Emerging Frontiers of Microbes as Agro-Waste Recycler

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Shalini Rai, Manoj Kumar Solanki, Ajit Kumar Dubedi Anal, Alka Sagar, Anjali Chandrol Solanki, Brijendra Kumar Kashyap, and Akhilesh Kumar Pandey

Abstract

Sustainable agriculture and environmental protection have the foremost importance in the welfare of human being. Annually, agro-wastes are generated at the millions of tonnes scale worldwide that must be degraded in terms of valuable products as well as the concept of sustainable agriculture can also be implemented through the bioconversion of agro residue into other resources without harming and depleting the natural ecosystem. Microbes are a crucial player for the conversion of agro-waste into valuable products, extraction of minerals, enhancement of agriculture, and agro-waste management. So the use of microorganisms with different biotechnological approaches is the most effective method to treat different wastes, in addition to being eco-friendly, cost-effective, and

S. Rai
Society of Higher Education and Practical Application, Varanasi, Uttar Pradesh, India

M. K. Solanki (✉)
Department of Food Quality & Safety, Institute for Post-harvest and Food Sciences, The Volcani Center, Agricultural Research Organization, Rishon LeZion, Israel

A. K. D. Anal
ICAR-National Research Center on Litchi, Muzaffarpur, Bihar, India

A. Sagar · A. C. Solanki
Department of Microbiology and Biotechnology, Meerut Institute of Engineering and Technology, Meerut, Uttar Pradesh, India

B. K. Kashyap
Department of Biotechnology Engineering, Institute of Engineering and Technology, Bundelkhand University, Jhansi, Uttar Pradesh, India

A. K. Pandey
Department of Biological Sciences, Rani Durgavati Vishwavidyalaya, Jabalpur, Madhya Pradesh, India

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environmentally sustainable method. Ultimately, in this way to a meaningful and significant extent, the present chapter can bridge the gap between the adoption of microbial bioconversion technologies for valuable product formation and recycling of agro-waste into wealth, considering innovative and potentially economical approach towards sustainable agriculture as well as the eco-friendly environment.

Keywords

Agro-waste · Microbes · Sustainable agriculture · Bioconversion

1.1 Introduction

Sustainable agriculture has emerged to be the central theme for researchers, scientist, and farmers due to excessive demand for food commodities to the fulfillment world population. In this regards, agricultural production has pressurized to the use of high-yield varieties which were contributed for the vast amount production of agricultural-based residues every year. A report of Belewu and Babalola (2009) were estimated the production of wheat straw and rice straws residues approximately 709.2 and 673.3 million metric tons, respectively. Recently, Sadh et al. (2018) reported that the total production of agro-waste fiber sources is approximately found 147.2 million metric tons in all over the world, which comprises crop residues and processed agricultural wastes. Thus, the accumulation of these agro-wastes causes a severe disposal problem (Sud et al. 2008; Leow et al. 2018). Improper disposal of these agricultural residues has raised several problems concerned with the soil fertility, soil agroecology, environmental pollution, and harmful effect on plant and animal health (Rodríguez-Couto 2008). Several researchers reported that the disposal of untreated agro-waste are treated by dumping, burning or unplanned landfilling (Bhuvaneshwari et al. 2019). Untreated agro-waste has led to a severe deleterious polluting impact on soil fertility, shifting of beneficial microbial communities, emission of greenhouse gases, air pollution, subsequent soil erosion, and climate change (Singh and Nain 2014; Bos and Hamelinck 2014). Indiscriminate and untreated agro-waste disposal have altered agricultural land and created physical, chemical, and biological deterioration of cultivable soil.

The composition of agro-wastes classified into two principal constituents, insoluble chemical constituents (e.g., cellulose, hemicellulose and lignin) and soluble constituents (e.g., sugar, amino acids, and organic acids). Some other reported constituents are fats, oil waxes, resins, pigment, protein, and mineral. However, due to high nutritional composition, these agro-wastes are considered as the primary source for other valuable product formation and developments. Therefore, agro-wastes are the cheapest source that can be used by microbes for growth and produce valuable products through bioconversion and fermentation process. Thus, researchers have been searching for naturally occurring technologies for enhancement of agriculture and management of agro-waste into valuable products through natural microbial conversion. Hence the recycling of these wastes is not only an ecological necessity but also an economic compulsion in the welfare of humanity.

Microorganisms are widely distributed in the biosphere because of their metabolic ability and nutritional versatility to utilize different substrates to grow in a wide range of environmental conditions. The metabolic activity and biosynthetic capability of certain microorganisms to modify, convert, and utilize agro-waste in order to obtain energy and biomass production give new insight towards microbes based natural bioconversion. In this order, wide ranges of microbial communities are bacteria, archaea, and fungi reported as prime natural bio-converter. The unique nature of microorganisms has been used to advance food processing and safety, food quality improvement, ecological restoration, environmental protection, high-yield crop production, and biotechnology-based bioconversion into valuable products. The application of agro-waste bioconversion through biotechnological process shows immense attention towards involving microorganisms for solving the dangers of many pollutants and advancing for the production of valuable products (Nguyen et al. 2010). In concern of development of effective, low-cost technologies for efficient bioconversion of agro-waste, the biotechnological process is the new thrust of research in concern of soil health, ecological, and environmental restoration and improvising plant nutrition through recycling of residues.

In order of successive bioconversion of agro-waste through different microbes mediated biotechnological processes utilized these as raw material for the production of value-added products such as amino acids, enzymes, organic acids, biofuel, single-cell protein (SCP) animal feed, edible mushroom, bioactive secondary metabolites, nanomaterial and biofertilizers. With the advent of biotechnological innovation, many new opportunities have opened for utilization of agro-waste with minimizing the threats of environmental pollution and animal hazards. This chapter covered the review on the significance of microbe-mediated agro-waste bioconversion and biotechnological approaches for valuable product formation and ecological recycling. The aim of this chapter is to express the current trend the application/role of microorganisms on agro-waste bioconversion or/fermentation into valuable and harmless products. The usefulness of microbe based biotechnological process in producing valuable products has also been summarized with specific examples.

