Chapter 13
Microbial Remediation of Agricultural Residues

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Abstract The rising crop production generates a high quantity of agricultural residues that are not fully recycled, e.g. in bedding for animals and feed production, thus leaving large amounts of unused residues that induce environemental pollution. For instance, the residue excess is often set to fire by the farming communities. Since residues contain nutrients, microbes can be used to convert residue into valuable products. Here we review the microbial conversion of agricultural residues into fuels, food and feed materials. Biofuels include bioethanol, biodiesel, biobutanol, and biogas. Microbial systems transform residues into useful compost for plants, and into nutrient-enriched feed for animals. Solid-state fermentation of residues can be used to produce food such as mushrooms.

Keywords Microbes · Residues · Soil · Biohydrogen · *Clostridium* · Lignocelluloytic · Bioethanol · Biogas · Biobutanol · Mushroom production

13.1 Introduction

A major proportion of the Indian population still depends on agricultural systems for livelihood directly or indirectly which makes India an agrarian economy. A greater proportion of land is utilized for agronomic practices and an extensive range of crops are cultivated in its diverse agro-ecosystems (Rani et al. 2019; Singh et al. 2019, 2021; Sharma et al. 2020a, b, 2021; Kumar et al. 2020). With a production of 93.9 million tons of wheat, 104.6 million tons of rice, 21.6 million tons of maize, 20.7 million tons of millets, 357.7 million tons of sugarcane, 8.1 million tons of fiber crops (jute, cotton), 17.2 million tons of pulses, and 30.0 million tons of

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oilseeds crops, in the year 2011–12 (Ministry of Agriculture 2012), it is an undeniable fact that such a major crop production would generate an enormous volume of crop residues both on-farm and off-farm. The crop production leads to the generation of around 500–550 million tons of the crop remains on an annual basis in the country. These remains of harvest often find usage as feed for animals, for producing bio-manures, soil mulching, thatching for houses in rural areas, and as fuel for home as well as industrial purposes. Such residual crops are of great significance to the farming community.

Conversely, a major proportion of these residues are set to fire at the site predominantly for the purpose of field clearance to sow the subsequent crop. Surprisingly, this problem of burning the residual crops is escalating in the current years as a result of the unavailability of human labor, inefficacy of traditional practices of residue removal, as well as the employment of high-tech machinery to harvest the crops. The remains of maize, cotton, rice, millet, jute, wheat, sugarcane, rapeseed-mustard, and groundnut are usually set to fire on fields in different parts of the country. The agricultural systems primarily relying on irrigation systems, predominantly the mechanized rice-wheat belt of northwest India is more prone to this problem (IARI 2012). However, there is a paradox; setting the residual crops to fire and prevailing insufficiency of fodder co-occur in the country, which thereby leads to a noteworthy and perpetual intensification in costs of fodder. But, the ease of removal and lack of awareness is sufficient enough to persuade the farming community to set the residual crops to fire. As per the reports of the Ministry of New and Renewable Energy, India burns around 92 MT of crop residues on an annual basis (Bhuvaneshwari et al. 2019).

The burning of these residual crops directs the generation of smoke as well as soot elements which results in severe animal and human health-related complications. Additionally, this act is also blamed for the release of several gases responsible for the greenhouse effect, such as, nitrous oxide and carbon dioxide which direct the happening of the phenomenon of global warming coupled with the harm to important plant nutrients. The act of burning also leads to the depletion of several valued possessions which have the potential of being utilized as a valuable basis of organic carbon, bio-active complexes, forage, and energy for rural households and small industries. The heat energy produced by the burning of crop leftovers is also responsible for elevating the temperature of soil which results in the mortality of diverse advantageous microbes. The burning of the crop remains leads to an immediate upsurge in the exchangeable $NH4^+$-N and bicarbonate- extractable P content, but there is no buildup of nutrients in the profile. Long-term burning reduces total N and C, and potentially mineralizable N in the upper soil layer. A diverse array of pollutants that originate in enormous amounts from biomass smoke are alleged to be potent carcinogens and thereby might be a chief source of concern directing numerous air-borne diseases (IARI 2012). Figure 13.1 illustrates the diverse consequences of agro-residue burning faced by different biotic and abiotic elements of the ecosystem which are associated with mankind in either a direct or an indirect manner.

The capability of the resources derived from biomass is getting ever-increased attention, and thus, has become a focus for ever-increasing research and debate as

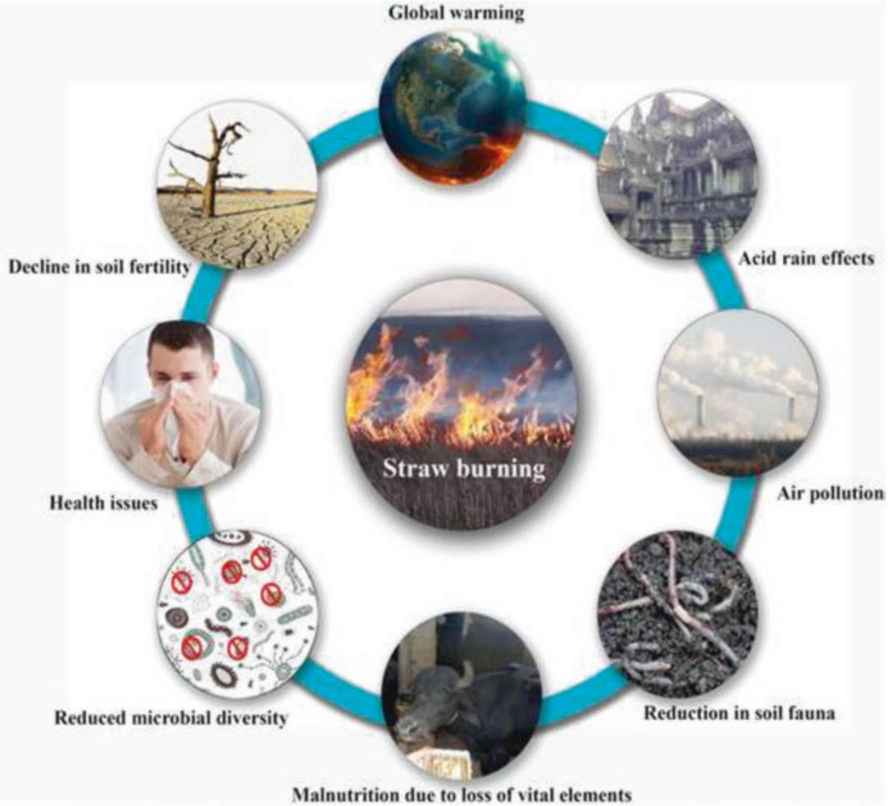

Fig. 13.1 Adverse effects of burning crops residues

well. There are numerous agreements happened across the globe, for instance, the Kyoto Protocol, EU Directives along with several policies such as the European 20:20:20 Plan and the US Recovery and Reinvestment Act which have collectively laid enormous pressure on the political proportion which in turn has directed the focus of mankind as well as the scientific community towards use of agricultural residues as a potential alternate candidate as effective energy carrier (Bentsen et al. 2014). Moreover, the perpetual and unexpected increase of the prices of crude oil in the year 2008 also carved commercial consideration for alternate energy assets. The United Nations have speculated that the global population will upsurge to 9.1 billion by the year 2050 (United Nations 2011), which as a consequence will lead to the increased demand for food, materials, and energy. The International Energy Agency estimates that the energy consumption will increase with an expected 1.6% annual rate from 2005 to 2030 (Hiloidhari et al. 2014).

