Chapter 2
Microbiota in Sustainable Degradation of Organic Waste and Its Utilisation in Agricultural Industry

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Abstract Biological treatment is a method that employ to degrade organic waste. Because of their metabolic activity, microorganisms can survive in every severe situation on Earth. Bioremediation is an all-inclusive action of microorganisms in the destruction, immobilisation or detoxification of various chemical wastes and harmful elements from the environment. Because of their specialised use, all biore-

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mediation strategies have their own pros and cons to choose based on the requirement. Increased waste products and depleting natural resources have shifted human focus to efficient green and clear production systems. Understanding the mechanisms of degradation, is critical to eliminating the need for additional pretreatment of lignocellulosic chemicals in the waste mixture and facilitating the commercialisation of organic waste technology. In addition to that, health of the soil and a measure of a complex series of biological, chemical and physical interactions driven by the nature of organic waste added to it must be explored to successfully utilize the technology. Effective microorganisms boost the beneficial microbial population and improve soil chemical and physical properties, allowing for long-term crop production. This chapter discusses the convergence of microbial technology, as well as the functions of microbiota in attaining sustainability in organic waste degradation and utilisation in the agricultural business.

Keywords Microbiota · Immobilisation · Degradation · Organic waste · Sustainable agriculture

1 Introduction

Sustainability in agriculture refers to the long-term preservation of soil productivity through the use of natural resources without harming the environment. The maintenance and protection of natural resources, particularly a diversified and functional microbial community in the soil, is critical for sustainable agriculture (Umesha et al. 2018). Environmentalists are beginning to adopt integrated soil management, which emphasises the management of ecosystem functioning through nutrient cycling, waste management and soil microbial diversity management (Naeem et al. 2002). Given a precise set of environmental and cultural conditions, microorganisms' distinctiveness, as well as their frequently unpredictable nature and biosynthetic capabilities, has made them plausible candidates for tackling exceptionally challenging challenges (Wu et al. 2012). Sustainable agriculture is a farming method based on ecological principles, which is the study of the interactions between organisms and their environments (Rastegari et al. 2020). Nonetheless, despite significant success in applying microbial technologies to different agricultural and environmental challenges in recent years, they have not been universally acknowledged by the scientific community since it is sometimes difficult to reliably recreate their beneficial effects (Trivedi et al. 2021). The United Nations established the 2030 Sustainable Development Goals in January 2016 to achieve environmental, social and economic growth through green approaches and cleaner industrial technology (Akinsemolu 2018). A wide range of microbial enzymes are involved in the biodegradation of an organic substance, changing both manmade and natural hydrocarbons into intermediate products that may be less dangerous than the parent chemicals. Because biodegradation is a step-by-step process, the intermediate molecules are transformed into carbon dioxide, water and soluble inorganic chemicals through further processing or degradation. Indigenous microorganisms are a type of intrinsic microbial consortia that lives in the soil and on the surfaces of all living things, inside and out, and have the capacity to biodegrade, fix nitrogen and improve soil fertility, act as phosphate solubilisers and promote plant growth (Kumar et al. 2018). Without these bacteria, life on our vibrant planet would be bleak and depressing for the survival of the human species. Microorganisms are the most diverse and numerous natural resources, but due to their smaller size, they are being overlooked. Recently, efforts have been made to incorporate microbial diversity into soil classification and management programmes (Rao and Patra 2009). The organic fraction of solid waste has been identified as a significant resource capable of being transformed into useful products by microbial-mediated transformations (Damtie et al. 2021). There are other strategies for treating organic waste, but anaerobic digestion appears to be a promising strategy. The anaerobic treatment of solid organic waste is less common than the aerobic procedure, owing to the longer time required for biostabilisation (Hakeem et al. 2021; Fernandez et al. 2022). The mechanism is also vulnerable to large quantities of free ammonia produced by anaerobic breakdown of nitrogen-rich protein components. The specific activity of methanogenic bacteria was discovered to decrease with increasing ammonia concentrations (Lee et al. 2019). The chemical content and structure of lignocellulosic materials slow the biodegradation rate of solid organic waste. Hydrolysis of complex organic materials to soluble molecules has been shown to be the rate-limiting step in anaerobic processes for wastes with a high solid content (Wang and Wang 2018). As a result, various physical, chemical and enzymatic pretreatments are necessary to increase substrate solubility and speed of solid organic waste biodegradation. Nonetheless, even with this limited data, considerable changes in the diversity of essential microorganisms engaged in nutrient conversions, antibiosis, plant disease control and growth promotion occur in response to various soil management strategies used in intensive agriculture (Bonanomi et al. 2018; Dar et al. 2022). This chapter will describe the role of bacteria in the long-term breakdown of organic waste and its application in agriculture.