Microorganisms are inhabiting the soil and the surfaces of all living things inside and outside which have the potentiality in biodegradation, bioleaching, bio-composting, nitrogen fixation, improving soil fertility and as well in the production of plant growth hormones. Bioconversion, more specifically composting of agricultural residues refers to step-wise bio-decomposition procedures carried out due to the intervention of different microbial communities under aerobic conditions (Pan et al. 2012). The end product of the aerobic composting yields stabilized organic product, which is beneficial for plant growth and development. Efforts on microbial intervention for better decomposition gained strength from the identification and characterization of such microbial communities from the agricultural soils, composts, vermicompost and humus-rich sites, that prominently catalyzed biodegradation and decomposition (Eida et al. 2012). Scaling-up of bioconversion processes and large-scale production technologies using microbial inoculants have resulted in producing mass-scale composted material that may be bio-augmented with beneficial microorganisms or fortified with organic inputs, bio-inoculants, and vermicompost (Singh and Sharma 2002; Nair and Okamitsu 2012; Malusá et al. 2012). Composted products were reported to act as soil conditioners in low-cost crop production practices for resource-poor farming communities (Gajalakshmi and Abbasi 2008).

1.2 Agro-Waste

Agro-waste is a considerable term that comprises complex materials such as straws and stems of cereal grains (rice, wheat, barley, and corn), legume waste, bagasse, husks, cobs, fruit peels, and any part of a processed plant source (Yazid et al. 2017). Due to extensive agricultural activities, the global production of agriculture residues in a year is approximately 998 million tons, while 500 million tons, alone reported in India (Loow et al. 2015; Bhuvaneshwari et al. 2019). Agro-waste is produced from various post-harvest agriculture activities. The chemical composition of agriculture residues is comprised of lignocellulosic materials and polyphenolic compounds that required complex processes for bioconversion (Sannik et al. 2013). Agro-waste is broadly classified into two different types of wastes, i.e., agriculture residues and processed agriculture residues (Fig. 1.1).

1.2.1 Agricultural Residues

Agriculture residues are usually produced through farming activities and post-crop harvesting. These residues consist of leaves, stems, plant stalks, hulls, seedpods, vegetable matter, mushroom bedding, molasses, husks, bagasse, seeds, straw, shell, pulp, stubble, peel, roots, that is often useless and will be discarded without proper disposal. In addition to this, various other crops like rice, lentils, maize, chickpeas, fruits, and vegetables are also produced all over the world. A tremendous amount of agriculture residues can be utilized as animal feed, soil improvement, fertilizers, manufacturing, and various other processes.

1.2.2 Processed Agricultural Residues

Processed agricultural residues can be defined as the generation of residues after the crop is processed into a valuable alternate resource. India is the second-largest cereals, fruits, and vegetables producer, while approximately 20% of the production is going waste every year (Rudra et al. 2015). A huge amount of processed agriculture residues are produced every year through the processing industries like juice, beverages, chips, confectionery, fruit, and oil industries. These residues can be utilized for different energy sources. The compositions of process agriculture wastes

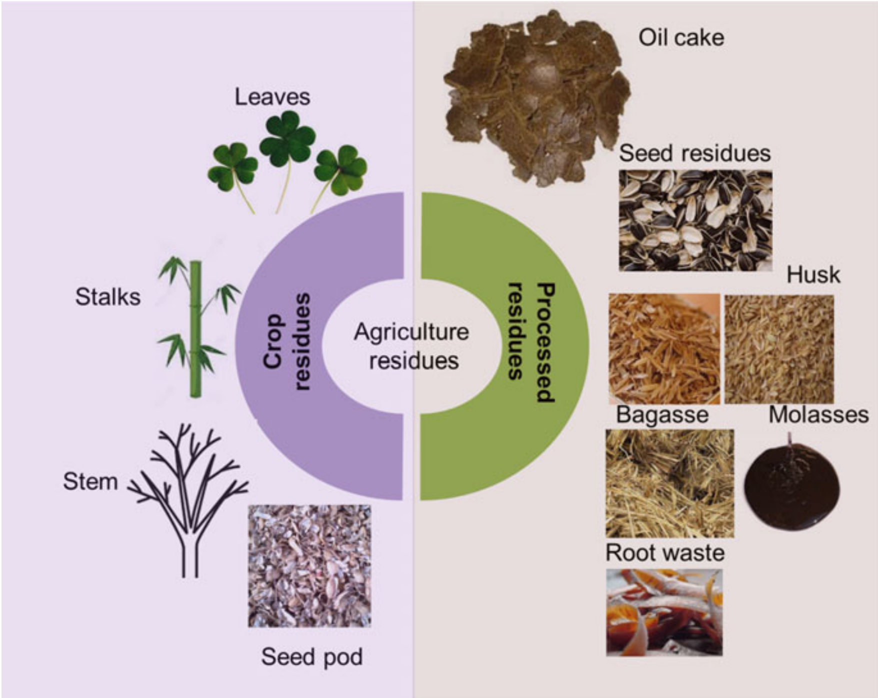

Fig. 1.1 Different kinds of agriculture residues

comprise cellulose, hemicellulose, lignin, moisture, ash, carbon, nitrogen, while bioconversion of these constituents has potential to produce useful products like biogas, bioethanol, biofertilizers, biodiesels, enzymes, and other commercially useful products that reduce the cost of production. One of the potential sources of processed residues is oil industries, produces through the process of oil extraction from seeds (known as oil cakes). The presence of substrate defines the types of oil cakes like canola oil cake, coconut oil cake, cottonseed cake, groundnut oil cake, mustard oil cake, palm kernel cake, sesame oil cake, sunflower oil cake, soybean cake, olive oil cake, and rapeseed cake (Ramachandran et al. 2007). These processed residues are relatively cheap, containing a high amount of constituents that have an unlimited prospective to be consumed as alternative substrates for fermentation.