Thereby, the numerous ill-effects of burning crop leftovers and present management practices coupled with their energy potential have directed the concerns of the global scientific community to find a potent and easily approachable alternate for managing the crop residues in such a way that would advocate sustainability, be economically viable and easy to execute (Table 13.1). Therefore, microbes having tremendous potential for remediation of agricultural residues seem to be an effective and viable means for managing crop residues. Microbes are potent enough to biologically transform the agro-residues into valuable feed for promoting animal health and into compost for up upgrading soil health thus indirectly promoting human health and alleviating stress from the petrochemical industries. The microbial systems bring out the biotransformation process through secretion of various primary and secondary metabolites (Kapoor et al. 2020; Sharma et al. 2019). Thereby, in this chapter, an attempt has been made to club the information available on microbial management of diverse agricultural residues.

13.2 Residue Potential in India

The non-eatable parts of plants that are left in the field after harvest is said to be crop residues. The wastes produced during the processing of crops and from crop-packing plants are also deliberated to crop residues (Sadh et al. 2018). The residues generated by diverse crops fluctuate extensively in terms of their approximate quantity. There is no direct measurement of these crop leftovers rather the estimates are made based on data on the area and manufacture of diverse crops, and research facts on the straw/grain ratio. The wastes engendered during the harvesting as well as the processing of agrarian vegetative crops are extensively classified into two types: (1) Field residues: these are the materials that are left in the cultivated land or plantation areas after reaping the crop. These are usually comprised of stalks, seed pods, stems, and leaves. Such residues can be nurtured unswervingly into the ground or burned first. The appropriate supervision of such leftovers can lead to an effective accomplishment of the irrigation proficiency along with an operative check on the soil erosion. (2) The other type of residues is called process residues: which results from the processing of a crop into a utilizable resource (Fig. 13.2). Such residues are often represented by seeds, bagasse, roots, husks, and molasses. Such residues have the capability of being utilized as fodder for animals and fertilizers for soil health enhancement (Ali et al. 2019).

It has been assessed that around 686 million tons of total residue is generated in India per year as a result of cultivation of 26 different crops which results in 39 types of the crop remains. A major proportion of around, 545 million tons is collectively added through the production of pulses, cereals, sugarcane, and oilseeds. The horticultural crops, primarily, banana, coconut, and areca nut contribute to around 61 million tons of residues whereas 80 million tons is contributed by other crops such as jute and cotton. If the classes of crops are concerned than the highest proportion of 368 million tons is contributed by the cereals which are equivalent to around 54% of the total residue generated. The residues generated by sugarcane are although much less as compared to those of cereals but they represent a significant proportion of around 16% equaling 111 million tons of residues. If the individual

Table 13.1 Environmental issues of agricultural residues

Agricultural residues	Problem associated with residue burning	Area of study	Environmental and health hazards	References
General crop residues	Enhancement in $PM_{2.5}$ and PM_{10} during crop residue burning period	Agra, India	The smoke plume originated from burning of agricultural crop-residue release particulate matter, carbon monoxide, carbon dioxide, nitric oxide, and volatile organic carbons.	Kumari et al. (2020)
Burning of wheat and paddy straw of about 20.3 and 9.6 million tons in Punjab and Haryana	Emission of 137.2 and 56.9 gigagrams of $PM_{2.5}$ and 163.7 and 72.1 gigagrams of PM_{10} for Punjab and Haryana, respectively	North India	The emissions of elemental carbon, organic carbon, and polycyclic aromatic hydrocarbons were 8.6, 45.7, and 0.08 gigagrams in Punjab, whereas in Haryana emissions were 3.7 Gg, 17.7 Gg, and 0.03 gigagrams, respectively. These were produced as a result of wheat and paddy straw burning in around 30,000 and 8500 active fires in Punjab and Haryana, respectively.	Singh et al. (2020)
Crops harvested in autumn	Increase in the levels of $PM_{2.5}$	North China plain	The levels of $PM_{2.5}$ during the harvesting and post-harvesting periods increase by a factor of 1.20 and 1.73, respectively.	Li et al. (2020)
General crop residues	Increased concentration of pollutants	North India	The average concentration of PM_{10}, $PM_{2.5}$, and PM_1 were 196.7 ± 30.6, 148.2 ± 20, and 51.2 ± 8.9 μgm^{-3} and daily average concentration were found several times higher than national ambient air quality standards for 24 h.	Ravindra et al. (2019a)
General crop residues	Air pollution	Nepal	More than 80% of air pollutants were generated during the months of February to May from the open burning of crop residue leading to health impact and regional warming.	Das et al. (2020)

(continued)

Table 13.1 (continued)

Agricultural residues	Problem associated with residue burning	Area of study	Environmental and health hazards	References
Rice straw	Sub-acute effect on pulmonary functions of healthy subjects	India	Crop residue burning events are highly dangerous for the health of the citizens.	Agarwal et al. (2012)
Rice and wheat residue burning	High PM levels	North India	Significant reduction in the Forced Vital Capacity and Peak Expiratory Flow and the lung capacity of children recovers only up to 80% after the crop residue burning events.	Gupta et al. (2016)
488 MT of total annual crop residue	Emissions of 824, 812, 58 and 239 gigagrams of $PM_{2.5}$, PM_{10}, elemental Carbon and organic Carbon respectively and 211 teragrams of CO_2 equivalent greenhouse gases	India	Residue burning emissions will increase by 45% in 2050. The crop residue has the potential to meet 10% of the current energy demands of India.	Ravindra et al. (2019b)
Paddy straw	Increased levels of benzenoids, acetonitrile, and isocyanic acid	India	Benzene exposure increase risks of cancer, cardiovascular diseases, and cataracts by 25 per million children and 10 per million adults.	Chandra and Sinha (2016)
General and regional crop residue	Increased levels of polycyclic aromatic hydrocarbons	Indo-Gangetic Plains of India	Increased levels of Anthracene, fluoranthene, pyrene, benzo[a] anthracene, and chrysene which be carcinogenic.	Singh et al. (2013)
Paddy straw	Soil health deterioration	Indo-Gangetic Plains, India	Burning of paddy straw cause rapid deterioration of soil microbial population and enzyme activity which compromise agricultural productivity.	Kumar et al. (2019)
Wheat straw	Reduced microbial dynamics of soil	Pakistan	Burning wheat residue significantly declines the soil microflora and also interfere with soil chemical and physical attributes like reduced soil carbon and nitrogen content along with the degradation and deterioration of soil.	Raheem et al. (2019)

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Table 13.1 (continued)

Agricultural residues	Problem associated with residue burning	Area of study	Environmental and health hazards	References
Wheat straw	Increase in atmospheric concentration of low-molecular weight monocarboxylic acids	China	High abundances of low molecular weight organic acids in the atmosphere can adversely affect the quality of air, human health and also increase the acidity of rainwater. Burning of agricultural residues also contributes to the formation of organic aerosols.	Mochizuki et al. (2017)
General and regional crop residue	Increase in aerosols over the South China Sea	China	Atmospheric aerosol particles can significantly affect the Earth's climate directly by absorbing and scattering solar irradiation, and indirectly by acting as cloud condensation nuclei.	Song et al. (2018)
Pinus sylvestris, P. abies	Reduced abundances and species richness of soil meso- and macrofauna	Sweden	Residues burning reduce the diversity of soil fauna and disturb the food chain which reduces ecosystem productivity due to the decreased number of predators and fungivores.	Malmström et al. (2009)

crops are considered for residue generation than rice is found to be dominating the league with a residue generation of around 154 million tons followed by wheat (131 million tons). However, if only the availability of surplus residue is considered than the national potential is found to be 234 million tons on an annual basis which represents around 34% of the gross residue generated in India.

