7 also indicates that the delivery of starter packs has been fairly uniform across the districts and metropolitans.

As indicated in Fig. 14.8, vegetable production was common among the households across the Gauteng Province. The Gauteng Department of Agriculture and Rural Development provided starter packs, which included six types of seeds namely, Swiss chard, carrots, beetroot, tomato, onion, and beans. It was emphasised

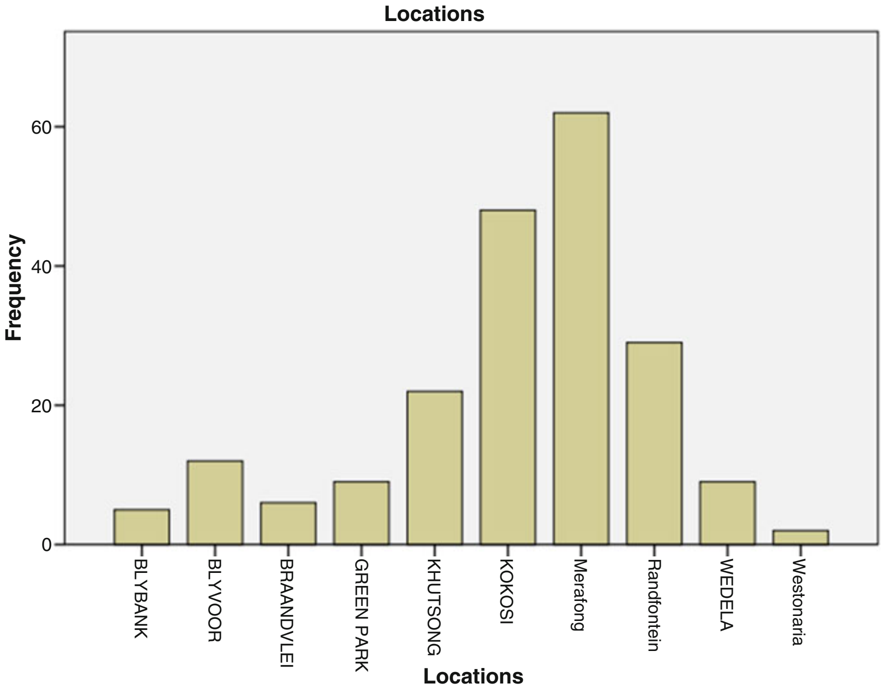


Fig. 14.4 Locations/townships/suburbs/informal settlements visited in the West Rand District

during the focus group discussions with officials that the seeds were chosen because they can thrive in small and densely planted areas, and because of the high nutritional value of these vegetables. Figure 14.8 also indicates that the delivery of starter packs has been fairly uniform across the districts and metropolitans. The distribution of the starter packs contributed significantly to food security and in line with Akrofi et al. (2010) who found that food items from home gardens significantly contributed to food security of rural households in the Eastern Region of Ghana.

Figure 14.9 indicates that the majority of households felt that the homestead initiative is very good (371), good (490), and fair (191). Only a few households felt that the initiative is poor (70) and very poor (28). Some households complained about the lack of monitoring and evaluation of the homestead initiative as the reasons for their fair, poor, and very poor response. The same trend was observed across districts and metropolitans. Figure 14.10 indicates that the majority of households felt that the support received is very good (443), good, (341) and fair (166). Quite a number of households felt that the support received was poor (105) and very poor (95). Some households complained about the lack of monitoring and evaluation of the homestead initiative as the reasons for their poor response. The same trend is observed across districts and metropolitans.

In terms of household food gardens sustainability, there is a consistent response regarding income generation across the districts as indicated in Fig. 14.11. 84% of

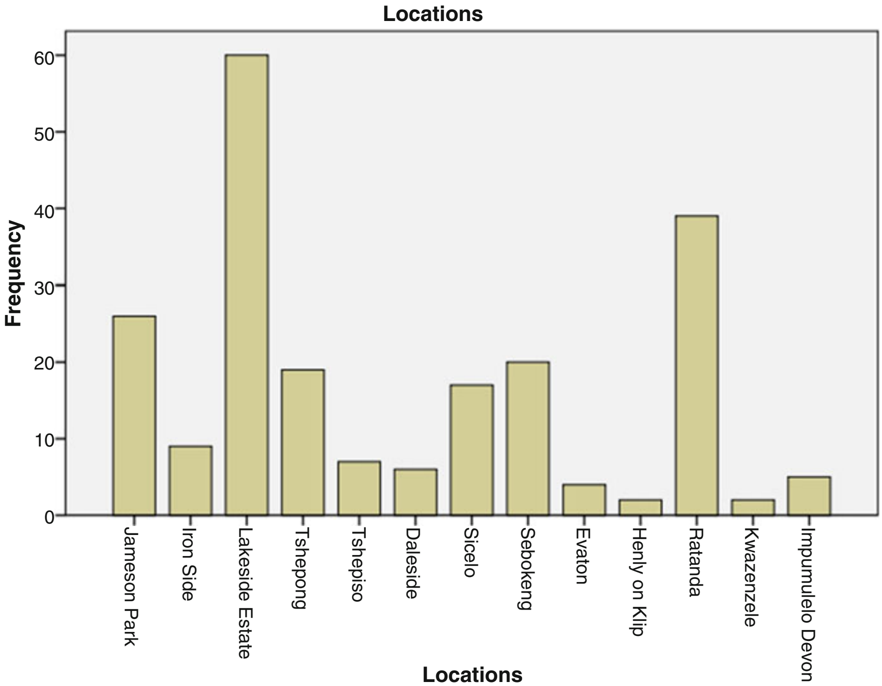


Fig. 14.5 Locations/townships/suburbs/informal settlements visited in the Sedibeng District

households indicated that gardens do not generate income, but provide food for the family. Very few households (179) emphasised that gardens were generating income for them, and most of them were located in or near city centres, i.e. close to high value markets. This situation results in some of the benefits of food gardens being lost, i.e. the reduction of household expenses for the purchasing of food, and the generation of income through the sale of surplus produce. The results in Fig. 14.12 indicate an almost equal response in terms of gardens supporting social initiatives. The contribution of some gardens towards social initiatives is well noted and should be further supported. The GDARD should also prioritise environmental awareness among their households.

As represented in Fig. 14.13, about 81% of households were not aware of the environmental and sustainability. The focus group discussions indicated that the low levels of environmental awareness among households is because the mandate of environmental issues belongs to another department. If households were properly educated about environmental issues and importance thereof, it would increase environmental benefits from the recycling of water and waste nutrients, controlling shade, dust and erosion, and maintaining or increasing local biodiversity. This would lead to a more sustainable environment and communities, as discussed during the face-to-face interviews, observations, focus group discussions, and available literature.