1.3 Microbes and Agro-Waste Bioconversion/Role of Microorganism in Bioconversion of Agro-Waste

Microorganisms are the key player in the recycling of agricultural wastes (Fig. 1.2). The exceptionality of microorganisms and their biodegrading quality have made them potential candidates for decomposing agricultural residues into valuable products (Kumar and Sai Gopal 2015). Recent reports also indicate multifarious

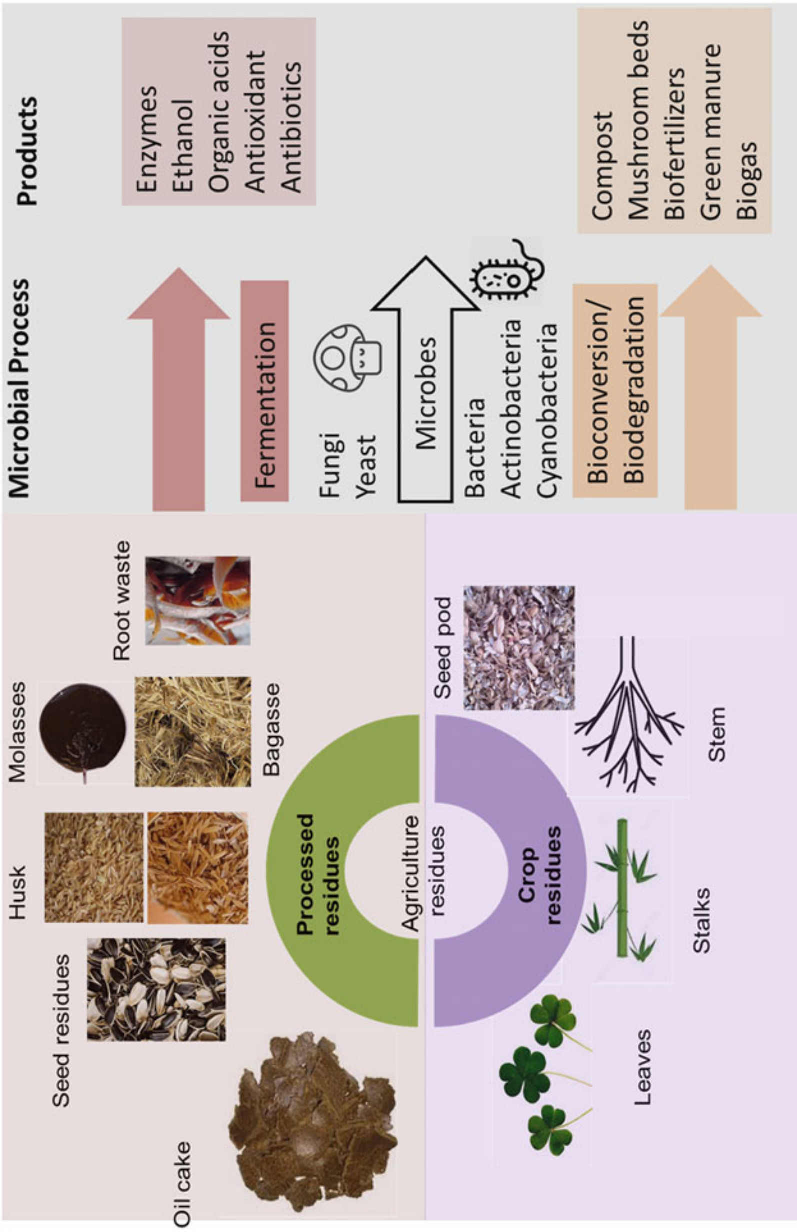

Fig. 1.2 Role of microbes in waste recycling

uses of microorganisms as a modern technique to provide an efficient way to advance human and animal health, food processing, food safety and quality, environmental protection, crop production and production of value-added products. There is a definite need to intensify research on effective microorganisms that convert agriculture waste into high-quality, valuable products in a relatively shorter duration and agricultural biotechnology has made alternatives for large-scale production.

Second most abundant plant material is lignocellulose that is composed of polysaccharides like cellulose, hemicellulose, and lignin which represents the major structural component of agricultural crop residues (Pothiraj et al. 2006; Singh and Nain 2014). Various agricultural residues that contain up to 20–30% lignin–hemicellulose–have potential biotechnological values, and their bioconversion and/or fermentation to yield industrially important constituents including biofuels, biofertilizers, biogas, enzymes, and organic acids (Sorek et al. 2014). The synergistic action microorganisms, viz. bacteria, fungi, and mycorrhiza, are immensely involved in bioconversion of complex lignocellulosic wastes into smaller molecules through the action of microbial enzymes such as cellulases, glucanases, hemicellulases, glycosidase hydrolases, polysaccharide lyases, and carbohydrate esterases (Himmel et al. 2010) which is utilized in the production of value-added products such as chemicals, fuel, textile, paper, and agricultural inputs (Pothiraj et al. 2006). There have been several reports on the isolation and characterization of potential microbial communities (bacteria, actinomycetes, yeast, fungi, and mycorrhizal fungi) that can significantly convert agro-waste and perform functionally better in combination with other organisms for the production of valuable products through different biotechnological approaches (Chandra et al. 2012; Yildirim et al. 2015; Vishan et al. 2017; Ribeiro et al. 2017).