The highest amount of surplus residue is also contributed by the cereals which are equivalent to 89 million tons of annual residue. It is mainly followed by the sugarcane with an annual residue generation of 56 MT, others (47 million tons), horticultural crops (23 million tons), oilseeds crops (14 million tons), and pulses (five million tons). If an individual crop is considered for the generation of surplus residue than sugarcane is found to be dominating the field with an annual production of around 56 million tons, followed by cotton with a residue potential of 47 million tons and rice (43 million tons). However, rice was found to be dominating in the gross residue production but it is lagging behind sugarcane when the generation of surplus residue is considered. This phenomenon is attributable to the fact that the residues generated by rice crops in the form of husk and straw often find more contending usages such as in cattle and animal feed, in packaging materials, and as fuel for heating and cooking purposes as compared to the residues generated by the

Fig. 13.2 Origin of diverse agricultural residues

sugarcane. The surplus residue generated by horticultural crops primarily coconut and banana also contribute to a significant proportion equivalent to 10 and 12 million tons, respectively.

The residue potential also varies state-wise, for instance, Uttar Pradesh generates a maximum crop residue of 121 million tons whereas Mizoram generates only 0.21 million tons of crop residues on an annual basis. Uttar Pradesh, being an agriculturally important state usually dominates in the crop production of sugarcane, wheat, and rice thereby a major proportion of around 90% of the crop residues generated is contributed by these three prime crops. Punjab follows Uttar Pradesh by generating an annual residue of 83 million tons. However, if only the generation of surplus residue is considered, still then, Uttar Pradesh dominates by an annual production of 40 million tons which is closely followed by Maharashtra by generating 31 million tons surplus residue, and by Punjab with a surplus residue generation of around 28 million tons (IARI 2012; Hiloidhari et al. 2014).

According to the Ministry of New and Renewable Energy India, a major proportion of the crop residues is set to fire at the field conditions. On a collective basis around 92.81 million tons of crop residues are burned on an annual basis. Uttar Pradesh is leading here as well with an annual burning of around 21.92 million tons of residues. Uttar Pradesh is followed by Punjab where 19.65 million tons residue is burned each year. Haryana and Maharashtra are also significant contributors in this race by annually burning of 9.08 and 7.42 million tons of crop residues, respectively (NPMCR 2014).

13.3 Current Management Practices

13.3.1 Bedding and Feed for Animals

The Indian farming community has traditionally been utilizing the crop remains as animal feed in their native form or by accompanying some additives. Conversely, the crop remains, are largely unpalatable and often show low digestibility, thereby, cannot be utilized solely as the feedstock. They are also low-density fibrous materials, having low nitrogen content, soluble carbohydrates, minerals, and vitamins. They may also have varying degrees of lignin content which acts as the physical constraint and obstructs the microbial breakdown of feed. Therefore, the residue needs to be preprocessed to meet the nutritional requirements of animals. It is also used in combination with other green fodders and legume (sun hemp, horse gram, cowpea, and gram) straws. Other low-quality residues are also often being used as bedding material for animals.

13.3.2 No-Tillage and Recycling of Crop Residues

It is a farming practice wherein the soil is not disturbed through the process of tillage. The crop residues are allowed to prevail in the field and are subject to natural decay. This practice is acclaimed for prevention of soil erosion since the crop residues hold the soil tightly and protect the soil from wind or water erosion (Triplett and Dick 2008; Telles et al. 2018); but there is a considerable drop in the yield of the crops.

The crop remains can also be recycled directly, by their amalgamation into the soil using several means. The crop residues can also be used as mulches and are often returned to the field in combination with animal manures. However, this is an indirect but traditional practice of agriculture that has made significant and irreplaceable contributions for promoting agricultural yield along with the advocation of environmental sustainability. The soil receiving such treatments are found to be rich in soil organic matter, facing very little soil erosion, enhanced water storage ability, and are collectively healthier as compared to others (Smil 1999; van der Wiel et al. 2019).

13.3.3 Biochar Production

Biochar is a high carbon material that is produced by slowly heating the biomass in the absence of oxygen. It is a fine-grained type of charcoal and is largely capable of storing carbon in the soil for a longer period. Conversely, the elevated production costs make its production process a highly costly affair, therefore, the practice of using biochar is not much prevalent in the farming community. However, the utilization of all the valuable goods and co-products, for instance, heat energy, hydrogen gas, and bio-oil that are generated during the process of biochar formation could make it an economically viable process. So, the development of a low-cost production process for generating biochar can also popularize its use.

13.4 Microbes for Residue Management

The wastes of agricultural origin are of significant importance and their proper management can prove to be highly economical due to the possession of numerous hidden capabilities. The microorganisms can be unbelievable agents for managing agricultural residues. Since the act of burning the residues at the field, conditions result in several ill effects. It leads to the loss of soil nutrients and therefore strongly affects the soil properties. Moreover, the emission of greenhouse gases deteriorates environmental health. The burning of agro residues also disturbs the microbial population as well as diversity at the field conditions which are considered to be very important elements for maintaining soil fertility. The ease of disposal often compels the farming community to burn the residues but it brings a gamut of challenges with it. Therefore, alternate ways for the management of agro residues are one of the most favorite agricultural technique being sought for.

The potential of microbes is often utilized to return the agricultural residues in the form of compost for elevating the nutrient status of the agricultural farms. The lignocellulolytic microbes are endowed with the capability of recycling and reusing agricultural wastes by transforming them into other forms. Therefore, the unique potential of microbes is being quested for managing the residues sustainably and more easily that could also be economically viable. The potential of microbes has already been explored for the transformation of biomass into biofuels and other useful products. Figure 13.3 depicts a diagrammatic representation of different products that can be produced by treating the agricultural residues with definite microbes.

13.5 Residue Management by Compost Preparation

Agriculture and food industries are among the ancient practices of mankind, but they too lead to the generation of a gamut of wastes thereby are strongly correlated with other industrial sectors in this particular aspect. The administration, as well as

Fig. 13.3 Products from microbially-treated agro-residues

control of wastes generated by the food and agronomic sector, is going to play an imperative role in the near future as per the preservation of diverse natural possessions is concerned. The process of composting agricultural residues is a much efficacious strategy utilizing the principles of microbiology for managing the residual products of agro-ecosystems sustainably. The word "composting" means the process of controlled and organized biological development where the complex forms of organic matter found their origin from either animal or plant resources is disintegrated into materials having shorter molecular chains, enhanced stability, clean, humus-rich, and are advantageous for the cultivated crops and recycling of soil organic matter (Sequi 1996; Sánchez et al. 2017). A diverse array of microbes is known for mediating the process of composting: bacteria, fungi, actinomycetes, algae, and protozoa, which contribute naturally to the organic biomass or are added artificially (Tuomela et al. 2000; Sánchez et al. 2017).

The process of composting agro-residues is largely governed by the activity of lignocellulolytic microbes which seem to be proficient agents for managing as well as recycling the lignocellulosic wastes having a great pecuniary competence. The recycled matter on application to the soil systems enhances the fertility as well as the health of the soil. The process of composting allows the biological degradation and steadying of the organic matter under a set of conditions that promote the thermophilic microflora to proliferate as an outcome of the biologically originated heat (Gaur 1999; Onwosi et al. 2017).

Initially, there is a succession of mesophilic microbes which consume the nutrients and are responsible for raising the pile temperature. The next phase allows the progression of thermophilic microbes which further results in a stable final product that is devoid of any kind of pathogen and suitable for application to the fields. A diverse array of agricultural wastes can be utilized for composting like paddy straw, sugarcane trash, and other agro-residues. The process of composting experiences the natural succession of microbes. Several fungi are known to play a significant role in degrading lignocellulosic wastes during composting, for instance, *Phanerochaete chrysosporium*, *Trichoderma harzianum*, *Polyporus ostriformis*, and *Pleurotus ostreatus* (Singh et al. 2012).