Table 14.3 Gauteng Province household demographics

	CTM	CJM	EM	SD	WD	GP
Household gender						
Female	212	225	111	193	174	915
Male	58	94	30	23	30	235
Total	270	319	141	216	204	1150
Household age categories						
<35	18	32	4	36	40	128
36–45	49	54	13	57	58	221
46–55	69	94	24	54	65	286
>56	134	139	100	69	41	454
Total	270	319	141	216	204	1150
Household level of education						
No education	27	23	26	26	23	114
Primary education	105	133	52	41	54	367
Secondary education	125	149	54	149	121	574
Tertiary education	13	14	9	0	6	34
Total	270	319	141	216	204	1150
Household income						
<R500	8	34	7	15	28	87
R501–R1000	41	83	1	49	60	221
R1001–R2500	115	69	87	109	68	417
>R2501	11	66	14	18	14	116
No income	95	67	32	25	34	248
Total	270	319	141	216	204	1150
Household monthly expenditure on food						
<R200	8	17	0	4	13	40
R201–R400	27	35	2	39	27	121
R401–R600	78	57	11	48	42	223
>R601	157	210	126	122	121	699
No expenditure	0	0	2	3	1	6
Total	270	319	141	216	204	1150
Household members						
1–5	177	186	73	161	133	730
6–10	82	108	49	50	59	348
>10	11	25	19	5	12	72
Total	270	319	141	216	204	1150

CTM City Tshwane Metropolitan, *CJM* City of Johannesburg Metropolitan, *EM* Ekurhuleni District, *SD* Sedibeng District, *WP* West Rand District, *GP* Gauteng Province

14.4.4 Correlation Analysis

There is a positive correlation between the variables of gardens still owned and available and household members/size in the Gauteng Province (Table 14.4). It is generally expected that household members who are able to work are most likely to

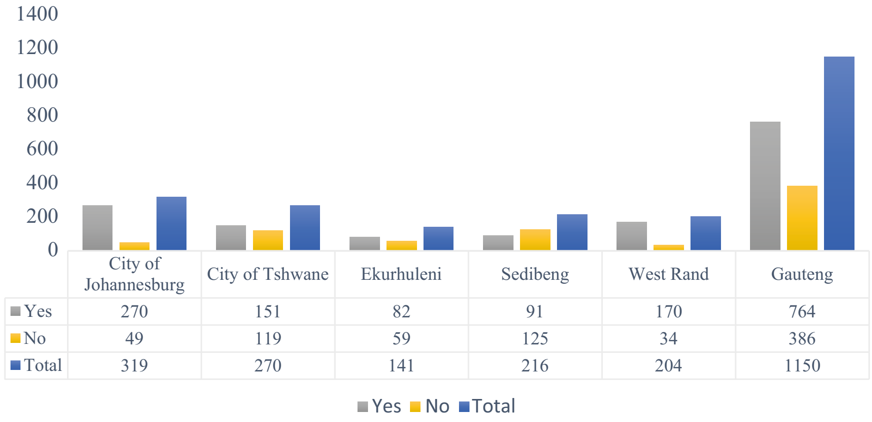


Fig. 14.6 Status of households practising gardening

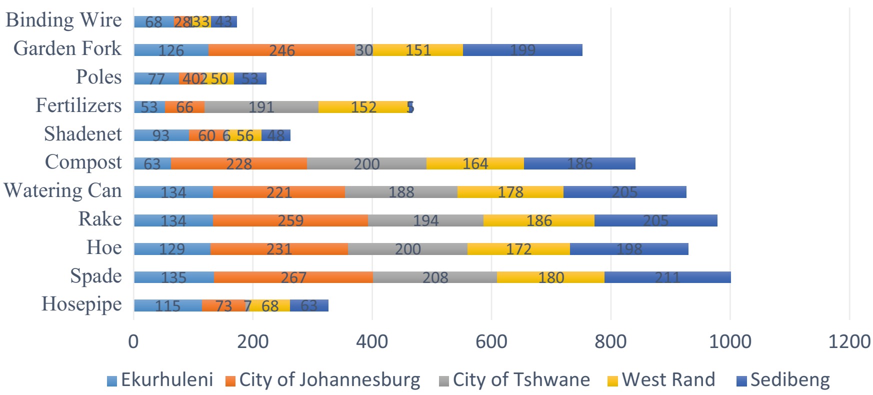
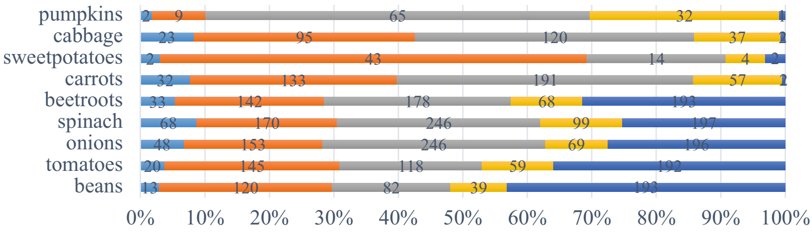


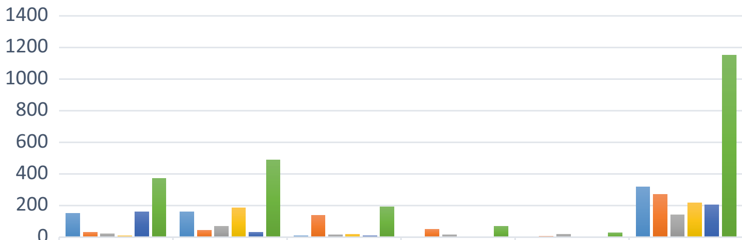
Fig. 14.7 Tools received by households

contribute to household food consumption, either through formal employment or being actively involved in food gardening. According to Maponya and Moja (2012), households with more members who are economically active are generally more food secure than those with less economically active members. There is a positive correlation between gender and gardens still owned and available (Table 14.4). This study's gender results are also in line with findings by Ndobo (2013), who indicated that households headed by females are more likely to face mild-to-moderate, as well as severe forms of food insecurity than those headed by males. Similar results were found by Mohammadi et al. (2011), who reported that severe food insecurity was more frequent in female-headed households. The study further emphasised that age category and gardens owned and availability are positively correlated, and both variables are significant at 5%. There is a positive correlation between household income and gardens owned and still available. It is thus expected that households



	beans	tomatoes	onions	spinach	beetroots	carrots	sweetpotatoes	cabbage	pumpkins
sedibeng	13	20	48	68	33	32	2	23	2
West Rand	120	145	153	170	142	133	43	95	9
City of Johannessburg	82	118	246	246	178	191	14	120	65
ekurhuleni	39	59	69	99	68	57	4	37	32
City of Tshwane	193	192	196	197	193	2	2	2	1