Microbial communities have emerged to decompose the discarded agro-waste and maintained the nutrient pool in the soils, which mobilized into the plants and microbial biomass (Miki et al. 2010; Sadh et al. 2018). It further regulates the cycling of nutrients into the soils. To maintain the nutrient pool in the soil, composting is another way of biological degradation and stabilization of organic agro residues with several benefits such as enhanced soil fertility and soil health which can lead to increased agricultural productivity, improved soil biodiversity, reduced ecological risks, and a healthier environment. These advantages make composting an ideal option for processing of the enormous quantities of agro residues through a natural succession of microflora. Several fungi like *Trichoderma harzianum, Pleurotus ostreatus*, *Polyporus ostriformis,* and *Phanerochaete chrysosporium* are known to play an essential role in composting of lignocellulosic materials. A series of microorganisms and their metabolic actions that help in fast decomposition, biodegradation, and bioconversion of agro residues into valuable products are listed in Table 1.1.

Table 1.1 List of major studies illustrating effect of microorganisms in bioconversion activity of agro-waste

Microorganisms	Agro-waste nature	Mode of bioconversion	Impact	Reference
Bacteria and actinomycetes				
Pseudomonas putida	Agro-waste	Manganese peroxydases and laccase	High potential for degradation of xenobiotic compounds	Ahmad et al. (2010)
Geobacillus strains	Vegetable waste	Ligninolytic enzymes	Boost the total bacterial count to enhance bioconversion process	Pal et al. (2010)
Pseudomonas aeruginosa	Agro-waste	Manganese peroxidases, lipid peroxidase, and laccase	Enhance agro-waste bioconversion and the synthesis of monomer for other product formation	Bholay et al. (2012)
Serratia marcescens	Agro-waste	Manganese peroxidases, lipid peroxidase, and laccase	Degradation of agro-waste into organic material rich compost	Chandra et al. (2012)
Mono and co-cultures of *Bacillus subtilis* and *P. ostreatus*	Apple and plum wastes mixed with cereal wastes	Cellulase	Effective degradation of agro-waste and minimize pollutant effect	Petre et al. (2014)
Citrobacter freundii	Combination of agro-waste and saw dust	Manganese peroxidases, lignin degradation	Degradation of lignocellulytic waste and enhance rate of bioremediation	Ali et al. (2017)
B. cereus, B. megaterium	Organic substrate	Cellulase	Breakdown of cellulose and hemicelluloses in simplest sugar	Ribeiro et al. (2017)
Pseudomonas fragi, P. simiae, Clostridium vincentii, P. jessenii, and Iodobacter fluviatilis	Food waste and maize straw	Cellulase, manganese peroxidases, laccase, and xylanase	Contributed to enhanced composting process with mixed culture at low temperature	
Enterobacter spp	Sugarcane trash, grass powder, sorghum husk, wheat straw,	Cellulase and xylanase	Contributed to enhanced conversion of biomass into enzyme production	Waghmare et al. (2018)

(continued)

Table 1.1 (continued)

Microorganisms	Agro-waste nature	Mode of bioconversion	Impact	Reference
	and water hyacinth			
Actinomycetes strain	Domestic agro-waste	Cellulase, manganese peroxidases, laccase, and xylanase	Contributed to enhanced conversion of biomass into compost formation	Limaye et al. (2017)
Streptomycetes sp	Saw dust and coffee residue	Cellulase	Contributed to enhanced composting process	Eida et al. (2012)
Fungi				
Aspergillus awamori	Agro-wastes	Action of Cellulases	Degradation of cellulose and hemicellulose-containing biomass	Pleissner et al. (2013)
Phanerochaete chrysosporium	Wood shavings, agro-wastes	Lignin peroxydases, glyoxal oxidase, manganese peroxydases enzyme activity	Increased degradation of lignin and phenolics, minimizes risk of composting of lead contaminated agricultural waste	Zhang et al. (2013)
Pleurotus eryngii	Agricultural wastes	Lignocellulose degradation through laccase enzyme activity	Bioconversion and degradation of phenolics	Yildirim et al. (2015)
Pestalotiopsis sp	Forest litter mixed with agro-waste	Cellulases and laccases	Degradation of cellulose and lignocellulosic biomass and enzyme production for bioremediation	
Trichoderma harzianum, T. Koningii	Oil palm empty fruit bunches	Hemicellulose degradation	Pre-decomposition of organic matter for production of compost	Saud et al. (2013)
Marasmius sp	Agricultural wastes	Laccase	Bioconversion of lignocellulosic biomass and enzyme production for bioremediation of azo dyes	Vantamuri and Kaliwal (2016)

1.3.1 Bacterial Bioconversion

The role of bacterial community as bioconversion agents is essential due to their fast ability to convert cellulosic and lignocellulosic wastes into organic materials. Cellulose-degrading bacterial community is ubiquitous that hasten the biodegradation of crop residues such as straw, leaves, trash, etc., that ultimately solubilize and modify into the nonhazardous and valuable products in human welfare. Successful bioconversion of organic matter by the addition of bacteria had been reported earlier for many agro residues, including rice bran, wheat bran, maize straw, paddy straw, black gram husk, vegetable waste, apple, plum wastes mixed with cereal wastes, and sawdust (Faisal et al. 2014; Kaur et al. 2015; Oliveira et al. 2017; Singh et al. 2019). Recent findings concerning cellulose-degrading bacteria include the *Bacillus cereus, B. megaterium*, *Amycolatopsis mediterranean, Xanthomonas campestris, Pseudomonas* spp., and *Serratia marcescens* able to degrade lignocellulosic material with the action of bacterial enzymes, such as cellulase, xylanase, laccase, manganese peroxidases, and lipid peroxidase (Vastrad and Neelagund 2011a, b; Vidhyalakshmi et al. 2012; Chandra et al. 2012; Faisal et al. 2014; Sadh et al. 2018).