The higher lignin content of the crop residues is often responsible for restricting the enzymatic attack by microflora; which is largely responsible for the long periods required for composting. Numerous members belonging to the group fungi are known for their possession of lignocellulolytic activity. They are broadly classified into three major groups: soft rot fungi, brown rot fungi, and white-rot fungi (Kirk 1983; Singh et al. 2012). The soft rot fungi, such as *Chaetomium globosum*, *Phialophora malorum*, *P. mutabilis*, *Aspergillus niger*, *Penicillium chrysogenum*, and *Chaetomium globosum* are eminently capable of degrading cellulose but they decompose lignin slowly and almost incompletely. The brown rot fungi, for instance, *Oligoporus placenta*, *Coniophora puteana*, *Fomitopsis palustris*, *Coniophora puteana*, and *Poria placenta* preferably degrade the carbohydrate constituents and are also responsible for the demethylation of lignin. White rot fungi, such as *Schizophyllum commune*, *Pleurotus sajor caju*, *Trametes versicolor*, and *Phanerochaete chrysosporium* are endowed with the incredible capability of decomposing cellulose as well as lignin. There are numerous other bacteria and actinomycetes which convert the complex matter into simpler ones that are suitable for soil application. The application of compost to the soil systems is highly beneficial for enhancing soil as well as plant health.

The application of compost in the soil is an important way of improving the physical, chemical as well as biological properties of the soil. It also works well for restoring the organic carbon pool of the soil. It results in better mineral nutrition of the plant, and hence, is responsible for increasing the yield of agricultural produces. The composts enriched with a particular mineral are potent enough to compete with the costly chemical fertilizers. The application of composts is also acknowledged for the suppression of soil-borne pathogens (Singh et al. 2012). The action of composts also restricts the bioavailability of toxic heavy metals owing to the occurrence of different humic substances and iron oxide in composts. The steadied organic matter is deliberated to form multiplexes with metals which results in the constrained movement of heavy metals and thus reduction in their availability for plant systems (Paré et al. 1999; Piccolo et al. 2019). The dynamic activity of microbial systems throughout the progression of composting has the potential to hasten the disintegration of xenobiotic compounds in the soil (Büyüksönmez et al. 2000). The soil dehydrogenase activity also increases considerably by the addition of compost to the soil. Therefore, the act of composting of agro-residues not only helps in getting rid of the complex agricultural residues but can also be utilized effectively for uplifting the health status of agro-ecosystems.

13.6 Transforming Residues into Biofuel

The atmospheric level of carbon dioxide along with other greenhouse gases is increasing ever since the commencement of domestication of plants for agricultural systems 10,000 years ago (Ruddiman 2003). The onset of the Industrial Revolution since about 1850 has directed the international attention in ascertaining newer approaches for a reduction in the levels of gaseous emissions (IPCC 2000). The agro-ecosystems can be a basis as well as a basin for the atmospheric carbon dioxide as per the land use patterns and its management options are concerned. The transformation of biomass into biofuel received major consideration in the course of the 1970s on account of the insistence of accomplishing energy autonomy. The quest for mitigating global climatic changes developed an improved concentration in biomass energy since the mid-1990s. The approach of utilizing crop residues as a potential substrate for biofuel production has significant implications for comprehending these goals.

The crop residues have the capability of becoming a chief source of energy attributable to their influence on compensating emissions resulting from the use of fossil fuels. The crop leftovers are supposed to have a heating worth of around 3×10^6 kilocalories/megagram, which is approximately 50% of that of coal and 33% of that of diesel. The fuel value of 1 megagram of crop residue is appraised at 18.6×10^9 Joule, 2 barrels of diesel, 3×10^6 kilocalories, or 16×10^6 British Thermal Units (Lal 2005). Therefore, it can be said that agriculture is deliberated to be a rich source of energy because it fabricates biomass, which has the potential of being utilized as biofuel and is a renewable resource (Table 13.2). However, the energy content of different crop residues varies among crop species.

13.6.1 Bioethanol Production

The ethanol originated from the biomass resources is highly potent to be used as a sustainable fuel for transport, along with a fuel oxygenate that has the capability of replacing gasoline. The energy content of ethanol is further found to be higher than the energy required to produce it (Wang 2000; Kim and Dale 2004). Brazil and the US are deliberated to be major producers of ethanol and they account for 62% of global ethanol production. The foremost substrate, however, used in Brazil is sugar cane, while corn grain is utilized for ethanol production in the US. The increasing debate over the food/feed vs fuel issue and the ever-increasing global attention for managing the residual crops have directed the focus of mankind towards the

Table 13.2 Agricultural residues as substrates for microbial production of biofuels

Biofuels	Residue type	Pretreatments	Mechanisms/ processes	Microorganisms involved	Significant findings	References
Bioethanol	Coffee husk, cassava stem, and coconut coir	Popping pretreatment	Saccharification and fermentation	*Saccharomyces cerevisiae* KCTC 7906	Production of bioethanol from mixed biomass is a more promising approach	Nguyen et al. (2017)
	Rice residue	Microwave-assisted alkali and acid pretreatment	Saccharification and fermentation	*Trichoderma reesei* NCIM 1052 for Saccharification and *Pichia stipitis* NCIM 3499 for fermentation	*P. stipitis* NCIM 3499 gave a yield of 25.3 g/L of ethanol which exhibits its commercial potential.	Prasad et al. (2020)
	Paddy straw	Pretreatment with white-rot fungus, *Trametes hirsuta*	Saccharification and fermentation	*Saccharomyces cerevisiae*	Biological pretreatment proved to be a feasible method generating higher sugar yields.	Arora et al. (2016)
	Wheat straw	Pretreatment with H_3PO_4 plus H_2O_2	Simultaneous saccharification and fermentation	*Saccharomyces cerevisiae*	15.5 g ethanol was harvested from 100 g wheat straw which indicates its commercialization potential.	Qiu et al. (2018)
Biohydrogen	Wheat straw	Ozonation	Simultaneous enzyme hydrolysis and dark fermentation	Native microbiota of a slurry mixture of cow manure and a sediment	The ozone pretreatment efficiently degraded wheat straw lignin, and the delignification increased with an increase in the applied ozone dose	Wu et al. (2013)
	Fruits and vegetables waste and corn Stover	Acid pretreatment	Dark Fermentation	Hydrogenogenic inoculum was obtained from an anaerobic digester fed	Hydrogen production presented economic benefits such as net revenues of 0.009 USD per kg of co-substrates	Rodríguez-Valderrama et al. (2020)