Fig. 14.8 Vegetables grown by households



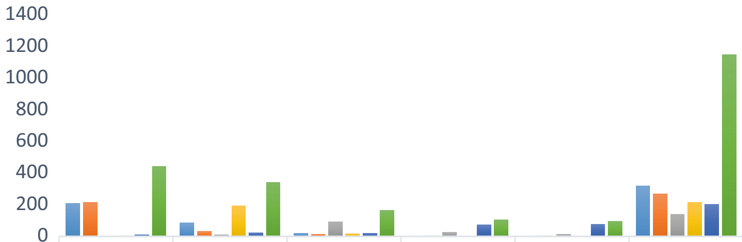
	Very Good	Good	Fair	Poor	Very Poor	Total
City of Johannesburg	150	160	8	0	1	319
City of Tshwane	31	45	137	51	6	270
Ekurhuleni	21	69	17	16	18	141
Sedibeng	8	185	20	3	0	216
West Rand	161	31	9	0	3	204
Gauteng	371	490	191	70	28	1150

Fig. 14.9 Overall feeling about the homestead garden initiative

with gardens can make extra income from surplus production. It is also expected that an increase in a household income can reduce food insecurity among households. According to Maponya and Moja (2012), the combination of income generation and production improves food security among households.

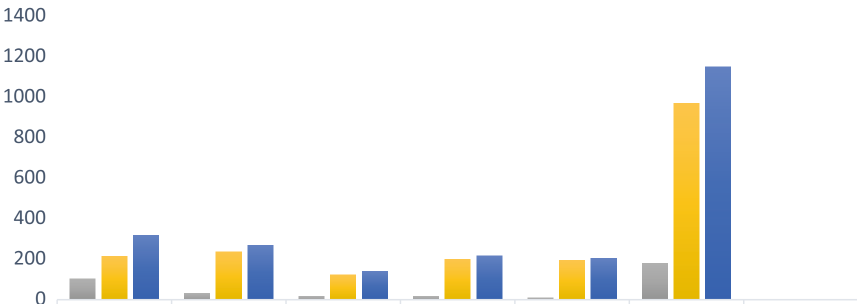
14.4.5 Univariate Analysis

There is a higher association among the following variables: gardens owned and still available, household income, agricultural training, and access to irrigation, garden tools, and a home garden initiative (Table 14.5). This is supported by the fact that their estimate values are more than 1 at the 95% confidence interval.



	Very Good	Good	Fair	Poor	Very Poor	Total
City of Johannesburg	210	85	21	2	1	319
City of Tshwane	216	31	15	4	4	270
Ekurhuleni	2	9	92	25	13	141
Sedibeng	4	193	17	2	0	216
West Rand	11	23	21	72	77	204
Gauteng	443	341	166	105	95	1150

Fig. 14.10 Households' overall impression about the support received



	City of Johannesburg	City of Tshwane	Ekurhuleni	Sedibeng	West Rand	Gauteng
Yes	104	32	17	16	10	179
No	215	238	124	200	194	971
Total	319	270	141	216	204	1150

Fig. 14.11 Homestead garden income generation

The odds of households of receiving income from the availability of gardens were 1.299 (Table 14.5). This will in turn lead to higher food security levels and enhance the odds of households being food secure. The odds of households with irrigation water to have available garden were 1.29. This is true as agricultural production requires large quantities of good quality water for use in various production processes. According to the FAO (2012), irrigation uses up to 70% of all fresh water appropriated for human use. According to Table 14.5, the odds of households with garden tools to have an available garden was 1.07. Obviously, in order to grow crops in the garden, tools play an important role. The odds of agricultural training and available gardens were 1.25. This is true as non-formal and formal education plays an important role in household/smallholder farmer involvement in agriculture. Finally, it is not surprising to realise the association between the homestead garden

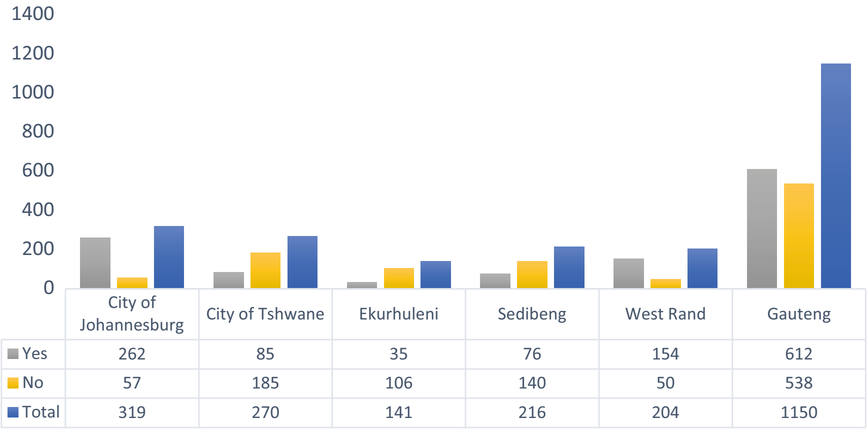


Fig. 14.12 Homestead gardens supporting social initiatives

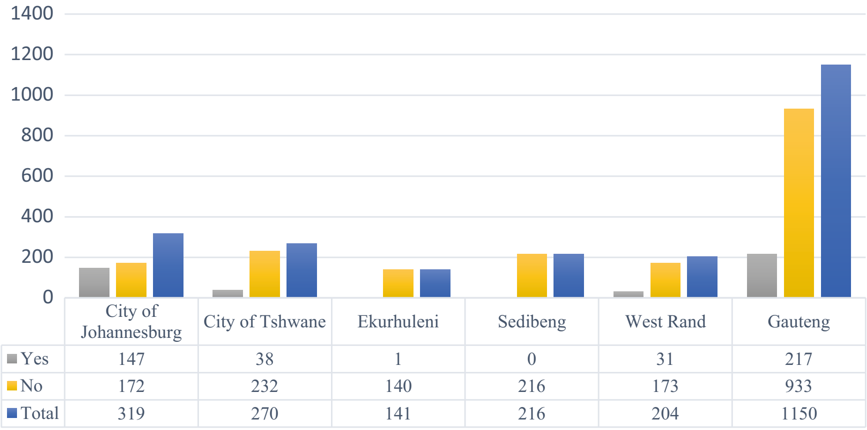


Fig. 14.13 Environmental awareness among the households

Table 14.4 Spearman Correlation coefficients among variables

	GAR[a]	GEN[b]	HOU[c]	AGE[d]	HOU1[e]
GAR	1.00	0.011**	0.040*	0.027*	0.013**
GEN		1.00	0.009	0.180	–0.19
HOU			1.00	–0.76	–0.025
AGE				1.00	0.57
HOUI					1.00