1.3.2 Fungal and Mycorrhizal Bioconversion

Fungi are eukaryotic, saprophytic, aerobic microorganisms which include unicellular (yeasts) to mycelial (molds). Fungal communities have emerged to influence agro-waste decomposability and maintain the nutrient pool in the soils. Fungi are considered as the most efficient bio-degrader of natural polymeric compounds of agro-waste with the help of extracellular multienzyme complexes and eliminate the hazardous wastes from the environment. Similarly, mycorrhiza is an association between a fungus and roots of a vascular plant that can degrade complicated organic matter of agro-waste, induce nutrient mineralization and maintain the nutrient pool in the soils.

Various fungal communities were reported as fast decomposers, bio-degraders, and bio-converters of non-useful products (Gautam et al. 2012). Fungal communities are saprophytic and develop fast in the straw residue due to the presence of well-equipped enzymatic machinery and metabolic pathways that help to degrade agro residues (Ma et al. 2013). Their hyphal system provides a mechanical assistant to colonize and penetrate substrates rapidly that helps in transporting and redistribution of nutrients within their biomass. Several fungi like *Aspergillus niger*, *A. awamori*, *Trichoderma harzianum, T. reesei, Penicillium brasilianum, Pleurotus ostreatus, P. eryngii, Polyporus ostriformis,* and *Phanerochaete chrysosporium* are known to play an important role in biodegradation/bioconversion of lignocellulosic materials through production of several enzymes, viz., cellulases, xylanases, lignin peroxidases, glyoxal oxidase, manganese peroxidases, laccase, glucosidase, and esterase (Jorgensen et al. 2003; Romero et al. 2007; Pleissner et al. 2013; Zhang et al. 2013; Yildirim et al. 2015; Mahalakshmi and Jayalakshmi 2016). Several researchers reported various fungal genera, namely, *Pleurotus fabellatus*, *Trametes versicolor,* and *Phanerochaete chrysosporium* were proved to be the potential organisms for enhanced decomposition and degradation when applied on a different combination of agricultural residues (Rice straw, sisal leaves, sugarcane bagasse, and woody shavings) (Cabuk et al. 2006; Mshandete and Cuf 2008; Huang et al. 2009). Potential microorganisms with impressive enzymatic capabilities for fast degradation/bioconversion/fermentation of rich lignocellulosic material and their impact on the environment are discussed (Table 1.1).

1.4 Factor Affecting Microbial Agro-Waste Conversion

Bioconversion process is the sequential degradation, immobilization, and/or detoxification of various agro-wastes comprising high lignocellulosic material from the environment through the action of bacteria, fungi, invertebrates, and plants. The efficiency of bioconversion depends on many factors; including, the biochemical nature and concentration of organic content in agro-waste, physicochemical characteristics of the environment, and their availability to microorganisms (Abatenh et al. 2017; Singh et al. 2019). The bioconversion processes is a complex system due to many factors, such as a microbial population capable of degrading the agro-waste, the availability of nutrient of agro-waste to the microbial population and environment factors (types of soil, temperature, pH, the presence of oxygen or other electron acceptors, and nutrients). The metabolic characteristics of the microorganisms and physicochemical properties of the different agro-wastes determine possible interaction during the bioconversion process. Microorganism growth, activity and kinetics of degradation are affected by soil structure, solubility in water, and availability of nutrients, pH, temperature, moisture, redox potential, and oxygen content.

To survive and continue their microbial activities microorganisms need a number of nutrients such as carbon, nitrogen, and phosphorous that channelize the nutrient balance for microbial growth and reproduction as well as increasing the biodegradation rate and effectiveness of agro-waste. Other most important determining physical factors for the survival of microorganisms and degradation of constituents of the agro-waste are temperature. The microbial physiological properties fluctuate due to change in temperature. As a result, temperature influence the bioconversion process either speed up or slow down. Microbial enzymes have participated in the degradation pathway that is maximum at optimum temperature and will not have the same metabolic turnover for every temperature.

Moreover, the degradation process for the specific composition of agro-waste needs specific temperature. Among the physical factors, pH is the most important one to determining the survival of microorganisms and nature of the agro-waste which may be acidic, basic, and alkaline that can be converted into the valuable product through microbial metabolic. Higher or lower pH values showed inferior results, while metabolic processes are optimum at the correct pH. Microorganisms require adequate water to accomplish their growth, so moisture content has a significant effect on the bioconversion of agro-waste. The concentration of oxygen is another decisive factor for microbial growth as well as bioconversion of agro-waste. The requirement of oxygen is different for different organisms (aerobic, anaerobic, facultative, and obligate aerobic or anaerobic) which facilitate the bio-conversion rate in a better way. Microbial degradation is carried out in aerobic and anaerobic condition through degradation, bioconversion, and fermentation process because oxygen is a gaseous requirement for most living organisms.

1.5 Biotechnological Approaches of Microbial Bioconversion of Agro-Waste

The application of biotechnological approaches in the production of different bio-products has been widely reported including enzymes, organic acids, biofertilizers, biopesticides, biosurfactants, bioethanol, aroma compounds, animal feed, pigments, vitamins, and antibiotics (Tsouko et al. 2017). A variety of microorganisms are used for the production of these valuable products through bioconversion/fermentation processes. These biotechnological approaches have opened a new model of bioconversion of agro-wastes through the production of biologically active metabolites both at the lab and industrial scale. Therefore, biotechnological approaches and their technologies for the formation of value-added products by bioconversion/fermentation process are reviewed and listed in Table 1.2.