	Fruit wastes	Moist heat treatment	Fermentation	*Clostridium strain* BOH3	*Clostridium strain* BOH3 has the unique capability of excreting saccharolytic and pectinolytic enzymes and producing a high level of hydrogen	Mahato et al. (2020)
	Waste corn cobs	Alkaline pre-treatment	Dark fermentation	Native microbiota of mixed wastewater sludge from the municipal sewage treatment plant	The alkaline pretreatment method proved to be effective	Kucharska et al. (2020)
Biodiesel	Corncob	Acid hydrolysis	Yeast based fermentation	*Rhodotorula taiwanensis* AM2352	Yeast based conversion of corncob hydrolysate into microbial lipid followed by the lipid transmethylation for biodiesel production	Miao et al. (2020)
	Barley Hull	Acid hydrolysis	Conversion of barley hull hydrolysate into lipid by yeast	*Trichosporon cutaneum*	*Trichosporon cutaneum* is a promising yeast for biodiesel production	Guerfali et al. (2018)
Biobutanol	Rice straw	Acid and Alkali pretreatment	Fermentation	Co-culture of *Saccharomyces cerevisiae* and *Pichia*	Addition of *S. cerevisiae* promoted butanol synthesis pathway which led to the higher butanol concentration	Mohapatra et al. (2020)
	Potato peel	Acid pretreatment	Acetone-butanol-ethanol fermentation	*Clostridium acetobutylicum*	Acetone-butanol-ethanol concentration of 24.8 g/L indicates that potato peel is an appropriate substrate for butanol production	Abedini et al. (2020)
	Banana peel	Acid pretreatment	Separate enzymatic hydrolysis and co-fermentation	Co-culture of *Saccharomyces cerevisiae* and *Pichia*	Co-culture of *Saccharomyces cerevisiae* and *Pichia* proved better for butanol production as compared to monocultures	Mishra et al. (2020)

(continued)

Table 13.2 (continued)

Biofuels	Residue type	Pretreatments	Mechanisms/ processes	Microorganisms involved	Significant findings	References
Biogas	Paddy straw	NaOH-microwave pretreatment	Anaerobic digestion	Native microbiota of digested biogas slurry	Supplementation of microwave irradiations enhanced the effectiveness of NaOH	Kaur and Phutela (2016)
	Wheat and pearl millet straw	Alkaline pretreatment	Anaerobic digestion	Biogas slurry of another biogas plant was used as inoculum	Mild alkaline pretreatment was effective in enhancing biogas production from both straws	Kumar et al. (2019)

agricultural residues as the potential substrate for ethanol production (Wyman 2018). The abundant biomass resources are largely comprised of agricultural and forestry residues and various other woody and herbaceous crops that are often cultivated on underutilized lands.

The net release of carbon dioxide gas that can contribute to global climate change can be practically zero by employing biomass as the substrate. The behaviors of ethanol as a cleaner fuel with low emissions of carbon monoxide and its capability to improve combustion in addition to gasoline strongly advocate its production (Lynd et al. 1991; Tyson 1993; Gupta and Verma 2015). In the US ethanol is blended with gasoline at the rate of 10% whereas in Brazil it is blended at the level of 22%. Surprisingly, India, being an agrarian country is lagging in executing such environmental policies up to this level. The vast volume of agro-residues generated in India offers a low-cost substrate for ethanol production which would surely decrease the reliance on petroleum resources along with the transformation of the problematic crop leftovers into cleaner fuel.

The crop residues are usually called as lignocellulosic substrates. The worldwide generation of plant biomass is approximately 200×10^9 tons/year; however, nearly 8×10^9–20×10^9 tons is potent enough to be employed as a substrate for biofuel production (Zabed et al. 2017) which is either available at no cost or at a low cost thereby attracting attention as a potential substrate for bioethanol production. A major proportion of lignocellulosic biomass of about 35–50% is comprised of cellulose and 20–35% is made up of hemicellulose. The bulky portion of the residual material is made up of lignin.

Cellulose and hemicellulose together represent around 65–75% of the total lignocellulosic biomass composition; these materials can be broken down into their component sugars for fermentation into bioethanol, as much as for starch conversion to sugars. However, producing sugars from cellulose and hemicellulose at high yields is far more difficult than deriving sugars from corn or sugar cane. Therefore, even though the cost of lignocellulosic biomass is far less than that of sugar and starch crops, the cost of obtaining sugars from such materials for fermentation into bioethanol has historically been far too high to attract industrial interest. However, with the emergence of new technology, economics have improved considerably (Wyman 2018).

Globally rice straw can produce 205 gigalitres of bioethanol, which is the largest amount from a single biomass feedstock. The next highest potential feedstock is wheat straw, which can produce 104 gigalitres of bioethanol (Kim and Dale 2004). The microbes that could be employed for bringing out such fermentation processes should be resistant to the presence of inhibitory compounds, should be tolerant to higher ethanol levels along with the ability for production of higher ethanol yields. The yeast *Saccharomyces cerevisiae* is usually used for such fermentation processes.

However, several other yeast strains, for instance, *Pichia stipitis* (NRRL-Y-7124), and *Kluyveromyces fagilis* (Kf1) are described as potent ethanol producers from diverse substrates. The hemicellulose is largely comprised of a mixture of pentose and hexose sugars. Only a few yeasts belonging to the genera *Pichia*, *Schizosaccharomyces*, *Candida*, and *Pachysolen* are proficient enough to ferment pentose sugars to ethanol (Mussatto et al. 2012). The yeast *K. Marxianus* has got the unique capability of co-fermenting both hexose as well as pentose sugars (Yanase et al. 2010).

The major hindrance in bioethanol production is the problem in pentose fermentation which can be resolved by using hybrid, genetically modified, or co-culture of two yeast strains. The hybrid yeast cells have the unique ability to utilize pentose as well as hexose concurrently for ethanol production. The genetically engineered yeast strains contain genes from other microbes which makes them capable of utilizing a previously non-utilizable substrate. The approach of using co-culture employs two diverse yeasts simultaneously in the same reactor. It gives an elevated yield as compared to the employment of pure cultures.

The yeast which is capable of pentose fermentation, for instance, *Pichia fermentans* and *Pichia stipitis* can be employed with a hexose fermenting yeast such as with *S. cerevisiae* with the intention of effective co-consumption of hexose as well as pentose sugars (Azhar et al. 2017). The bacterium *Zymomonas mobilis* is also capable of bringing out such conversions. But they are often limited by their capability of utilizing only a single substrate for bioethanol production coupled with the complexity of the biomass substrates. However, several attempts have been made to genetically modify other microbes like *Escherichia coli* and *Klebsiella oxytoca* to upgrade their substrate utilization range as well as capability.

13.6.2 Biobutanol Production

Ethanol has been widely accepted as a biofuel and has also been found much suitable than methanol owing to its renewability; therefore, it has been widely employed as an additive or alternate fuel in several nations like the US, China, Brazil, etc. Conversely, the employment of ethanol invites numerous grave concerns which further need to be addressed for use of ethanol as a fuel. The use of ethanol is found to corrode the prevailing pipelines by common corrosion, wet corrosion as well as dry corrosion. The general corrosion is, however, a result of different ionic contaminations whereas the dry corrosion is accredited to the ethanol molecule as well as its polarity (Jin et al. 2011).

There are various metals, for instance, lead, aluminium, and magnesium which are vulnerable to be attacked chemically by dry ethanol. Ethanol, by absorbing moisture from the air is also responsible for wet corrosion which results in oxidation of most of the metals. It is also known to affect various nonmetallic parts in different ways (Hansen et al. 2005). Therefore, butanol seems to be a much competent biofuel attributable to its diverse advantages. It is also a biomass-derived biofuel that is renewable in nature and can be produced by fermentation processes using biomass feedstocks as substrates. Although, being a 4-carbon entity, it is much complex as compared to simpler alcohols; however, it is equally competent to be blended with gasoline. Furthermore, it has the incredible ability to get blended with diesel oil also. Since it contains more oxygen than methanol, ethanol can effectively reduce soot generation when used with diesel oil. It requires a lower temperature for combustion, therefore, owes a greater heat of evaporation thus can also help in the reduction of NOx discharges (Rakopoulos et al. 2010). Consequently, the employment of butanol as biofuel seems to be more appealing as equated to the extensively used ethanol as well as biodiesel.