2 Organic Waste Generation and Its Sources

Human development and growth depend greatly on agriculture. This is a result of the production of fibre and food, both of which are essential to human life on Earth. However, the production of a lot of wastes like animal manure and crop residues is also a part of agriculture. These wastes are typically difficult to dispose of and frequently degrade the quality of the environment. Hence, they are dumped on open fields or burned in the majority of the regions across the world, while those left on the field are subject to wetting and dry processes that may occasionally result in anaerobic conditions leading to bad odour and facilitate the spread of epidemic diseases (Lokeshwari and Swamy 2010). According to Aiyelari et al. (2011), burning agricultural wastes could have a negative impact on both human health and the environment due to the release of greenhouse gases into the atmosphere that could have an impact on global warming. The effects of this phenomenon include potential for chaotic weather patterns, food insecurity, starvation and malnutrition (Preston and Leng 1989). In recent years, agricultural production has advanced beyond the emphasis on high-yield production to improved food quality, human nutrition and environmental quality through practices that enhance food security while advancing environmental health and sound ecology. Rodale (2011) suggested that the goal should be an agricultural management system that has the ability to preserve or improve soil quality and the environment rather than concentrating on higher yields, which will eventually exhaust soil nutrients. The majority of agricultural wastes, according to Lokeshwari and Swamy (2010), contain biodegradable hemicellulose and cellulose materials, which when decomposed improve soil qualities and supply crops with nutrients. They can be processed properly to become marketable materials or used as a source of energy, bedding, manure, mulch, compost, organic matter or plant nutrients. With the expansion of the population, waste generation is rising daily, which has an immediate impact on the environment and the economy. The agricultural and municipal solid waste (MSW) sectors in India contribute the most to waste production while its improper handling harms the environment and poses health risks. As a result, managing organic waste is crucial given the rising demand for energy. Agro-waste comes in a variety of forms depending on the source and accessibility in the environment. As a result, these wastes can be divided into four main generations according to their capacity to produce various products (ElMekawy et al. 2015):

First generation This group includes a variety of food crop classes, including sorghum, corn, rice and wheat. The direct use of these crops as a primary feedstock of interest is frequently linked to the production of energy and a variety of goods. The competition between this generation's use in the production of fuel and food is one of its greatest problems. Production of fuel is thought to have a higher return on investment than that of food.

Second generation This generation typically consists of lignocellulosic wastes that can be used to produce bioenergy using various waste beneficiation techniques such as the following:

1. Sugarcane bagasse
2. Wood chips
3. Crop residues
4. Organic waste

This kind of waste is linked to the removal of significant barriers present in first-generation biomass.

Third generation Microalgal biomass is used as a feedstock in energy source production systems. As a result, its cultivation can be accomplished with ease in lagoons and open ponds using wastewater that contains a nitrogen-rich agro-waste compound.

Fourth generation This kind of biomass is produced by metabolically modified organisms like bacteria, including algae produced as a result of cleaner disposal, or by emission control techniques like CO_2 capture systems. This raises the generation's value because it can be used to produce high-value goods with higher requirements for polymeric hydrocarbon content or other bioenergy products.

According to the Solid Waste Rule (2016), waste should be divided into three different streams by the generator and stored in appropriate bins: domestic hazardous, biodegradable and non-biodegradable wastes. The Ministry of Urban Development (MUD) aimed at achieving sustainable municipal solid waste management (MSWM) system based on 3R principles, such as reduce, reuse and recycle, with appropriate systems of collection, segregation, processing, transportation and disposal with the introduction of the Solid Waste Rule (2016) of the Ministry of Environment, Forest and Climate Change (MoEF& CC). The MSWM system in India still does not fully follow every link in its chain. Only 21.45% of MSW is treated, and the remainder is still being dumped in landfills, according to the Swachh Bharat Mission (SBM) database and State-by-State status of implementation of various components under SBM (up to September 2016).

As per the direction given by the local authorities from time to time, the segregated wastes should be given to the authorised waste pickers or waste collectors. Municipalities are primarily in charge of waste collection. However, one of the biggest issues is the segregation component. The majority of urban local bodies (ULBs) lack the resources, the capacity and the necessary action plan to implement and enforce the solid waste rule. After China, India is the second largest producer of paddy in the world. Currently, India produces around 130 million metric tonnes (MT) of rice straw and 98 million MT of paddy. Nowadays, on average 50% of rice straw is used as animal feed, and the other 50% is simply thrown away with other solid wastes. India also generates about 50 million MT of cane trash from its 350,000 MT of cane production, which has the potential to be used to make fuel with the right processing. Cane trash, which has no commercial use and is entirely burned to reduce volume, has a very high silica content. Other agricultural wastes are also available in India, including maize, cotton, millets, pulses, sunflower and other stalks, groundnut shells and coconut trash. Due to crop cycle and time constraints, farmers frequently burn large amounts of biomass, which increases haze, contributes to global warming and has a negative impact on the environment and human health. In India, MSW's primary physical components are recyclable, compostable and inert. Around 40–60% of Indian MSW is biodegradable, 30–50% is inert waste and 10–30% is recyclable (Kumar et al. 2009). He also found that the nitrogen content of MSW is 0.64 ± 0.8%, the phosphorus content is 0.67 ± 0.15%, the potassium content is 0.68 ± 0.15% and the C/N ratio is 26 ± 5.

3 Mechanisms of Microbial Degradation of Organic Wastes

Bianchi (2011) stated that natural organic matter (NOM) is the planet's greatest reactive source of reduced carbon (C), and the transformation and breakdown of NOM are of vital importance because of their effects on the global carbon cycle and ecosystem C flow (Heimann and Reichstein 2008). In a wide range of environments including soil, sediment, the ocean and freshwater, microorganisms are important mediators in the generation, mobilisation, transformation and storage of NOM (Xue et al. 2016).