*5% Significant level; **1% Significant level
[a]Garden owned and still available
[b]Gender
[c]Household members
[d]Age
[e]Household income

Table 14.5 Univariate analysis determining gardens owned and still available ($N = 1150$)

Variables	OR and 95% CI
Household income	*1.299 [0.36–41.1]1
Access to irrigation	*1.29 [14.5–87.9]1
Garden tools	*1.07 [0.09–0.67]1
Agricultural training	*1.25 [0.20–2.79]1
Home garden initiative	*1.78 [1.15–12.7]1
Gender	0.85 [1.01–15.1]1
Age	0.70 [0.65–14.5]1
Level of education	0.997 [0.92–2.41]1
Land acquisition	0.998 [0.93–2.44]1
Household language	0.59 [1.1–16.4]1
Household expenditure	0.42 [0.3–15.1]1
Household head	0.23 [0.1–13.0]1

OR odds ratio, *95% CI* 95% confidence intervals, *1*< no association, **1*> association

initiative and available gardens (odds at 1.78) because the homestead garden initiative can only function if there are available gardens.

14.4.6 Focus Group Discussion Analysis

Focus group discussions with 57 GDARD officials responsible for the Homestead Food Gardens Programme were conducted on the 5th to 9th February 2018. The responses offered by the GDARD officials are as follows:

1. Follow-up visits are to be conducted, but the challenge of the huge number of households being supported results in only a few follow-ups and monitoring.
2. The department works very closely with community ward councillors to encourage social cohesion, but the relationship is not well sustained.
3. There is a once off three-day training session of which households complained about its contents and length, and after successful participation in the training part of the programme, starter packages are given to the participants.
4. The GDARD is already working closely with other government departments to augment other responsibilities not related to household gardening. For example, the Department of Social Development is assisting in food parcels in some districts, and the Department of Health is offering training on nutrition in some districts.
5. The Gauteng Department of Agriculture and Rural Development indicated the need for youth involvement in the homestead garden programme as any future agricultural development should be tailor made to attract the youth.
6. The department has encouraged the households to use rainwater harvesting, mulching, and the use of grey water. The department has also requested the

Agricultural Research Council to undertake grey water usage research and provide recommendations.

14.4.7 Mechanism for Improving the Sustainability of Homestead Food Gardens

There are a number of gaps in the current approach used to support homestead food gardens in the Gauteng Province. The mechanism for improving the sustainability of homestead food gardens in the Gauteng Province should include the following key activities:

14.4.7.1 Stakeholder and Communities Mobilisation

Involvement and participation of the communities and stakeholders in project design and implementation, and evaluation is very crucial for the sustainability of gardens. Having two-way channels for information exchange is instrumental for achieving sustainable, improved gardening practices. Different government departments (Education, Social Development, Health, Rural Development, Municipalities), households, councillors, NGOs, etc., should be mobilised in this regard based on research results. The mobilisation is working well in some districts/metropolitans and should be encouraged across the Gauteng Province.

14.4.7.2 Situational Analysis

It is very important to establish provincial data for soil, water, and climate as this is a prerequisite for agricultural production. Desktop natural resource audits and crop suitability maps are critical before implementation of the Homestead Garden Programme. This will enable the determination of biophysical viability of homestead food gardens in the Gauteng Province.

14.4.7.3 Food Garden Inputs

Access to the necessary inputs for gardening from a sustainable source is an important element for successful gardening. Such inputs include seeds, seedlings and saplings, a regular water supply, environmental friendly soil improvement techniques and pest control, and tools. The current starter pack approach being used by GDARD should be reviewed. It was established that some households are given tools/seeds that they do not need. As a result, households end up selling the tools or donating them. A comprehensive needs analysis should be undertaken by the department. This will ensure that funding is spent on what is needed and based on properly planned initiatives. It will improve service delivery and contribute to better suited equipment being distributed and less money being wasted.

14.4.7.4 Technical Assistance, Training, and Demonstrations

Technical support is especially important when gardening techniques are being promoted such as growing new or an increased number of varieties or year-round vegetable production. Practical training in each household garden can serve to demonstrate different varieties, or other important gardening techniques such as year-round production, etc. Most households indicated that the limited training, demonstrations, and technical assistance are not enough to enable a good understanding of agricultural production. These activities should be structured during every stage of the growing of crops such as soil preparation, managing pests and diseases, harvesting, etc. Some households complained about land size and that the department should consider and implement alternative production systems such as vertical production systems or container production in bags in those households.

14.4.7.5 Nutrition Education

Nutrition education is a very important aspect of food security. It was evident from the survey conducted that most households were falling behind in terms of nutrition education. An understanding of the cultural context and feeding practices will offer guidance on nutrition education and ensure nutrition education programmes that meet the needs of the people. It is critical for the people to understand the importance of nutrition and having balanced diets that contain all the required minerals and vitamins. Other districts/metropolitans have indicated that they are working closely with the Department of Health to address nutrition education. This practice should be encouraged across whole of the Gauteng Province.

14.4.7.6 Monitoring and Evaluation

Monitoring and evaluation are big challenges for HFG sustainability in the Gauteng Province. Most households indicated that the department officials were not visible and the officials acknowledged the concerns of the household. The GDARD officials emphasised that the number of households being supported is too many because of capacity challenges. It must be emphasised that monitoring serves as a tool for ensuring that activities are carried out as planned and to improve performance as required. Monitoring, evaluation, and follow-ups will facilitate the identification of problems and the development of solutions based on information sharing between the households and the department officials. The department should introduce a weekly/monthly/quarterly/annual monitoring tool for participating households to gather information on production, consumption, distribution of seeds/tools, training requirements, technical requirements, household list updating, etc. This mechanism will be useful for GDARD to monitor the overall progress of the HFG programme and ensure that the three legs of sustainability (economic, social, and environmental) are addressed.

14.5 Conclusion

The households in the Gauteng Province have been described to be food and nutrition insecure despite a significant drive towards addressing household food security by the GDARD. The Homestead Food Garden (HFG) programme is an important intervention with great potential to further benefit the Gauteng Province's households. The study found that the programme has some challenges. Monitoring and evaluation remain a key challenge and an investment in continued training and follow-ups with households could significantly increase the sustainability of gardens, and thus food security, health, and economic benefits of households. On the other hand, the households were benefitting in a number of ways: households were receiving seed starter packs and tools which are used to produce food, augmenting household nutritional intake, and in some cases, their income. The households and GDARD officials were well informed that the sustainability of the HFG programme can be improved by a regular water supply, environmental friendly soil improvement techniques and pest control, involvement and participation of the community in HFG programme design, implementation and evaluation (two-way channels for information exchange is instrumental for achieving sustainable, improved gardening practices), technical assistance, demonstrations and training and nutrition education within the gardening activities. Further, monitoring is critical as it serves as a tool for ensuring that activities are carried out as planned and to improve performance as required. The study offered a good perspective on how HFG should be implemented as it paved the way for the identification of problems with the programme, gaps, and the development of solutions based on information sharing between the households and the Department of Agriculture and Rural Development.