Butanol is produced by the process of fermentation by several rod-shaped, spore-forming, anaerobic, and Gram-positive bacteria called clostridia. The industrial production of butanol is restricted by several factors and one among them is the elevated substrate cost coupled with lower yields. The economics behind the production process is largely governed by the fermentation substrate. Therefore, various renewable, as well as economically realistic substrates are always a matter of concern (Lépiz-Aguilar et al. 2011). Therefore, the easily available and low-cost lignocellulose materials seem to be offering several potential benefits over prevailing, energy-demanding bioethanol manufacturing methods. An acetone-butanol-ethanol fermentation plant in Russia is supposed to be the only fermentation plant that works at an industrial scale by utilizing lignocellulosic waste materials as a substrate for butanol fermentation (Jin et al. 2011). The bacteria *Clostridium acetobutylicum*/*Clostridium beijerinckii* are most often employed for the production of acetone–butanol–ethanol. Furthermore, it is also found that pentose sugars accompanied by hexose sugars are competently utilized by the same microbial culture.

The usage of both the sugars as substrate at similar times may make acetone–butanol–ethanol fermentation much striking than ethanol or any other solvent production process (D'Aquino 2007). The additional benefit of employing these bacteria as compared to others is their capability of utilizing both these lignocellulosic hydrolysate sugars as opposed to conventional ethanol-fabricating yeast species which are unable to use them. It has been reported by several researchers that the agricultural residues receiving proper pretreatment are fermented by the microorganism especially by *Clostridium beijerinckii* without any inhibition. Furthermore, it has also been found that the bacteria are capable of fermenting the agro-residues at a rate quicker than the control fermentations utilizing glucose as the substrate (Qureshi et al. 2008). There are numerous microbial strains that can also be utilized for butanol production, for example, *Clostridium acetobutylicum* P262 (renamed as *C. saccharobutylicum*), *C. beijerinckii* P260, *C. acetobutylicum* NRRL B643, *C. acetobutylicum* ATCC 824, *C. beijerinckii* LMD 27.6, *C. acetobutylicum* B18, *C. beijerinckii* BA101, *C. saccharobutylicum* P262, *C. aurantibutyricum*, *C. butylicum*, and *C. tetanomorphum*.

All these producer strains have earlier been used for industrial production processes. However, the culture of *Escherichia coli* has also been manipulated genetically for enhanced production of butanol (Qureshi and Ezeji 2008). Several other microorganisms have also been manipulated genetically in the quest to produce more robust and butanol tolerant species comprising *Corynebacterium glutamicum*, *Lactobacillus brevis*, *Pseudomonas putida*, *Bacillus subtilis*, and *Lactobacillus* *buchneri* (Qureshi et al. 2013a). Several agricultural residues have been studied for the production of butanol, for instance, wheat straw, corn stover, switchgrass, barley straw (Qureshi et al. 2013b). Therefore, the correct pretreatment coupled with optimal downstream processing could be an effective measure for exploiting agro-residues at an industrial scale for enhanced butanol production.

13.6.3 Biohydrogen Production

Nations across the globe are in continuous quest to find novel, pollution-free, and renewable sources of energy. The previous decades, however, have largely been dedicated to the production of bioethanol as well as biodiesel. The extra pressure levied by first-generation biofuels on the global food costs has largely added to the contemporary universal food crunch. Therefore, the utilization of agro-residues for energy production via biofuel synthesis seems to be a viable and renewable source of energy (Ni et al. 2006; Angelidaki et al. 2007). Hydrogen gas is deliberated to be one among the encouraging applicants for substituting fossil fuels. The progressions of biological origin are always reflected as the supreme eco-friendly substitutes for sustaining upcoming demands for hydrogen.

Like other biofuels, the production of biohydrogen by utilizing agro-wastes seems to be of many advantages owing to their abundance, low cost, renewability, and extreme biodegradability (Guo et al. 2010). Biohydrogen has the potential to be utilized unswervingly in combustion engines for conveyance, and after decontamination, it can also be used for generating electric power. It has a very high energy content per unit weight (142 kJ/g). The generation of water as the sole by-product by oxidative combustion, makes it a perfect and greatest eco-friendly substitute to fossil fuels (Piera et al. 2006). The elevated costs of hydrogen production, complex storage necessities, and distribution systems are the major factors that have largely restricted the employment of hydrogen gas as fuel (Dunn 2002). Presently, a major proportion of hydrogen is derived from fossil fuels (Nath and Das 2003) and the technique of water electrolysis has comprehensively advanced in current years. Nevertheless, all these methods are energy-demanding and are unsustainable progressions.

The hydrogen finding its origin from biological sources needs much less energy for its synthesis as compared to other methods. Furthermore, the utilization of agro-wastes which are further made up of multifaceted components by complex microbial systems by dark fermentation can prove to be the key technology for the production of biohydrogen gas by utilizing several crops remains (livestock waste and food waste) (Guo et al. 2010). The yield of hydrogen gas from different crop residues varies greatly. The yield of hydrogen is further found to be higher at thermophilic conditions as compared to mesophilic conditions (Karlsson et al. 2008). The varied contents of cellulose, hemicellulose and lignin are largely responsible for the variable yields of hydrogen gas.

The yield of hydrogen is considered to be inversely proportional to the lignin content of the crop residue (Guo et al. 2010). The hydrolytic activity of the producer microbes is often responsible for limiting biohydrogen production. The residue sample receiving suitable pretreatment can give elevated yields of biohydrogen (MTui 2009). A diverse array of microbial cultures is known to be eminent producers of biohydrogen. The pure cultures of hydrogen-producing bacteria mainly belong to *Enterobacter aerogenes*, *Bacillus coagulans*, *Clostridium butyricum*, and *Thermoanaerobacterium* spp. whereas the other bacteria that have been isolated from mixed cultures belong to *Clostridium saccharobutylicum*, *Clostridium pasteurianum*, *C. butyricum*, *Enterobacter aerogenes*, *Thermoanaerobacterium thermosaccharolyticum*, *Caldicellulosiruptor saccharolyticus*, *C. thermocellum*, and *Bacillus thermozeamaize* (Guo et al. 2010).

13.6.4 Biogas Production

Another important way of utilizing the dormant energy of crop residues is through anaerobic digestion. It is also a significant and sustainable measure of guaranteeing the energy supply and would surely play an imperative role in sustaining the future of energy supply from renewable and low-cost substrates. Biogas represents a multifaceted and renewable source of energy that has the potential to bring out the replacement of traditional fuels for producing power as well as heat. Furthermore, it can also be utilized as a gaseous fuel in motorized applications. The advanced form of biogas, biomethane, has the potential to replace natural gas in chemicals production.

Biogas is a renewable source of energy that is produced by the process of anaerobic digestion utilizing several organic and biodegradable substrates, such as, municipal wastes, animal and agricultural remains. It has a methane content of around 40–70% that can further be progressed (Mittal et al. 2018). It has also been well established that the biogas generated utilizing anaerobic digestion is significantly advantageous over other forms of bioenergy attributable to the energy-competent and eco-friendly aptitude of the production technology (Nishio and Nakashimada 2007; van Foreest 2012). In addition, the side product of this process, called digestate, is a high-value fertilizer utilized for crop farming and has the potential to replace common mineral fertilizers.

The biogas production technology is a well-established technology in European countries where the annual production has reached a level of 1.35×10^7 tons in the year 2014 (EurObserv'ER 2014). Germany is the pioneer nation in the worldwide production of biogas, with around 25% installed capability owing to the robust expansion of agricultural biogas plants on farms. It was also found that over and above 8000 agricultural biogas production units were functional in Germany in the year 2014 (Wagner 2015). A large number of countries are in a quest to develop novel pathways for biogas production utilizing biomass as well as residues and wastes as substrates (Edita 2015). The nations like US, China, and India are also spending a lot on developing substitute technologies for biogas production from cellulosic resources, and are deliberated to lead in future biogas production (Soetaert and Vandamme 2009).