In the context of microbiology, "biodegradation" refers to the breakdown of all organic materials by living things, primarily bacteria, fungi, protozoa and other organisms. By definition, biodegradation means "the transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria". Hazardous toxic pollutants are changed into less toxic or nontoxic materials through this naturally usual process. Secondary metabolites, intermediate molecules or any breakdown products from one species can feed another, serve as a source of energy and carbon for that organism and continue the process of decomposing remaining organic matter (Eskander and Saleh 2017). As nearly every waste product created by other living things is degraded or eliminated with the aid of some of its enzymes, microorganisms play a crucial role in biogeochemical cycling and help recycle nutrients. Therefore, waste does not exist from a microbiological standpoint (Eskander and Saleh 2017). Organic wastes are substances that may biodegrade and are primarily produced by both plants and animals. Fruit waste, food waste, grass clippings, cow manure, human waste, abattoir waste, paper trash and agricultural leftovers are some types of organic waste. These wastes are frequently disposed of by landfill disposal, incineration or composting. As a result of varied disposal methods, greenhouse gases including methane and carbon dioxide are frequently produced. The disposal techniques must be closely watched because poor disposal practices can cause serious environmental issues like drain clogging, insect infestations, air pollution in the vicinity of the landfill site, leachate contamination of nearby reservoirs and frequently burning in the landfill site. Microorganisms use different pathways for degrading organic wastes. Depending on the type of microorganisms, either they may consume the entire organic molecule in a process called "ultimate biodegradation" or they will consume only a portion of it, destroying the full parent component. During the energy-producing phase of metabolic activity, oxygen is used, which causes the "mineralisation" process, which immediately produces carbon dioxide, water and mineral salts.

4 Types of Biodegradations

A biochemical process, "biodegradation", is mediated by microorganisms. Based on microbial involvement and respiration behaviour, biodegradation is classified as aerobic biodegradation and anaerobic biodegradation. Aerobic biodegradation refers to the process by which microbes convert complex organic substances to simpler ones in the presence of oxygen, while in the latter anaerobic process, the process occurs in the absence of oxygen. An electron acceptor, which is itself reduced, often oxidises an organic substance (which loses electrons) (which gains electrons). Oxygen serves as the electron acceptor in an aerobic environment or a poisonous environment. Aerobic respiration is defined as the oxidation of organic substances along with the reduction of molecular oxygen. Microorganisms can utilise organic compounds or inorganic anions as alternate electron acceptors in anaerobic environments (the absence of oxygen). Anaerobic biodegradation can occur under fermentative, denitrifying, iron-reducing, sulphate-reducing or methanogenic conditions.

4.1 Aerobic Biodegradation of Organic Wastes

Composting is indeed the technique used to turn organic wastes into valuable products via the aerobic route. It is defined as the biological metabolic action of microorganisms such as bacteria, fungi and actinomycetes under ideal circumstances over some time to produce a stable end product. The final output is called compost. The stoichiometries involved in the composting process are as given below.

$$\text{Complex organic substrates/Organic Matter} + O_2 + \text{Nutrients (for microbial growth)} \xrightarrow{\text{Aerobic Microbes}} CO_2 + H_2O + NH_3 + SO_4^{2-} + PO_4^{2-} + \text{Resistant organic matter} + \text{New microbial cells} + \text{Heat}$$

Liwarska-Bizukojc and Ledakowicz (2003)

The processes involved during the waste stabilisation stage are hydrolysis, oxidation, biomass synthesis and endogenous respiration (Ramana and Singh 2000). The initial process is hydrolysis, which is the breakdown of complex substrates like sugars and amino acids by enzymes produced by microbes like bacteria. Oxidation reactions are carried out to meet the energy requirements of the newly generated microorganisms. Oxygen is the terminal electron acceptor in the aerobic process. Subsequently, microbial proliferation occurs and leads to biomass synthesis.

4.1.1 Phases of Aerobic Composting

The composting process is characterised by rapid decomposition in the initial stage leading to a temperature rise followed by slower decay of the remaining substrates. The initial phase is dominated by mesophilic organisms which thrive in the temperature range of 20–40 °C. The mesophilic stage is dominated by bacteria and fungi. They encourage organic decomposition during composting by releasing several substrate-based hydrolytic extracellular enzymes like cellulases, xylanases, amylases, ligninase and laccase that break down the complexly structured molecules (i.e. plant polymers, cellulose, hemicellulose and lignin) and produce water-soluble compounds (Echeverria et al. 2012). These reactions supply the substrate for biomass generation required for further stages of composting.

The composting pile's temperature rises as a result of the mesophilic organisms' tendency to emit heat during their metabolic processes. The mesophilic species die as a result of the temperature increase, and a new population of creatures known as thermophilic organisms takes their place in the compost pile that can adapt to higher temperatures. They can endure temperatures greater than 40 °C. The pasteurisation and stability of the compost are aided by this step, which may witness temperatures reaching 65 °C. When temperatures naturally climb to 55 °C, harmful pathogens are killed (Ravindran and Sekaran 2010), and weed seeds and pathogens are destroyed (Zhang and Sun 2014) if high temperatures persist for 3 days, helping to produce a higher-quality product. Complex substrates, including lignin, lipids, cellulose and hemicellulose complexes, break down during this phase. Due to nutrient depletion in the medium, bacteria begin to eat their protoplasm through endogenous respiration. Cells die and lyse as a result of this event. As a result, between 5% and 80% of the components of the cell are oxidised. In the end, the population of thermophiles decreases with the decrease in the availability of substrates, the mesophilic microbial community once again proliferates and this phase of composting is called the curing or maturation phase. A reduced temperature and a decline in microbial activity mark the cooling phase. Mesophilic microorganisms recolonise the compost pile, degrading the remaining sugars, cellulose and hemicellulose to produce humic-like compounds (Albrecht et al. 2010). The rate of organic matter breakdown declines after that, while the rate of humification and polymerisation of the organic compounds rises. This ensures the effective production of an amorphous dark-brown humus-rich material that may be directly applied to plants.

4.2 Anaerobic Biodegradation of Organic Wastes

Anaerobic digestion (AD) is a multiphase microbial-driven complicated biochemical process that is widely used to generate biomethane. The process is the same as aerobic composting, but the difference is that here anaerobes play the major role and convert organic wastes to methane and carbon dioxide. AD involves four main phases hydrolysis, acidogenesis, acetogenesis and methanogenesis.