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Conflict of Interest The authors declare that they have no conflict of interest.

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15 Assessment of Potassium Nutrient Balance in Agricultural Farming System: A Pathway to Sustainable Production of Crops

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Abstract

Sustainable soil nutrient management is essential for achieving food security, ecosystem sustainability, employment generation and economic development. Soil gets nutrients in particular potassium (K) from various sources like organic and inorganic sources. In recent times, inorganic sources account for a larger share of flow and stock of nutrients in the soil and cause environmental pollution. The dynamic nutrient budget tool was used to assess the stock of soil K nutrient by the inclusion of inflow and outflow of K sources from 1990–1991 to 2012–2013. We used cross-sectional data of inorganic fertilizers, organic manure, area under various crops and their productivity. Per ha K outflow was significantly higher than per ha K inflow in most regions of the Tamil Nadu State. It resulted in negative K balance. The static model was initially included to find out net inflow, i.e. nutrient balance but empirical estimation gives a negative value which becomes unable to calculate stock of K in the same period. It infers that amount of K addition to the soil in the Tamil Nadu State was low, while the area under nutrient intensive crops had significantly increased. Hence, it is suggested that more awareness on balanced K nutrient application need to be created among the farmers and to formulate appropriate policy measure in sustainable production and distribution of K fertilizers to the farmers.

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Keywords

Potassium · Nutrient economy · Soil nutrient balance · Static model · Fertilizers · Manures · Crop output

15.1 Introduction

Soil nutrient is an important factor for sustainable agriculture and food security (Pathak 2010). The nutrient such as potassium (K) is one of the imperial factors to produce estimated crop production. K nutrient is applied to soil either excessively or below recommended level based on the capacity of farm class. When farmers are using an excess amount of K in a given area, i.e. continuous cultivation, beyond the recommended amount of K nutrient to crops resulted in an increase of pollution. Excessive nutrients application further follows the principle of diminishing marginal returns in output and this surplus is lost through leaching to water and evapotranspiration to air. This process induces eutrophication to surface waters (Kuosmanen 2014) and increases social cost. On the other hand, nutrient deficiency occurs due to continuous cropping and soil erosion. Soil erosion results in loss of nutrients. The nutrient loss is more than the expected renewable level (Henao and Baanante 1999). In addition, the price of K significantly alters farm decision to buy relatively lesser quantum compared with nitrogen and phosphorus. Therefore, both situations raise the average cost of production to farming households.

Managing a balanced amount of K nutrient in the soil is not only maximizing productivity of crops but also reduces the social cost incurred on soil conservation and environment pollution. Nutrient balance is the best tool to assess the soil nutrients balance and draw a picture of the optimal and sub-optimal position of K nutrient. This method includes nutrient outflow and nutrient inflow parameters to find out the amount of soil degradation and pollution over statically and dynamically, thereby provide a strategic solution for current and future soil sustainability management.

In Tamil Nadu, the average fertilizer consumption is 197 kg/ha. Out of the total fertilizer consumption, while nitrogenous fertilizer consumption accounts for 109 kg/ha, the phosphate fertilizer consumption is 54 kg/ha. However, potash consumption is only 34 kg/ha (Sivagnanam and Murugan 2019). Indiscriminate and irrational use of synthetic inorganic fertilizers leads to inelasticity of production and reduction of "output-fertilizers ratio". According to Kapur (2011), crop output response to chemical fertilizers has a mean of 25 kilogram (kg) of grain per kg of inorganic fertilizers during the 1960s and this was declined to 8 kg during 1990s. During 2000–2010 alone, application of chemical fertilizers has soared up to 50% (Kishore et al. 2013). The factors such as high yielding varieties, improper cultivation practices (Mujeri et al. 2012) and existing crop based nutrient management led to more outflow of K nutrient from the soil. Ultimately, these factors deteriorate agroecosystems and result in higher cost of production (Paoletti et al. 1989; Edwards and Wali 1993; Sinebo and Yirga 2002; Ram 2003). Therefore, the present study was intended to estimate the soil K balance in various regions of Tamil Nadu from 1990 to 2013 and also to estimate soil stock and removal of K per hectare in the Tamil Nadu State.

15.2 Material and Methods

15.2.1 Dynamic Nutrient Balance Accounting

Nutrient budget or balance is a support for optimizing soil nutrient stock. Addition of nutrients (flow sources) to soil has a significant effect on the determination of stock, the flow substance (source) was represented by z (lowercase) and stock substance by Z. We, initially, use static model to calculate yearly net substances, which meant residual substance deducted from inflow–outflow substances. This is estimated by using conventional material balance equation (Ayres and Kneese 1969).

$$z = a^{'}x - b^{'}y \tag{15.1}$$

In Eq. (15.1), "z is named flow balance implying the difference between the quantum of inputs and outputs in z, respectively, and, x and y denote the flow of input and output vectors, a and b are non-negative vectors" (Paramasivam et al. 2017). The vectors represent the sources of flow and its coefficient in x and y (Kuosmanen and Kuosmanen 2013; Paramasivam et al. 2017). Ebert and Welsch (2007) indicate that production process must follow the thermodynamics law, which explain that environment provides certain amount of flow services for economic improvement and contribute back the equivalent amount of resource to the environment (Paramasivam et al. 2017). The production process, therefore, is likely to adapt the management of inputs and outputs (Pethig 2006). Equation (15.1) is a linear, static model and not a dynamic model as absence of time variable and used for estimation of flow balance. Assume that once we include time variable in Eq. (15.1), then it becomes a dynamic model of material balance. Therefore, Eq. (15.1) is

$$Z_t = (1 - \delta)\, Z_{t-1} + a^{'}x_t - b^{'}y_t \tag{15.2}$$

where Z_t and Z_{t-1} represent the stock of nutrients in time periods t and $t-1$, respectively, and $\delta \in [0,1]$ is the decay rate, which varies among nutrients and regions (Kuosmanen and Kuosmanen 2013; Paramasivam et al. 2017). The decay rate for soil potassium varies based on erosion, leaching, runoff and transformation, etc.