The production of different valuable products depends upon the basic composition of agro-waste. The variety of processed agro-waste such as coconut husks, corn cobs, candelilla stalks, oil cakes, fruit peel waste, Rice bran, wheat bran, black gram bran, soybean, and sugarcane bagasse were used by several researchers for the production valuable enzymes (Buenrostro et al. 2013; Mehta and Duhan 2014; Saharan et al. 2017). The variable composition of agro-waste supports the growth of microorganisms and through fermentation different valuable enzymes such as amylase (Duhan et al. 2013; Kumar et al. 2013), glucoamylase (Suganthi et al. 2011), invertase (Mehta and Duhan 2014), cellulase, lipase (Oliveira et al. 2017), xylanase, Pectin methylesterase (Gayen and Ghosh 2011), and β-glucosidase (Sadh et al. 2017). Several researchers reported enormous bacterial, viz., *Bacillus* sp. (Sodhi et al. 2005), *Pseudomonas aeruginosa* (Dharmendra 2012), and fungal, viz., *Aspergillus niger* (Sharanappa et al. 2011; Sindiri et al. 2013), *Penicillium notatum* (Gayen and Ghosh 2011), *Candida rugosa* (Rekha et al. 2012) species for different enzymes production. Similarly, antioxidants are produced through different agro-waste (pineapple waste, orange peel, pomegranate, and lemon peel) with the use of microorganisms (*A. awamori* and *A. oryzae*) (Hegazy and Ibrahium 2012; Singh and Genitha 2014; Rashad et al. 2015; Sadh et al. 2017). The beneficial properties of natural antioxidants such as antiviral, anti-inflammatory, anti-cancer, anti-tumor, and hepatoprotective activity tend it to be safer use for human beings (Nigam et al. 2009). Recent studies have demonstrated that antibiotics production through different agro-waste including coconut oil cake, ground nutshell, corn cobs, sawdust, and rice hulls, are another promising valuable product for the production of different.

Table 1.2 Recent studies of biotechnological approaches using different microorganisms and agro-wastes for bioconversion and degradation of agricultural residues into valuable products

Agro-waste nature	Microorganisms	Biotechnological approaches	Valuable products	Reference
Potato peel	*Xanthomonas campestris*	Solid state fermentation	Xanthan	Vidhyalakshmi et al. (2012)
Wheat bran, rice husk, black gram husk, wheat straw, sugarcane bagasse, maize straw, and paddy straw	*Bacillus licheniformis, B. amyloliquefaciens*	Solid state fermentation	Amylase	Rai and Solanki (2014), Kaur et al. (2015)
BUP6 groundnut oil cake, coconut oil cake, SOC, and CSC	*Pseudomonas* spp.	Solid state fermentation	Lipase	Faisal et al. (2014)
Rice bran, wheat bran, black gram bran, soybean, groundnut oil cake, and coconut oil cake	*Aspergillus niger, Achromobacter, xylosoxidans*	Solid state fermentation	Amylase, cellulase and xylanase	Kumar and Duhan (2011), Suganthi et al. (2011), Mahalakshmi and Jayalakshmi (2016)
Soybean meal waste	*A. oryzae*	Solid state fermentation	Protease enzyme	Thakur et al. (2015)
Corn cob cassava peel, soybeans, wheat bran, and citrus pulp	*Rhizopus arrhizus* and *Mucor subtillissimus*	Solid state fermentation	Protease	Nascimento et al. (2015)
Banana stem	*A. ellipticus* and *A. fumigatus*	Fermentation technique	Bioethanol	Ingale et al. (2014)
Starch containing agriculture waste	*Clostridium beijerinckii*	Fermentation technique	Butanol	Maiti et al. (2016)
Vegetable's waste-potato peel, carrot peel,	*Saccharomyces cerevisiae*	Fermentation technique	Bioethanol	Mushimiyimana and Tallapragada (2016)

(continued)

Table 1.2 (continued)

Agro-waste nature	Microorganisms	Biotechnological approaches	Valuable products	Reference
and onion peel				
Pineapple wastes	–	Fermentation technique	Antioxidant	Rashad et al. (2015)
Fruits peel	–	Fermentation technique	Antioxidant	Singh and Genitha (2014)
Paddy and pulses waste	*A. awamori* and *A. oryzae*	Solid state fermentation	Antioxidant	Saharan and Duhan (2013), Sadh et al. (2017)
Coconut oil cake and ground nut shell	*Amycolatopsis mediterranean*	Solid state fermentation	Antibiotics	Vastrad and Neelagund (2011a, b)
Fruits peel waste	*A. niger*	Fermentation technique	Invertase enzyme	Mehta and Duhan (2014)
Papaya waste and orange peel	*A. niger*	Fermentation technique	α-Amylase enzyme	Sharanappa et al. (2011), Sindiri et al. (2013)
Apple pomace	*A. niger*	Solid state fermentation	β-Mannanase	Yin et al. 2013
Groundnut oil and linseed oil waste	*P. aeruginosa, C. rugosa*	Fermentation technique	Lipase	Dharmendra (2012), Rekha et al. (2012)
Rice bran	*Pediococcal* sp.	Biotransformation	Ferulic acid	Kaur et al. (2013)
Paddy straw	Bacteria (*Eupenicillium crustaceum, Paceliomyces* sp., *Bacillus atropheus* and *Bacillus* sp.) and commercial fungal consortia (*Aspergillus awamori, Aspergillus nidulans, Trichoderma viride* and *Phanerochaete chrysosporium*)	Aerobic and anaerobic bioconversion	Biofertilizer	Shukla et al. (2016)
Rice straw, maize stover, and mixed weed biomass	Combined inoculation of earthworm (*Eisenia fetida*) and cellulose-degrading	Bioconversion	Compost	Rajkhowa et al. (2019)

(continued)

Table 1.2 (continued)