4.2.1 Steps Involved in the Anaerobic Process

The hydrolysis phase involves breaking down the complex organic molecules like polysaccharides, proteins and lipids to low molecular weight and simpler water-soluble monomers like glucose, amino acids and fatty acids by the action of hydrolytic enzymes produced by facultative anaerobic bacteria. The first step is very crucial as more complex materials are first broken down. Ventorino et al. (2018) stated that fermentative bacteria make use of the extracellular enzymes connected to their cell wall, including cellulase, protease and lipase. The most prevalent phyla of bacteria include Firmicutes, Actinobacteria, Bacteroidetes, Chloroflexi and Proteobacteria, which are reported to be the primary hydrolytic fermentative bacteria implicated in the AD process (Luo et al. 2018; Yadav and Vivekanand 2021). *Streptococcus* and *Enterobacter* are the principal taxa involved in hydrolysis, with *Bacteroides*, *Lactobacillus*, *Propionibacterium*, *Sphingomonas*, *Sporobacterium* and *Bifidobacterium* also participating (Yadav et al. 2022).

$$\underset{\text{(polysaccharides)}}{\left(C_6H_{10}O_5\right)_n} + 6H_2O \rightarrow \underset{\text{(glucose)}}{C_6H_{12}O_6}$$

Then the fermentative microbes termed acidogenic bacteria produce volatile fatty acids (VFAs) like acetic acid, propionic acid and formic acid from the monomers along with the production of H_2S, CO_2 and NH_3 (Dhanya et al. 2020). Bacteroidetes, Firmicutes and Clostridium are the dominant phyla in the process while the *Ruminococcus*, *Paenibacillus* and *Clostridium* are the most active genera in the acidogenesis phase. Out of all phases in AD, acidogenesis is the most important phase. The formation of VFA follows many different pathways depending upon the end product, but pyruvate plays a major role in the formation of each VFA. These metabolic pathways are classified as acetate-ethanol, propionate, butyrate, mixed-acid and lactate-generating metabolic pathways based on the end product (Zhou et al. 2018). Only formate, acetate and H_2/CO_2 may be directly absorbed by methanogens as a substrate for methane synthesis. Propionate, butyrate, ethanol, butanol, lactate and other products must be oxidised syntrophic acetogens into formate, acetate and H_2/CO_2. The fatty acids produced from the acidogenesis phase are converted to acetate, hydrogen and CO_2 by acetogenic bacteria. The phase proceeds with two types of organisms, namely, acetogenic bacteria, that produces acetate from VFAs, and the other group of organisms called acetate-degrading organisms, which oxidise the acetate to produce H_2 and CO_2. The final step is the conversion of acetate or H_2 to methane by methane-forming microorganisms belonging to archaea. The acetoclastic methanogens convert acetate to CH_4, while another group of methanogens called hydrogenotrophic methanogens reduce CO_2 and H_2 to CH_4.

$$CH_3COOH \rightarrow CH_4 + CO_2 \left(\text{acetoclastic methanogenesis}\right)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 3H_2O\left(\text{hydrogenotrophic methanogenesis}\right)$$

Methanosaeta, *Methanosarcina*, *Methanococcoides*, *Methanosalsus* and *Methanogenium* are some of the predominant genera involved in AD (Kong et al. 2019; Yadav and Vivekanand 2021).

5 Microbial Intervention in the Breakdown of Organic Wastes

Sustainable degradation stresses the importance of the development of new technologies for the environmental management of organic waste due to the escalating anthropogenic activities. Microbes, indigenous as well as inoculated, play a prominent role in the degradation of organic wastes either by (1) aerobic or (2) anaerobic method of degradation (Fig. 2.1 and 2.2). Oxygen is the key factor in controlling the nature and rate of degradation. Microbes are responsible for mineralisation of plant nutrients and depolymerisation of complex molecules by extracellular enzymes along with heat generation (Bernardi et al. 2018; Holman et al. 2016; Kutu et al. 2019). Recycling of organic wastes results in the generation of organic manure,