15.2.2 Modelling Nutrient Stocks

Before proceeding to estimate nutrient stock model, it is necessary to know flow sources that form negative or positive substance. Now, dynamic nutrient Eq. (15.2) is rewritten as:

$$Z_t = (1 - \delta)\, Z_{t-1} + z_t \tag{15.3}$$

where $z_t = ax_t - by_t$ is inferred as the nutrient balance. We adopted the methodology of nutrient balance from the Organisation for Economic Co-operation and Development (OECD) and Eurostat (OECD 2007a; 2007b) for the present study, net nutrient flow z_t for period t can be written as:

$$z_t = (\alpha_1 \mathrm{FR}_t + \alpha_2 \mathrm{LM}_t + \alpha_3 \mathrm{BF}_t + \alpha_4 \mathrm{AD}_t) - (\beta_1 \mathrm{CC}_t + \beta_2 \mathrm{NCC}_t) \tag{15.4}$$

Inflow variables included in Eq. (15.4) are FR_t (fertilizer), LM_t (livestock manure), BF_t (biological fixation) and AD_t (atmospheric deposition). “Outflow consists of nutrient removals by commercial crops CC_t and non-commercial fodder crops NCC_t. $\alpha_{1\ldots}\,\alpha_4$, β_1 and β_2 are nutrient conversion factors. Net nutrient flow z_t attained from Eq. 15.4 resulted as either nutrient surplus or deficit status” (Paramasivam et al. 2017).

15.2.3 Empirical Estimation Model

Equation 15.4 infers net nutrient balance consists of inflow and outflow substance. However, the estimation process perhaps varies for different nutrients. For example, K nutrient gets inflow from limited sources, while nitrogen has more options and receives huge amounts. It, therefore, is essential to distinguish individual nutrient inflow from collective sources. Equation (15.4) can be rewritten as:

$$Z_{wt} = \sum_{i=1}^{m} (a' x_{it}) - \sum_{j=1}^{n} (b'^{y_{jt}}) \tag{15.5}$$

where w indicates N, P and K, respectively, i denotes various sources of nutrient inflow and j is outflow. Consequently, i and j are not same for all nutrients and vary among the nutrients.

15.2.4 Estimation of K Inflow from Various Sources

$$\text{K inflow (kg per year)} = K_{IN,t} + K_{LM,t} + K_{CM,t} + K_{CR,t} + K_{SB,t} + K_{RN,t} + K_{IR,t} \quad (15.6)$$

where K_{IN}, K_{LM}, K_{CM}, K_{CR}, K_{SB}, K_{RN} and K_{IR} are additions of potassium (kg per year) through fertilizers, livestock manure, compost, crop residue, rice straw burning, rain and irrigation, respectively. Murate of potash and complex fertilizers are the major sources of total K to soil (Pathak 2010; Paramasivam et al. 2017).

K inflow from livestock manure (K_{LM}) was assessed by using the equation given by Pathak (2010).

$$N_{LM,t} = \Sigma_T \left(N_T * N_{ex(T)}\right) * [1 - (LM_{FL,t} + LM_{CL,t} + LM_{CN,t})] \quad (15.7)$$

where "T implies the number of the defined livestock group as cattle, buffalo, sheep and goat; K_T is the number of livestock in each group from each district; $K_{ex(T)}$ is the annual average K excretion (kg per year) per head for each livestock group; and LM_{FL}, LM_{CL} and LM_{CN} are the fractions of livestock manure that are burnt as fuel, used for construction and lost during collection, respectively" (Paramasivam et al. 2017). "Contribution of animal urine towards K addition was not included in the study because almost all urine is lost from the cattle-shed before and during collection and negligible amount is recycled into agricultural fields. For the present study, cow, buffalo, goat and sheep manures were considered for the estimation" (Pathak 2010; Paramasivam et al. 2017). Source of data and crops for calibrating in the present analysis are given in Tables 15.1 and 15.2. It is noted that the present estimation ignored some sources of inputs such as compost, crop residue, rice straw burning, rain and irrigation due to data inadequacy in the study area.

Table 15.1 Details of selected crops

Agricultural crops			Horticultural crops	
Cereals	Pulses	Oil seeds	Fruits	Vegetables
Paddy	Green gram	Ground nut	Banana	Tomato
Sorghum	Black gram	Sesame	Mango	Ladies finger
Cumbu	Bengal gram	Coconut	Lemon	Brinjal
Ragi	Red gram	Castor	Cashew nut	Tapioca
Maize	Horse gram	Sunflower	*Spices*	Onion
Thenai	Cow pea	Soybean	Turmeric	Sweet potato
Samai	Mochai	*Fibre*	Chilly	*Drug crops*
Varagu	*Sugar crops*	Cotton	Coriander	Tobacco
	Sugarcane			Tea

Table 15.2 Details of data source

Parameter	Source
Consumption of N, P and K fertilizer in each district	Economic Appraisal of Tamil Nadu (1990–2012)
Major crop area (irrigated and unirrigated), production and productivity in each district	Season and Crop Report (1990–2012)
Livestock population	Department of Economics and Statistics (1989–2013), Economic Survey (2013–14)
Dung produced by different categories of livestock	Dikshit and Birthal (2013)
Proportion of wet dung utilized as manure	CSO, GOI (1996)
Nutrients content of manure (nitrogen, phosphorus and potash)	Ghosh et al. (2004)
Nutrient content in different crops with biological fixation	Subbaian et al. (2000)
Nutrient content in different crops	Surendran et al. (2005)

15.2.5 Estimation of Outflow of K

The principle which applied to compute inflows was used to estimate outflows of various form of losses and crop uptake method. Uptake of nutrients differs among crops and type of land. Based on available uptake coefficient (kg per year) of K, the amount of depletion was assessed by crop removals, i.e. crop yield. Leaching of K was assumed as 15% of the K input (Regmi et al. 2002).

15.2.6 Period of Study and Sources of Data

The study used both cross-sectional (districts) and time series data (1990–1991 to 2012–2013). Secondary data were collected on area, production and productivity of irrigated and unirrigated crops, major nutrient (K) supply, livestock population and climate variables. Season and Crop Reports published by Department of Economics and Statistics, Government of Tamil Nadu were the main sources for data for crops, area, production and productivity. District wise supply of fertilizers and livestock data were gathered from Economic Appraisal of Tamil Nadu and Statistical Abstract of Tamil Nadu for the above period. The collected data were compiled and analysed for composite districts. Conversion factors of nutrients for various formulations of fertilizers and nutrient sources were derived from literature previously published. The details of sources for data set and nutrient conversion factors are presented in Table 15.2.

15.3 Results and Discussion

15.3.1 Nutrient Inflow

K nutrient, in general, is accrued in the soil through different processes and sources like rainfall, erosion, inorganic fertilizers and organic manures. However, the lack of data availability and troubles were faced during calibration. This analysis excluded an inclusion of nutrients supply by the soil weathering process. Inorganic fertilizers and livestock manure were included as the major sources of K nutrients in the present analysis.