Agro-waste nature	Microorganisms	Biotechnological approaches	Valuable products	Reference
	microorganism (*Pseudomonas* sp.)			
Agro-waste	Recombinant *Pediococcus acidilactici BD16*	Bioconversion	Vanillin	Chakraborty et al. (2017)
Wheat bran and orange peel	*Penicillium notatum*	Fermentation technique	Pectin methyl esterase	Gayen and Ghosh (2011)
Castor oil, sunflower oil, barley bran, peanut cake, and rice bran	*Pseudomonas aeruginosa*	Solid state fermentation	Biosurfactant	Saravanan and Vijayakumar (2014)
Paddy straw, Banana stalks, Bahia grass	*Pleurotus tuber-regium, P. sajor-caju, P. eryngii*	Bio-conservation of lingo-cellulosic wastes	Edible mushroom	Siqueira et al. (2011), Kumhomkul and Panich (2013), Lakshmi and Sornaraj (2014), Yildirim et al. (2015)
Cucumber and orange peels	*S. cerevisiae*	Submerged fermentation	Single-cell protein	Mondal et al. (2012)
Agro-waste	*Methylomicrobium alcaliphilum, Methylosinus trichosporium,* and *Methylococcus capsulatus*	Bio-conservation of lingo-cellulosic wastes	Biogas	Henard et al. (2018)

Oxytetracycline, rifamycin B, L-Asparagine, Penicillin, and other important antibiotics, were also described as a potential product for inhibiting the growth or kill pathogenic microorganisms (Tripathi 2008; Vastrad and Neelagund 2011b). At present, most of the microorganisms are mainly reported to have production of antibiotics such as *Streptomyces rimosus, Amycolatopsis mediterranean*, *Penicillin chrysogenum,* and *Pseudomonas plecoglossicida*. Recently, there is an increasing interest in developing the potential biotechnological applications of high yield producing microorganism/or genetically modified organism for enzyme production, purification and quantification of end products during downstream processing of fermentation technology. Biosurfactant is another beneficial product for humankind that can be produced by using agro-waste such as castor oil, sunflower oil, barley bran, peanut cake, and rice bran, through the action of microbes (*Pseudomonas aeruginosa*) (Saravanan and Vijayakumar 2014).

The fast-growing population and rapid development of industrialization cause the high input demand for fuels. The production of the low-priced energy source as biofuel from agricultural waste residues becomes attractive substitute of fossil fuels. Several studies revealed the production of biofuels from different agro residues containing high lignocellulosic composition like corn stalks, rice straw, potato waste, sweet potato waste, sawdust, sugarcane bagasse, sugar beet, and vegetable waste like potato peel, carrot peel, and onion peel (Duhan et al. 2013; Saini et al. 2014; Kumar et al. 2014, 2016). The most promising microorganisms that reported for the making of ethanol were described by researchers as, *Saccharomyces cerevisiae* (Mushimiyimana and Tallapragada 2016), *Aspergillus ellipticus,* and *Aspergillus fumigatus* (Ingale et al. 2014), *Clostridium beijerinckii* (Maiti et al. 2016). Biogas production from agro-waste is another significant approach as a substitute of fuels. Paepatung et al. (2009) reported the production of biogas from various agriculture residues as well as two weeds, i.e., *Typha angustifolia* L. and *Eichornia crassipessolms*. Another researcher reported the production of biogas by sequential bioconversion of various agriculture residues, and slurries of animal residues were carried out by a series of microorganism (Paepatung et al. 2009). The lignocellulosic-derived biofuels production through biotechnological approaches is cost-effective as well as eco-friendly and alternative source of energy for the upcoming future.

Production of mushroom worked as a noticeable method of biotechnology for the ecological as well as economic points of view by the transformation of agro-based residues into protein-rich food using various microorganisms (Randive 2012). Mushroom used either as a protein-rich food or bioremediation tool for degradation of lignocellulosic material rich agro-waste (wheat bran, rice bran, paddy straw, banana stalks, and bahiagrass) through the action of dominating fruiting bodies as *Pleurotus tuber-regium, Pleurotus sajor-caju, Pleurotus eous, and Pleurotus platypus* (Babu and Subhasree 2010; Siqueira et al. 2011; Jonathan and Babalola 2013; Lakshmi and Sornaraj 2014). Similarly, a single-cell protein obtained from the bioconversion of agro-wastes (cucumber and orange peels) using microbes, viz., *S. cerevisiae* is economical and nutritionally contained a high content of protein (Mondal et al. 2012).

1.6 Bioconversion of Agro-Waste in Bio-Compost for Sustainable Agriculture

Composting is a sequential bioconversion of agricultural waste into a useful resource. The agricultural residues degraded through the action of lignocellulolytic microorganisms to manage and recycle this waste into a high economic valuable product and efficient compost (Sánchez 2009; Lauwers et al. 2013). The application of compost in the soil improves physical, chemical, and biological properties of soil, restore nutrient pools, enhance soil fertility and health (Huang et al. 2010; Clara et al.