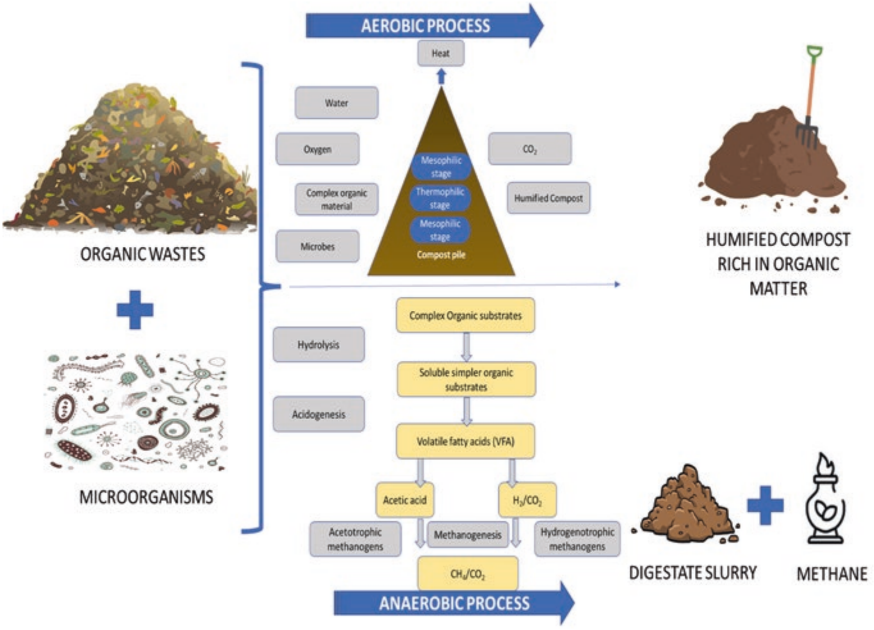

Fig. 2.1 Mechanisms involved in organic waste degradation

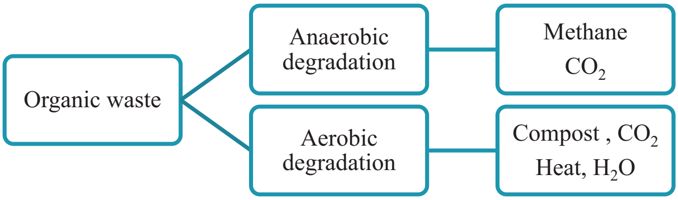

Fig. 2.2 Basic schema of microbial breakdown of organic wastes

animal feed, liquid fertiliser, biogas, peat alternatives, etc. Microorganisms such as *Bacillus*, *Pseudomonas*, *Flavobacterium*, *Mycobacterium*, *Xanthobacter*, *Nocardia*, *Trichoderma*, *Phanerochaete*, *Cyanobacteria* and many more are actively involved in the degradation of organic waste (Hassan and Sabreena 2022).

Microbes are either applied in pure or mixed cultures to accelerate the rate of disintegration. Mostly multiple consortiums are inoculated to accelerate the maturation which is effective (Duan et al. 2020; Abdel-Rahman et al. 2016). In some cases, mixed cultures resulted in unfavourable results in contrast to other findings. For instance, commercial inoculants such as EM and LDD1 were used against food scraps with dry leaves which denied the introduction of mixed consortia (Karnchanawong and Nissaikla 2014). Time of inoculation also plays a dividend role in decomposition. Mostly, cultures are introduced at the initial stage. Some researchers reported the inoculation at different phases such as cooling phase to reduce the effect of high temperatures (Zhao et al. 2016), inoculation of trichoderma at maturation phase and suppressed fusarium wilt (Bernal-Vicente et al. 2012) in case of composting. Microbial enzymes such as cellulose, hemicellulase, amylase and laccase act on the complex molecules rich in lignin, cellulose and hemicelluloses which also inhibit the growth of fungal pathogens.

5.1 Aerobic Degradation

Bioconversion of organic wastes with oxygen is termed to be aerobic degradation. This group of microorganisms utilise oxygen in order to feed nutrients from the organic matter developing into cell protoplasm (Cadena et al. 2009; Mehta and Sirari 2018). Forest is a best example for aerobic degradation where leaf litters and other plant and animal residues get converted into stable organic matter. In most of the waste treatment processes, aerobic degradation is used as a pretreatment process followed by anaerobic digestion. The major advantages are fast degradation, reduction in volume of wastes, detoxification of organic wastes, no odour, no emission of greenhouse gases and other volatile organic compounds (Gómez et al. 2012). Table 2.1 enlists some of the microbes associated with the aerobic breakdown of different organic wastes.

In general, organic waste comprises of 40–60% protein, 25–50% carbohydrates and 10% fats and oils. Basic biochemical reactions in the breakdown process were hydrolysis, oxidation, cell synthesis and biomass generation followed by endogenous respiration (Ramana and Singh 2000). A massive breakthrough in aerobic degradation is greenhouse gas emission reduction. For instance, at a swine farm in the USA, replacing lagoon technology with aerobic technique resulted in 96.9% reduction in greenhouse gas emission (methane from anaerobic decomposition and nitrous oxide from handling and storage) from 4972 tonnes of carbon dioxide equivalent to 153 carbon dioxide equivalents (Vanotti et al. 2008).

Table 2.1 Microbes in aerobic degradation of organic wastes

Microorganism	Substrate/type of waste	References
Bacillus, Brevibacillus, Paenibacillus, Pseudomonas and *Klebsiella*	Food waste	Ren et al. (2021) Msarah et al. (2020)
Bacillus paralicheniformis and *Bacillus velezensis*	Food waste	Roslan et al. (2021)
Bacillus and *Halobacillus*	Farm and food waste	Chander et al. (2018)
Aspergillus and *Penicillium*	Wood chips	Jia et al. (2021)
Terrisporobacter	Piggery waste	Wei et al. (2022)
Enterococcus, *Pseudomonas* and *Idiomarina*	Food and sewage sludge	Chen et al. (2021)
Trichoderma, *Phanerochaete*, *Aspergillus*, *Penicillium* and *Azotobacter*	Rice straw and cattle manure	Greff et al. (2022)

5.2 *Anaerobic Degradation*

Anaerobic degradation involves the conversion of complex molecules into simpler products under anoxic conditions. It tends to benefit us with energy-rich products rather than aerobic degradation. Similar to aerobic degradation, anaerobic microbes feed on organic wastes without oxygen and develop their cell protoplasm (Cayuela et al. 2012). Anaerobic digestion mainly involves four stages (1) hydrolysis, breakdown of polysaccharides to monosaccharides with the aid of hydrolytic bacteria and its enzymes (xylanase, cellulose, glucosidase, peptidase); (2) acidogenesis, sugars and amino acids to alcohols and ketones; (3) acetogenesis, alcohols to acetic acid; and (4) methanogenesis, generation of methane (*Methanobacterium*, *Methanosarcina*, *Desulfovibrio*, *Methanococcus*, *Methanobrevibacter*, *Methanothrix* and *Methanospirillum*). Table 2.2 enlists microbes in anaerobic decomposition of wastes into compost, biogas, biodiesel, enzyme recovery, liquid fertiliser, etc.