The energy potential of agro-residues has also attracted major attention for being utilized as a substrate for biogas production, for instance, one hectare of cereal straw is endowed with an energy potential of 73 GJ which is approximately comparable to 200 liters of oil. However, straw and other products in this category have different combustion characteristics from those of woody fuels. Point transformation in ash and emission behavior of biomass-type straw means that different technical approaches are needed (Ionel and Cioabla 2010). Although it is highly suspicious that biogas derived from waste would meet the global energy consumption; however, the requirement for global sustainable waste management practices has led to research interest in alternate substrates based on agro-wastes (Weiland et al. 2009).

The crop residues generated as agricultural wastes are usually lignocellulosic in nature and appear to be an appealing substrate for biogas production. Their multifaceted structure proves to be a financial as well as a technical obstruction for operating bio-refineries (Yang and Wyman 2004). However, the efficiency can be fairly improved by the choice of proper pretreatment which indirectly governs the performance. The main objective behind the pretreatment is to make the process of anaerobic digestion quicker to increase the biogas yield. Once the complex substrate is converted into simpler units and is subjected to anaerobic digestion, it receives a succession of microbes which ultimately yields a mixture of gases with a major proportion of methane (Achinas et al. 2017).

In the Indian scenario, small and family-type biogas systems primarily exist and prevail in rural communities with their capacities usually alternating from 1 to 10 m^3 biogas production per day. Such plants mainly use animal excreta coupled with agricultural wastes as potential substrates for domestic biogas digesters, yielding biogas as well as bio-slurry with the potential of being used as organic fertilizers. Such plants are mainly accomplished by discrete families for generating energy for self-usage. On the flip side, outsized and industrial-level biogas units having a capacity above 5000 m^3 biogas predominantly use municipal or industrial organic wastes as substrates (Mittal et al. 2018).

However, there are continuous efforts by the government that introduce newer policies and offer biogas plants at subsidized rates for the promotion as well as increasing awareness among the people for setting up newer biogas plants along with the utilization of agricultural residues as substrates rather than burning them. Furthermore, the maintenance of soil organic matter is also advocated by utilizing agro-residues as substrates because the slurry is returned to the field as fertilizer. The slurry also contains a large part of chief nutrients such as phosphorus, nitrogen, potassium, etc. therefore the requirement of chemical fertilizers is reduced considerably since a considerable portion of the harvest from the field is being returned in another form. Additionally, the usage of agro-residues in combination with other substrates can also prove to be much efficacious.

13.7 Residues for Feed and Food Production

Rapid developments in science and technology have increased the living standard of human beings and have resulted in increased demands of food and animal feed. However, the introduction of high-yielding varieties along with chemical fertilizers has contributed a lot towards the enhancement in food crop production which has also led to the generation of huge biomass of agricultural wastes. The exploitation of such wastes is getting increased attention as the recycling of agro-wastes considerably advocates environmental sustainability by significantly reducing the environmental pollution. Moreover, the prevailing scarcity of feed for animals can also be addressed by fashioning new produce from crop residues through involvement of active microbes.

In addition, transforming crop residues into animal feed would be of dual benefit to mankind as it would also address the problem of waste disposal along with livestock feeding. The involvement of microbial systems can fairly improve the available nutrient content along with the enhanced digestibility. Besides, the crop leftovers can also act as a substrate for various kinds of solid-state fermentation for producing food like mushroom cultivation. Therefore, the extended applications of utilizing agro-residues for food and feed production can largely address the problem of food and feed scarcity.

13.7.1 Feed Production

The enhancement in animal feeding is among the significant and basic requirements for the proper management of livestock. The pitiable eminence of food is largely responsible for poor animal health as well as performance. The increased costs of feed have also contributed a lot to the deprivation of livestock from a good quality feed. Thus, acceptable and good-quality feed materials are among the most vital elements in farm administration. A major proportion of around 70% of the expenditure in livestock rearing is mostly for animal feed (Ajila et al. 2012). The fabrication of feed for animals is one of the most reasonable ways that pertain to utilize an extensive share of the agro-residues. However, this approach has been a part of conventional farming practices since the dawn of civilization. The manufacture of feed from agro-residues also signifies one of the chief cash returns to the farming community attributable to the fact that the claim for animal feed is always steady and enormous. The marketing is also relatively easy and the technologies involved are not too complicated.

The agro-residues for instance husk, pods, leaves, and tender stems are feeds with high nutritional value and contain a considerable amount of easily digestible protein. Therefore, they can be utilized for nourishing livestock in consort with the concentrate mixture (Ranjhan 1993; Bhatti and Khan 1996; Godoy et al. 2018). Furthermore, it has also been reported that the treatment of such residues with urea improves the digestibility as well as their nutritive value in a substantial way (Wanapat et al. 2009). The byproducts of one particular crop used in combination with the residues of other crops are also a useful measure of improving the nutritional status of the crop residues used as feed (Ranjhan 1993; Godoy et al. 2018). However, the higher concentration of a particular nutrient in a particular crop often limits its usage, for instance, the chief factor that limits the employment of legume byproducts as feed is the elevated concentrations of phosphorus in it, which results in inhibition of the feed consumption. Such residues are made suitable for consumption by the addition of various other substrates, such as the addition of a combination of molasses and diammonium phosphate or rather a balanced liquid supplement on chopped groundnut straw can help to overcome the feeding inhibition (Maglad et al. 1986; Ajila et al. 2012).

Different crop residues are often utilized directly for feeding animals, such as, wheat bran, which is also the main constituent for feed formulation, can be used to feed sick animals deprived of any side effect and is also known to produce laxative effects in the animal intestine. Bran has also a higher concentration of amino acids as compared to wheat and is also deliberated to be a rich source of water-soluble vitamins. The husk of rice is another important animal feed and is considered to be a good source of fibers. The use of rice bran alone as feed often results in colic pain because it leads to ball formation inside the intestine. Therefore, the use of rice bran in combination with some other residual crops can prove to be efficacious feed. The high oil content of rice bran makes it a suitable substrate for using it as a feed-in combination with other substrates. Maize gluten is also considered to be a very good feed attributable to its higher protein content. The wastes generated by the processing of agricultural products are also utilized as animal feeds. Although, there are certain advantages of using these residues as feed; however, their employment is often restricted by the presence of naturally occurring anti-nutritional elements, variability in the nutritional value of the feeds, and presence of pathogenic microbes and their toxins (Cheeke 1991; Ranjhan 1993; Ajila et al. 2012).

The agricultural residues are found to be highly contaminated due to the presence of mycotoxins which are highly toxic. Such mycotoxins can be reduced by using potent organisms endowed with the capability of bio-transforming mycotoxins into other non-toxic metabolites (Schatzmayr et al. 2006). Several bacterial and fungal species, for instance, *Flavobacterium aurantiacum*, *Aspergillus niger*, *Armillariella tabescens*, *Candida lipolitica*, *Corynebacterium rubrum*, *Trichoderma viride*, *Mucor*, *Neurospora*, *Rhizopu*s have the potential to detoxify numerous kinds of mycotoxins (Bata and Lásztity 1999). Several lactic acid bacteria are also found to be capable of degrading mycotoxins (Peltonen et al. 2001).