15.3.2 Per ha K Inflow

District wise rate of K inflow in a hectare is presented in Table 15.3. Per hectare K supply from inorganic fertilizers was around 33 kg in the first decade (1990–1999) and it rose up to about 45 kg in the second decade (2000–2009) in the state of Tamil Nadu. Similarly, per hectare supply of K from livestock manure also increased from 7.09 kg in the first decade to 8.95 kg in the second decade. District wise K inflow, the maximum supply of potassium from inorganic fertilizers was witnessed in Madurai, Coimbatore, Tirunelveli, Pudukkottai and Trichy at an average of 63.80, 57.87, 48.45, 47.12 and 45.89 kg/ha, respectively, in the first decade, whereas Ramnad district had less than 10 kg/ha in the same period. Nevertheless, per hectare supply of K from inorganic fertilizers was lesser in these districts in the second decade. However, the rest of the districts shows an increasing trend. Highest per hectare K inflow from livestock manure was found in Pudukkottai district followed by Tirunelveli, Trichy, Sivagangai and Tiruvannamalai in both decades. Further, Pudukkottai, Tirunelveli and Sivagangai districts marked an increased inflow of K from livestock manure more than 16 kg/ha in the second decade. The successive inflow by both the sources has presumably increased overall mean of K inflow in all the district during 1990–1991 to 2012–2013. It was noted that raise of sugarcane area in Pudukkottai district from 1686 to 9124 ha from 1990–1991 to 2012–2013 would increase the inflow rate. Perhaps, the share of supply of inorganic fertilizers in Pudukkottai district to the State was more than the share of gross cropped area, there may be chances for soil degradation. Meanwhile, increased goat population from 1.56 to 4.98 lakhs may help to improve soil fertility in the same district. Tirunelveli and Sivagangai districts are also be noted with an increased trend of goat population from 2.25 to 4.61 and 1.33 to 2.27 lakhs, respectively, during the same period. Among the various districts, Vellore, Erode, Trichy, Pudukkottai, Madurai and Tirunelveli districts registered a higher supply of K from inorganic fertilizers and livestock manure. This shows that these districts may move towards integrated use of inorganic and organic fertilizers for farming.

Table 15.3 District wise average per ha potassium inflow from 1990–1991 to 2012–2013 (kg/ha)

	1990–1999		2000–2009		1990–2012	
Districts	Fertilizers	Livestock	Fertilizers	Livestock	Fertilizers	Livestock
Kanchipuram	30.89	8.16	58.04	12.61	43.18	11.50
Cuddalore	31.31	7.08	43.59	7.80	38.10	7.44
Vellore	40.44	8.26	49.55	10.05	45.27	9.40
Tiruvannamalai	20.81	8.45	38.15	9.23	31.80	9.09
Salem	24.99	6.91	52.76	10.62	39.79	9.01
Dharmapuri	11.81	5.47	14.72	7.26	14.47	6.16
Coimbatore	57.87	4.68	67.69	4.66	61.63	4.59
Erode	36.33	7.55	57.38	11.67	53.37	10.95
Trichy	45.89	8.91	67.62	10.18	58.31	9.88
Pudukkottai	47.12	11.96	70.46	15.79	56.67	15.63
Thanjavur	34.90	5.88	36.33	6.36	35.11	6.18
Madurai	63.80	6.38	68.89	9.09	65.71	8.56
Dindigul	21.84	6.01	30.40	7.31	27.47	6.78
Ramnad	9.58	5.95	6.26	6.83	7.90	6.73
Virudhunagar	25.38	8.05	23.30	9.31	24.53	9.06
Sivagangai	17.72	8.85	18.89	15.65	18.90	13.32
Tirunelveli	48.45	10.09	65.06	15.92	55.71	15.04
Thoothukudi	14.32	7.24	14.02	9.42	15.05	8.76
Kanyakumari	39.26	3.28	48.65	4.21	44.20	3.94
Tamil Nadu	33.02	7.09	45.02	8.95	39.54	8.36

15.3.3 Measurement of K Outflow

The stock of K in the soil is based on different factors like leasing, crop uptake, erosion, volatilization, denitrification, etc. The present study considered nutrient losses through crop uptake only. For example, removal of nutrients by different crops can be estimated with the help of corresponding nutrient conversion factors in each year from 1990–1991 to 2012–2013. Further crop uptake was estimated in the irrigated and unirrigated area separately.

15.3.4 Per Hectare Potassium Uptake

The district wise average per hectare uptake of K in Tamil Nadu is presented in Table 15.4. Higher amounts of K depletion were observed in Erode (96.54 kg), Cuddalore (89.17 kg), Madurai (74.63 kg) and Vellore (73.65 kg) districts in the first decade (1990–1999), while rest of the districts accounted for less than 70 kg/ha in the same period. Specifically, Ramnad district consumed only a tiny amount (9.48 kg). In the second decade, all the districts showed an increased amount of K depletion.

Cuddalore district registered a larger amount of K depletion at 151.60 kg/kg under irrigated regions followed by Trichy, Erode, Thoothukudi and Salem districts during 1990–1999. In contrast, Ramnad district was found to be the least consumer of per ha K in the same period. During 2000–2009, per hectare uptake of K was increased in most of the districts except in Coimbatore, Thanjavur and Trichy. Since only nitrogen intensive crops like paddy are cultivated predominantly in Thanjavur and Trichy districts, K uptake was less in these districts compared to other districts.

In unirrigated regions, K removal by crops was found to be highest in Erode (7.42 kg) followed by Tiruvannamalai, Kanchipuram, Vellore and Salem districts. Thoothukudi and Kanyakumari districts depleted only scanty amount of K. In the second decade, Erode and Tiruvannamalai districts consumed at the rate of 7.53 and 7.48 kg/ha, respectively, whereas Madurai and Coimbatore depleted small amounts of 4.51 and 4.91 kg/ha, respectively. Higher uptake of K in unirrigated area of Erode and Tiruvannamalai district was associated with groundnut productions.