Engineered microbial consortia are also encouraged for product generation. Jiang et al. (2020) developed an anaerobic coculture for butanol production from hemicelluloses by combining *Clostridium acetobutylicum* and *Thermoanaerobacterium saccharolyticum*. Coculture was developed from methanogen and anaerobic fungi, and performance was compared with native microbes (Gilmore et al. 2019). These technologies got the attention of scientific community, and several researches were being carried out to manage the waste into getting desired end product.

Table 2.2 Microbes in anaerobic degradation of organic wastes

Microorganism	Substrate/type of waste	References
Pseudomonas aeruginosa and *Klebsiella pneumoniae*	Waste cooking oil	Sharma et al. (2022) Liu et al. (2018)
Bacillus thuringiensis, *Brevibacillus borstelensis* and *Bacillus licheniformis*	Food waste	Awasthi et al. (2018)
Firmicutes, *Bacteroidetes* and *Proteobacteria*	Wheat straw waste	Jin et al. (2022)
Rhizomucor	Orange peel and oatmeal	Yang et al. (2015)
Rhizopus and *Fusarium*	Vegetable waste	Sabater et al. (2020)
Actinomyces, *Bifidobacterium*, *Clostridium*, *Propionibacterium* and *Staphylococcus*	Sewage sludge	Cyprowski et al. (2018)

6 Utilisation of Value-Added Products from Sustainable Microbial Degradation in Agriculture

The past few decades witnessed a soar in food production due to the advent of the green revolution. This boosted grain production and increased agrochemicals' use to increase crop yield. Though there was an increase in food grain production, poverty and hunger could not be eradicated because of land degradation problems, deforestation, etc., to increase the agricultural land availability for feeding the rising human population. This, together with the usage of agrochemicals, exacerbated the concerns of deteriorating human health by contaminating neighbouring reservoirs and remaining in the soil for extended periods. In addition, the cost of those products went so high that marginal farmers could not afford them. As a result, the globe needs a cost-effective and eco-friendlier product that can preserve both the ecology and human health at the same time (Fig. 2.3).

Thus, sustainable agriculture emerged as an alternative concept that is not only eco-friendly but also lowers the farmers' expenditure on agriculture. It refers to agriculture's ability to contribute to general well-being over time by producing enough food and other commodities and services in economically effective and successful, socially responsible and ecologically sound ways. This practice involves the combined use of agriculture and livestock practices in a way that reduces the need for external inputs, thereby increasing the health of the environment and consumers. It accounts for practices that manipulate the local natural processes like nutrient cycling and nitrogen fixation. Composting is one such practice that recycles the organic waste produced by the farm, thereby returning the nutrients to the soil.

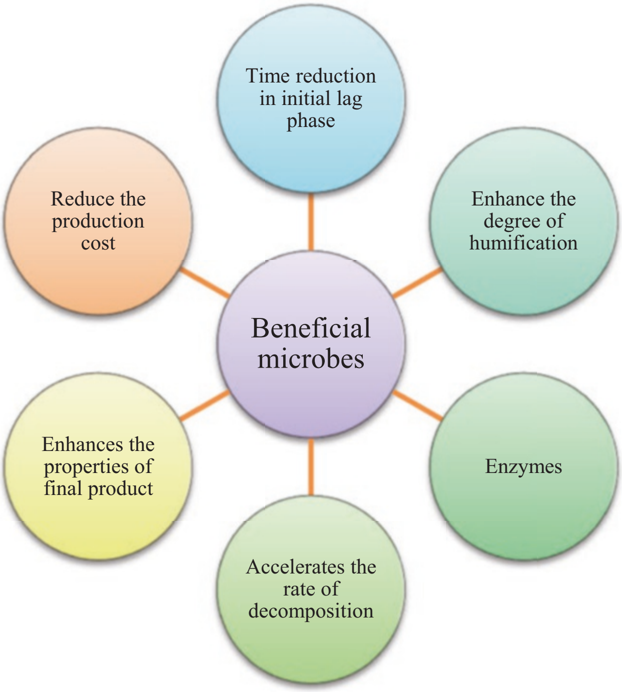

Fig. 2.3 Significance of microbial degradation of organic wastes (Chi et al. 2020; Fang et al. 2019; Wang et al. 2019; Gou et al. 2017)

(i) *Compost*

Compost is an ideal alternative solution for fertilisers as it has a great effect on microbial activity in the soil and its organic matter content (Garcia et al. 2017). Healthy soil is when it contains higher microbial activities, and it is a key factor in nutrient recycling through enzymatic activities (Bünemann et al. 2018; Li et al. 2015). Compost application was found to be an effective method for enhancing the rhizosphere microbial activities of the soil, which also increases plant growth and yield (Sayara et al. 2020). This is because the compost slowly releases nutrients into the soil so that microbial growth can be sustained for longer periods. Also, the compost supplies microorganisms that are capable of transforming the complex substrates into nutrients. These microbes often form a framework in the soil for creating a natural immune system for the plant. Compost addition also improves the soil structure, decreases the bulk density and increases soil porosity, thereby increasing the exchange of gas and water transfer, reducing erosion and evaporation, increasing cation exchange capacity and facilitating improved drainage conditions.