The crop residues are also found to be holding a higher proportion of lignin which is difficult to be digested by the ruminants. The treatment with appropriate microorganisms can considerably reduce the lignin content of the feed and thus can upgrade the nutrient status and improvement in the taste of the feed. Moreover, the chemical treatments for delignification are inapplicable for feed preparation due to the generation of toxic byproducts. Therefore, the crop residues receiving appropriate microbial treatment can prove to be easily digestible feed for animals. Treatment of processing residues with the co-culture of *A. niger* and *Candida utilis* has the potential to enhance the protein content of the residue (Bhalla and Joshi 1994). Several other microbes like *Kloeckera apiculafa*, *Saccharomyces cerevisiae*, *Pleurotus ostreatus*, *Rhizopus oligosporus*, *Gongronella butleri*, *Trichoderma longiobrachiatum*, *Pleurotus sajor-caju*, *Enterococcus faecium*, *Phaffia rhodozyma*, and *Sporobolomyces roseus* have the potential to upgrade the nutritional value of animal feed (Ajila et al. 2012).

Preparation of silage is another kind of transformation of agricultural residues into animal feed which results in a low pH feed for ruminant animals. It is a multi-step fermentative process that decreases the pH of feed below 4 and thus makes it resistant to microbial spoilage. During this process, microbes break down the cellulose and hemicellulose constituents of the substrate into their corresponding sugars which are further metabolized to low molecular weight acids, generally lactic acid. This process is typically governed by the utilization of appropriate enzymes and microbial silage inoculants for silage making (Colombatto et al. 2004; Okine et al. 2005). The effective and competent fermentation process yields a pleasant and digestible feed. There is a strict requirement of anaerobic conditions in a quick manner to enable the lactic acid bacteria to grow and dominate so that the pH of a substrate can be brought down quickly (Arvidsson et al. 2008). This depresses the decay of the silage by putrefactive aerobic microbiota and also guarantees the maintenance of a major proportion of the nutrients in the final product.

13.7.2 Food Production

The process of photosynthesis can fix about 200 billion tons of organic matter on this beautiful planet on an annual basis (Zhang 2008). Conversely, a major proportion of this organic matter is not available for direct consumption of human beings as well as other animals and at several times such an organic matter also becomes a nuisance for humankind when it starts raising environmental concerns. The present world is, however, suffering from a continuous escalation in the prices and declining nutritional standards along with a perpetual decline in the accessibility of raw materials (Laufenberg et al. 2003). The generation of around four billion tons of crop remains on an annual basis where a major proportion finds its origin from cereals (Lal 2008) demands its up-gradation to other products of higher values by exploiting numerous chemical or biological progressions. The numerous possessions of lignocellulosic agro-residues mark their employment as a substrate with huge importance and biotechnological value. Such residual matter is endowed with the numerous potentials for being used as a substrate for solid-state fermentation to produce various food materials.

Mushroom cultivation is an economically effective process of great ecological significance that can be effectively utilized for bio-transforming agro-residues. The cultivated mushroom species is a wonderful food source and is endowed with numerous pharmacological possessions, for instance, antiparasitic, antiviral, antibacterial, antiatherosclerosis, antitumor, antidiabetic, antihypertension, hepatoprotective, anti-inflammatory, and immuno-modulatory effects. Industrial mushroom production is a biological process of small duration which marks the proteinaceous food production from the agricultural-residues attributable to the degrading aptitude of mushroom (Martınez-Carrera et al. 2000; Chiu and Moore 2001). The mushroom belonging to the class *Lentinula edodes* and *Pleurotus* species are endowed with exceptionally higher degradative potential with a capability of utilizing a vast number of lignocellulosic residues.

The mycelium of these organisms produces substantial magnitudes of numerous enzymes that are capable of degrading the complex lignocellulosic residues and exploit them as a source of nutrients for their growth as well as proliferation (Bushwell et al. 1996; Elisashvili et al. 2008). Conversely, the type and nature residue used for mushroom cultivation strongly affects the quality of the mushroom. The varieties of mushrooms that are cultivated globally are largely represented by *Agaricus bisporus*, *Pleurotus ostreatus*, and *L. edodes*, followed by *Auricularia auricula*, *Flammulina velutipes*, and *Volvariella volvacea*. Other mushroom species produced successfully on various substrates include *Agrocybe aegerita*, *Ganoderma* spp., *Grifola frondosa*, *Hericium erinaceus*, *Hypsizygus marmoreus*, *Lepista nuda*, *Coprinus comatus*, *Pholiota nameko*, and *Stropharia* spp. (Stamets 2000; Royse 2004).

The international mushroom harvest exceeds ten million metric tons, where China dominates the market followed by Europe and the US (Desrumaux 2007; Huang 2007). The marketable mushroom fabrication is also a solid-state fermentation process utilizing lignocellulosic materials at a much larger scale. The industry of mushroom cultivation is the biggest biotechnological industry which thrives on solid-state fermentation by utilizing lignocellulosic biomass as the feedstock (Moore and Chiu 2001).

The act of mushroom cultivation seems to be a much economic viable phenomenon attributable to the use of low-value remains of agro-ecosystems. Furthermore, these wastes are handled utilizing moderately cheaper microbial technologies to yield human foodstuff, which is further deliberated to be a functional food or as a source of numerous drugs and pharmaceuticals. Additionally, the operational utilization of resources finding their origin from agricultural leftovers is a comprehensive environmental protection approach (Zervakis and Philippoussis 2000). The process of mushroom cultivation is also a holistic approach to production. This approach attempts to join diverse goals, for instance, enhancement in the product quality, maximum production efficacy, and amalgamation of ecological characteristics into product formulation and food manufacturing. It is also an exceptional practice of crop management that manages the remaining growth medium after cropping as feed for animals as the mycelial tissue of mushroom improves the protein proportion, as fertilizer for soil attributable to its richness in nutrients and other diverse constituents that upgrade the soil structure, as a basis of enzymes, for the bio-control of plant pathogens and even utilized for the bioremediation drives as it encompasses a diverse community of microbes that is capable of digesting natural phenolic constituents of lignin (Philippoussis 2009).

13.8 Conclusion

Microbes are ubiquitous in nature and seem to be the last ray of hope when the prevailing practices seem to be challenging for mankind. The improper management of such a large volume of agricultural residues not only deteriorates soil health but is also responsible for the declining status of human health. The common practice of burning the agro residues generates a lot of particulate matter that is responsible for causing a large number of respiratory diseases along with several other metabolic disorders. Microbial systems can be carefully employed for altering the nature of resistant agro residues. The microbial treatment shapes them into new products which on application to soil significantly enhance the physical, chemical, and biological attributes of the soil. The transformation of the waste products into food and feed is of extreme importance as it can be used to combat the malnutrition and prevailing scarcity of food and feed.

In this era of technology, the comforts of human beings are largely guided by exploiting petroleum resources directly or indirectly which ultimately deteriorates the environmental status. The incredible capability of microorganisms of transforming waste products into different kinds of biofuels can prove to be a miracle for future generations under the limitations of petroleum resources. Furthermore, more robust technologies need to be developed to increase the yield of microbial fermentations regarding biofuel production. The major constraint experienced by the farming community in the composting of agro residues is the extended period taken during the compost preparation. This problem can be addressed by exploring the numerous hidden potentials of microbes or by isolating microbial members with enhanced capabilities of degrading the agro wastes. The development of such a microbial consortium that can degrade the agro residues on the field conditions in a quick manner can largely contribute to the prevailing concerns associated with the generation of such a vast amount of agro residues. In addition to it, microbes also generate several compounds that are synthesized at a level that is beyond the detection limits. Therefore, on a long way to the future, the sensitivity of currently operating detections systems will improve and multiple novel bioactive compounds of microbial origin will be identified. In addition, the bio-synthesis of these microbial origin compounds at the industrial level using waste products will see the future researcher's interest.

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