Per ha uptake of K was higher in Erode district. It is owing to the increasing area under turmeric, sugarcane and banana in irrigated conditions from 0.03 to 0.22 lakh ha, 0.15 to 0.31 lakh ha and 0.03 to 0.12 lakh ha, respectively, from 1990–1991 to 2012–2013. The data have been taken from the season and crop reports of Government of Tamil Nadu between 1990 and 2012. Trichy, Salem, Dharmapuri and Ramnad districts consumed the maximum amount of K under the unirrigated area. The statement explains that the State (Tamil Nadu) has surplus amount of K nutrient in soil. If the current practice of cropping pattern and fertilizer application (applying more of N and P) continues then surplus amount of K in soil likely to decline in the near future. Economic reforms of liberalization supporting the growth of export-oriented crops, adoption of high yielding varieties (HYV) and hybrid seeds are few factors to increase K uptake. Most importantly, the practices of K applications to soil still depend upon crop based instead of soil based nutrient recommendations. These

Table 15.4 Average per ha potassium uptake during 1990–1991 to 2012–2013 (kg/ha)

	Irrigated area			Unirrigated area			Total		
District	1990–1999	2000–2009	1990–2012	1990–1999	2000–2009	1990–2012	1990–1999	2000–2009	1990–2012
Kanchipuram	61.07	62.97	62.70	6.91	6.18	6.46	53.07	56.17	55.55
Cuddalore	151.60	191.96	176.96	4.89	5.04	4.96	89.17	127.48	113.32
Vellore	137.55	140.55	139.14	6.40	6.21	6.27	73.65	75.00	74.63
Tiruvannamalai	92.91	110.03	110.94	7.31	7.48	7.40	57.20	77.80	76.70
Salem	130.01	190.11	162.36	6.09	6.14	6.07	56.87	98.40	81.10
Dharmapuri	110.13	137.53	125.69	5.49	5.23	5.32	34.41	46.44	42.17
Coimbatore	83.64	82.72	82.40	5.18	4.91	5.07	42.83	49.28	47.32
Erode	148.45	263.68	205.24	7.42	7.53	7.48	96.54	179.50	140.40
Trichy	149.33	144.91	149.26	4.47	4.50	4.45	60.92	68.82	67.08
Pudukkottai	53.32	98.49	78.41	6.91	6.86	6.82	33.68	69.70	54.78
Thanjavur	50.49	48.51	48.84	5.10	4.97	5.02	38.23	35.83	36.66
Madurai	117.22	122.92	123.18	4.95	4.55	4.72	74.63	76.62	77.88
Dindigul	82.14	84.77	83.39	5.01	4.99	5.03	35.84	40.32	39.22
Ramnad	15.09	17.71	17.07	6.10	6.13	6.11	9.48	10.64	10.31
Virudhunagar	72.90	72.64	72.61	4.28	4.44	4.36	31.87	36.84	34.51
Sivagangai	57.21	58.94	60.02	6.60	6.33	6.45	41.01	44.42	44.59
Tirunelveli	68.12	82.39	75.56	4.70	4.87	4.77	52.92	62.63	58.10
Thoothukudi	131.02	196.80	170.17	3.66	3.87	3.81	40.37	56.63	48.57
Kanyakumari	68.68	104.98	88.12	4.78	4.74	4.75	43.55	62.17	54.17
Tamil Nadu	96.01	115.61	107.63	5.44	5.31	5.34	53.85	68.75	63.20

Table 15.5 Average K balance in kg per ha

Districts	1990–1999	2000–2009	1990–2012	Rank 1990–2012
Kanchipuram	−14.02	14.48	−0.88	7
Cuddalore	−50.77	−76.10	−67.79	18
Vellore	−24.96	−15.40	−19.96	13
Tiruvannamalai	−27.94	−30.42	−35.81	17
Salem	−24.97	−35.02	−32.30	16
Dharmapuri	−17.12	−24.46	−21.53	14
Coimbatore	19.73	23.06	18.89	1
Erode	−52.67	−110.45	−76.08	19
Trichy	−6.13	8.98	1.11	6
Pudukkottai	25.40	16.55	17.52	2
Thanjavur	2.56	6.86	4.63	4
Madurai	−4.45	1.36	−3.60	9
Dindigul	−7.98	−2.60	−4.98	10
Ramnad	6.06	2.46	4.32	5
Virudhunagar	1.56	−4.22	−0.92	8
Sivagangai	−14.44	−9.87	−12.37	12
Tirunelveli	5.63	18.35	12.64	3
Thoothukudi	−18.81	−33.20	−24.76	15
Kanyakumari	−1.01	−9.30	−6.03	11
State	−13.74	−14.78	−15.30	

factors are supposed to increase the depletion of K nutrients and create negative externalities.

15.3.5 Status of K Balance

Table 15.5 shows the district level K balance, which was assessed by material balance approach. Based on the amount of nutrient balance,[1] the districts are ranked. As regard the ranking of each district based on the nutrient balance, the district having the highest positive nutrient balance is assigned the first rank and other districts are ranked consequently. Further, the district with the highest negative balance which indicates the highest level of depletion of soil nutrients is ranked least. The positive nutrient balance, in effect, reveals the availability of soil nutrient after the removal of nutrients through crop uptake. On the other hand, the negative nutrient balance indicates the "excessive depletion of soil nutrients". Hence the ranking of districts based on the nutrient balance aids to decipher the nutrient status at the district level (Paramasivam et al. 2017). The assigned ranking is presented in Table 15.5. K balance was high in Coimbatore (18.89 kg/ha) followed by

[1]Nutrient balance arrived as nutrient inflow minus nutrient outflow

Pudukkottai (17.52 kg/ha), Tirunelveli (17.52 kg/ha), Thanjavur (4.63 kg/ha), Ramnad (4.32 kg/ha) and Trichy (1.11 kg/ha). The negative balance was observed in rest of the districts. The reason attributed to the negative balance of K was lesser usage of K fertilizer. It leads to the mining of soil K (Naidu et al. 2011). Surendran et al. (2005) also found a negative K balance in his nutrient budget study.

The reason behind the negative balance of K may be a mismatch between the application of inorganic fertilizers and continuous cropping. For instance, in the Dharmapuri district, the cultivation of vegetable and flower crops have depleted the potassium nutrient content in the soil, resulting in negative nutrient balance. Further, since the 1990s, replenishment of potassium through inorganic fertilizer was also less. In the case of Thoothukudi, the cultivation of nutrient depleting crops like sugarcane is attributed to negative potassium nutrient balance in the soil.

15.4 Conclusion

The practices of K inflow and outflow in the Tamil Nadu State over the years fluctuated and the amount of K outflow was higher than K inflow. The stock of K level slowly declined as the addition of K was lesser in most of the regions. The negative balance of K was registered in three-fourth districts of the Tamil Nadu State. Economic reforms of liberalization supporting the cultivation of export-oriented crops, adoption of high yielding varieties (HYV) and hybrid seeds are few factors responsible for the depletion of K. Most importantly, the practice of K applications to soil still depend upon crop based instead of soil based nutrient recommendations. These factors may increase the depletion of K nutrient and create negative externalities. It is suggested that the current practices of K application need to be adjusted according to soil status and type of crops; the timely inorganic fertilizers applications must be based on the requirement; adopting diversified cropping pattern and application of organic manures are the remedial measures to improve soil nutrient status and ensure the sustainability of agricultural bioeconomy.

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