(ii) *Biofertiliser*

Biofertilisers are live microbial inoculants that contain bacterial/microbial strains that are capable of fixing nitrogen, mobilising nutrients like phosphorus and improving plant health, drought and salt tolerance, etc. Biofertilisers can be grouped into various categories like nitrogen-fixing, phosphorus- or potassium-mobilising, zinc-solubilising, microbial strains that promote iron or sulphur uptake and plant growth-promoting rhizobacteria (Pathak et al. 2017). *Rhizobium*, blue-green algae (BGA), *Azotobacter*, etc., are nitrogen-fixing biofertilisers; *Pseudomonas*, *Bacillus* and arbuscular mycorrhiza (AM) fungi are examples of phosphorus-mobilising biofertilisers. *Thiobacillus* and *Pseudomonas fluorescens* are examples of sulphate and iron uptake biofertilisers, respectively. Nitrogen-fixing biofertilisers like *Rhizobium* can add up to 50–100 kgs of N/ha per year, and BGA can add up to 20–30 kgs of N/ha per year (Asoegwu et al. 2020). Phosphate-mobilising or phosphorus-solubilising biofertilisers/microorganisms (bacteria, fungi, mycorrhiza, etc.) convert the insoluble form of soil phosphate into soluble forms by secreting several organic acids and can solubilise/mobilise about 30–50 kg P_2O_5/ha under optimal conditions, increasing crop yield by 10–20%. Rhizobacteria colonise the plant roots and inhibit the growth of pathogenic microorganisms and stimulate plant growth, and endomycorrhizal fungi like AM improve the overall plant growth characteristics like plant height, root diameter and total dry weight. These growth parameters in the plant are also due to the phytohormone production by rhizobacteria like *Acetobacter diazotrophicus*, *Azospirillum lipoferum* and *Azospirillum brasilense* which produce indole-3-acetic acid, gibberellic acid and abscisic acid, respectively (Pathak et al. 2017).

(iii) *Biopesticide*

To get higher yields from crops to meet the growing population, pest control is very important. Conventional pesticides are disadvantageous because they leave more residues in the soil and kill beneficial insects also. Thus, biopesticides that are based on microorganisms are effective in protecting non-target organisms and humans (Gaši and Tanovi 2013). There are many different biopesticides each having a specific target, and their formulations also vary. Over 100 bacteria have been identified and listed as biopesticides, but more attention is given to *Bacillus thuringiensis* since this is widely used for insect control. Over 1000 viruses that infect insects have been identified like NPV capable of infecting 525 insects. Examples of entomopathogenic fungi are *Beauveria brongniartii* and *Nomuraea rileyi* which are capable of infecting Coleopteran and Lepidopteran insects, respectively (Thakre et al. 2011; Townsend et al. 2010). By-products from agricultural processes, namely, rice straw, wheat straw, stumps, husk, grass seed straw, barley straw, flax coil seed, corn stalks, sugarcane bagasse, sorghum stalks, hemp fibre, Sabai grass, reeds, cotton staples and stem fibres, are available throughout the year. Some by-products are recycled as fertiliser, feed or fuel, and some are considered as wastes. A significant amount is still being misused. To turn this waste into value-added products, a strategy is required. This conversion procedure should be technologically efficient, cost-effective and simple to use. Microbial degradation of agricultural wastes is one of the cost-effective and efficient technologies to produce value-added goods from the agricultural wastes. Crop waste and residues; by-products of the fruit and vegetable processing industries; by-products of the sugar, starch and confectionary industries;

by-products of the grain and legume milling industries and the oil industry; and by-products of distilleries and breweries are all examples of agro-wastes. The handling and technology utilised for processing agro-wastes are mostly determined by their nature.

(iv) *Animal Feed*

The problem with animal feed in most underdeveloped nations is the scarcity of protein sources, despite significant efforts to find alternative supplements. Crop residues are good source of fibre and lacking in protein, carbohydrates and fat. As a result, the traditional strategy of raising cattle farming by augmenting forage and pasture with grains and protein concentration may not be sufficient to fulfil future meat protein requirements. The use of grain and protein for human diet will compete with the use of grain and protein for animal feed. These issues can be avoided by feeding wastes to domesticated animals (Hussein and Sawan 2010). Many of the basic ingredients used in feed production are items that might be better utilised in human nutrition (Brum et al. 1999). As a result, it is preferable to employ lower-quality materials as the primary component of animal diets (Table 2.1). Most agro-industrial wastes and food industry residues, on the other hand, are lacking in nutrients such as proteins and vitamins and high in fibre with low digestion. Such materials are not suited for non-ruminant animals and, in some situations, have such low digestibility that they are not even good for ruminants (Lima et al. 2000). In the face of this issue, a potential solution exists: the use of microorganisms, primarily fungi, to convert agro-industrial wastes into products with higher nutritive value, particularly in terms of protein and vitamin contents and increased digestibility.

Large-scale cultivation of fungi, bacteria and seaweed can be used as feed. These microorganisms are highly appealing feedstuffs because they can be grown on agro-industrial wastes and produce enormous volumes of cells rich in proteins that often contain all of the essential amino acids, as well as vitamin and mineral levels that are favourable (Brum et al. 1999). Furthermore, the growth of microorganisms on lignocellulosic wastes can provide all of the hydrolytic enzymes commonly used in feed preparation and make minerals more accessible for absorption by the animal. The nutritional value and utility of a microbial protein are determined by its composition. Proteins must be nontoxic, free of antinutritional chemicals and easy to digest. Various agro-industrial leftovers, such as potato residues, rice bran, cassava residues and coffee shells and pulp, among others, produce microbial protein. World's productions of some agro-industrial wastes to animal feed are given in Table 2.2.