2017; Han et al. 2017). The composting is achieved by a natural succession of microflora that includes bacteria, actinomycetes, and several fungi (Vargas Garcia et al. 2010; Bohacz 2017). Most of the researchers reported significant degradation and bioconversion of agro-waste through bacterial and actinomycetes actions, named as, *Bacillus. Subtilis, B. polymyxa, B. licheniformis, B. pumilus, B. brevis, B. firmus, B. circulans, B. megaterium, B. cereus, Cellulomonas, Cytophaga*, *Pseudomonas* spp., *Clostridium vincentii*, *Sporocytophaga*, *Streptomyces, Micromonospora,* and *Thermoactinomyces* (Awasthi et al. 2016; Bohacz 2017). Several fungi like *Trichoderma harzianum, T. viride, Pleurotus ostreatus, Polyporus ostriformis,* and *Phanerochaete chrysosporium* are known to play an essential role in composting of lignocellulosic materials (Schuster and Schmoll 2010; Awasthi et al. 2016; Varma et al. 2015). The co-inoculation practices are applied to improve crop productivity through diverse mechanisms through nutrient acquisition, mineralization, carbon addition, and phytohormone production (Rashid et al. 2016; Meena et al. 2017). Several beneficial bacterial and fungal species of *Rhizobium, Azotobacter, Azospirillum, Pseudomonas, Bacillus, Burkholderia cepacia, Candida oleophila, Coniothyrium minitans, C. sclerotiorum, Aspergillus niger, Fusarium oxysporum* (nonpathogenic), *Gliocladium* spp., *Phlebia gigantean, Pythium oligandrum, Streptomyces griseoviridis,* and *Trichoderma* spp. that are currently being used with organic matter-rich compost can add to the soil health, when added in combination with the compost can also provide significant support to agriculture (Reddy and Saravanan 2013; Sharma et al. 2013; Rai et al. 2016). The process of decomposition of crop residues involves differentially variable conditions (pH, temperature, moisture, nutrient availability) for the microbial communities involved during the period of degradation.

In the context of sustainable agriculture, compost is an unavoidable natural resource for the management of agro-waste and high-yield production in the farmers' fields. In this order, controlled composting conducted by potential microbial communities to decompose agricultural residues properly and provide high-value low-cost bioorganic compost for farmers (Ahmad et al. 2007; Singh and Nain 2014; Sudharmaidevi et al. 2017). The way of composting processes can help farmers to attract towards organic compost rather than chemical fertilizers, and simultaneously it enhanced the production of high-value commercial crops like vegetables, fruits, flowers, and organic crops (Hoornweg et al. 2000; Seyedbagheri 2010). The application of biofortified compost with bioagents, controlled the soil-, seed- or seedling-borne fungal pathogens in the field that reduces the application of biopesticide (Siddiqui et al. 2008; Ng et al. 2016). Similarly, farmers also applied consortium of microorganisms that are capable for fixing nitrogen, solubilizing phosphorus, zinc, and mobilizing potassium that can be fortified with compost (Baig et al. 2012; Pallavi Chandra and Sharma 2017). These scientific approaches provide knowledge and progression in sustainable agriculture and awareness of the farmer's regarding their need, expertise, indigenous resource availability, local conditions, and existing human resources.

1.7 Develop Eco-Innovative Strategies to Agro-Waste Conversion to Farmers

The campaigning and adoption of these microbial technologies as eco-innovative strategies to farmers provide information about benefits of microbe-mediated composting processes, biotechnological aspects of agro-waste bioconversion, the involvement of microorganisms invaluable product formation, benefits of microbial fortified, and enriched compost in crop yield production. These eco-innovative strategies are simple and easily adaptable by the farming communities. The application of these technologies helps reintroduce organic matter to the soils along with the beneficial microorganisms that help soils to improve nutrient status for plant growth and development. The develop link between farmers, and eco-innovative technologies are a significant problem for sustainable agriculture.

The scientific approaches that targeted farmer-friendly microbe-mediated agro-waste bioconversion for composting among the grass-root stakeholders are a matter of perception and preference. Several factors that hamper the awareness of technologies among the farmers are lack of knowledge about soil and plant characters, less awareness about the effect of chemicals over agricultural foods with human health, a dilemma to adopt new technologies, and short-sightedness towards long-term benefits of organic and fortified compost in agriculture. To overcome these problems, awareness programs using ICT tools or by videos, learning materials or by technical demonstration kits, new government programs regarding sustainable agriculture are connect farmers to adopt these technologies (Karubanga et al. 2017). These efforts can yield desirable impacts on crop yield production, minimizes the application of high-cost chemical fertilizers, integrated farm management practices, limiting the risk of pollutants due to residual effects of pesticides, lowering the production cost of the crops, converting agriculture residue into useful compost and enhancing soil fertility level that lost due to countable changes among farming communities (Muller 2009; Aktar et al. 2009; Settle et al. 2012; Yadav et al. 2013). Therefore, the Indian government has shown keen interest in promoting the adaptation of such environment- and agriculture-friendly practices in farmers through various developmental schemes and funding projects.

1.8 Conclusion and Future Perspectives

Agro residues are rich in nutrient composition and bioactive compounds such as sugars, minerals, and proteins; that is why it considered as "raw material" for several industrial processes. The occurrence of such nutrients in these residues offers suitable productive conditions for the growth of microorganisms that can produce several value-added products through bioconversion/fermentation processes. With the help of microbial interventions and developing biotechnological approaches, the raw residues can be transformed firstly into demanding valuable products and subsequently, the spent waste can further be converted into microbe-enriched biofertilizers/bio-formulations/compost having the specific functional trait. One of the major benefits of using biotechnological approaches for agro-waste bioconversion is to making feasible the availability of the ready-to-use valuable product in the welfare of human beings. Secondly, this can also help to advent genetic engineering approaches to add desired microbial genes with specific functions, which perform fastest bioconversion/fermentation into the valuable product as well as also involved in other biological bioconversion/bioremediation process. Thirdly, proper composting of agro-waste through microbe-mediated process provides organic materials in the soil that enhances the mineralization of nutrient and ensures proper availability of micronutrients for a longer time duration in the soil. The presence of microbial communities in the soils as emerging frontiers in agro-waste recycling not only produced valuable product but also reduces the environmental risk. In an integrated way, these microbe-mediated processes help improve ecological services and awareness about the eco-innovative strategies of agro-waste recycling drag attention of significant farming communities of India for valuable product formation as well as sustainable agriculture.

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