Protein enrichment of apple bagasse is possible with three yeasts: *Saccharomyces cerevisiae*, *Candida utilis* and *Torula utilis*. Each yeast species produced a threefold rise in crude protein content, as well as a doubling of fat, vitamin C, minerals, fibre and ash (Joshi and Sandhu 1996). Enrichment of beet pulp, wheat bran and citrus residue utilises the fungus *Neurospora sitophila* with the goal of employing these residues as animal feed. After 5 days of fermentation, the protein content of beet pulp increased by 15%, wheat bran by 13% and citrus residue by 7% (Shojaosadati et al. 1999).

(v) *Methane*

Anaerobic methane production is preferred from agricultural wastes due to its use of renewable energy sources, little residual waste output and low cost. This method generates nutrient-rich waste that can be utilised as a soil conditioner or fertiliser (Kiran et al. 2014). Methane has an energy content of 55.5 MJ/kg. Anaerobic digestion generates methane by biodegrading organic waste and decreasing it. Several aspects influence methane synthesis in this process, including alkalinity, pH, organic loading rate, nutrients, reactor type, volatile fatty acids, C:N ratio, operation temperatures, ammonium ions and substrate properties (Park et al. 2018). The accumulation of volatile fatty acids and a drop in pH reduce the formation of methane gas during anaerobic digestion. Combining a microbial electrolysis cell (MEC) with an anaerobic digestion reactor increases methane production rate by 1.7 times when compared to the anaerobic digestion reactor alone. MEC accelerates the decomposition of volatile fatty acids, concentrated organic wastes and non-degradable organic debris, resulting in increased methane output. When MEC crosses a low voltage in the reactor, electrons produced by exoelectrogenic bacteria generate methane at the cathode.

Waste pretreatment could be an effective technique for boosting protein/lipid digestibility, lowering acidification rates and changing biological and physicochemical features, minimising process inhibition and increasing methane recovery. Physical (grinding), thermal, acid and alkali treatments, high-pressure treatment, pulse discharge of high voltage, microwave-assisted, micro-aeration and biological treatment are all typical pretreatment methods. The optimum pretreatment procedures for anaerobic waste digestion are thermal treatment followed by alkali treatment. Alkali pretreatment increased methane yield by 25%, and when paired with heat treatment, the yield increased to 32%. Fifty-four different fruit and vegetable wastes produced 180–732 mL methane per gram of volatile solid. Furthermore, by utilising 95.1% volatile solids, fruits and vegetables waste in a two-stage anaerobic digester yielded 530 mL per gram of volatile solid. According to Hou et al. (2022), low salt concentrations boosted acidification and hydrolysis while suppressing methanogenesis, but high quantities hindered both methanogenesis and acidification.

(vi) *Enzymes*

Enzymes are protein biomolecules that act as catalysts in chemical processes. Agricultural by-products' value addition encompasses the biotransformation of wastes into valuable products as well as the manufacture of crude enzymes utilising biowaste as a substrate. Agricultural wastes are typically made up of starch, cellulose, hemicellulose, lignin and cellulose and pectin. These substrate composition and enzyme production in the agricultural wastes are listed in Tables 2.3 and 2.4.

Enzymes are utilised in various industries, particularly the food industry, to produce both classic products and new molecules. Three key enzymes derived directly from fruit waste are papain (from papaya), bromelain (from pineapple) and ficin (from figs). Each is a protein-degrading enzyme having numerous

Table 2.3 Composition of agro-industrial residues

Agro-industrial residues	Lignin (%)	Cellulose (%)	Hemicellulose (%)
Corn cobs	6.1	33.7	31.9
Sugarcane bagasse	25	50	26
Wheat straw	8.9	32.9	24
Rice straw	12.56	35.45	23.78
Sunflower seed hull	29.40	24.10	28.60

Table 2.4 Enzyme production from different agro-industrial wastes

Support	Microbial strain	Enzyme
Sugarcane bagasse	*Trichoderma versicolor*, *Flammulina velutipes* and *Aspergillus niger*	MnP, laccase MnP, pectinolytic, cellulase and beta-glucosidase
Wheat bran	*Ganoderma*, *Aspergillus niger* and *Aspergillus niveus*	Laccases, MnP, pectinases, glucoamylase and catalase
Wheat straw	*Phlebia radiata* and *Bacillus subtilis*	Lip, MnP, laccase and protease
Banana skin	*Trametes pubescens* and cellulolytic and pectinolytic enzyme	Laccase
Grape pomace	*Aspergillus awamori*	Pectinases
Corn fibre	*Fusarium proliferatum*	Beta-xylosidase
Cauliflower waste	*Aspergillus niger*	Glucoamylase
Soybean hulls	*Trichoderma* and *Aspergillus*	Cellulolytic enzyme
Apple pomace	*Aspergillus niger*	Cellulases and pectinases, beta-fructofuranosidase and ethanol

applications, including laundry detergents, leather tanning and beer making. In addition to these three traditional enzymes, several additional industrially essential enzymes are being produced. Solid-state and semisolid fermentation processes are widely employed in the production of a wide range of enzymes from fruit and vegetable waste. Many of these fungal and bacterial species have been discovered to be extremely beneficial in the fermentation process; for example, *Aspergillus* sp., *Pseudomonas* sp., *Bacillus* sp. and *Trichoderma* sp. are important. On a large scale, the above said enzymes are produced from many fruit wastes, such as bananas, potatoes, dates, citrus fruits and mango kernels. Cellulases have been successfully produced by fermentation using a combination of microbes from grape pomace, banana waste, kinnow residues and palm kernel cakes. Invertase, pectinases, tannases, xylanases, proteases and laccases have also been successfully produced by fermentation using a combination of microbes. Fungi or yeasts produce 50% of accessible enzymes, and bacteria produce 35%, while plants and animals produce 15%.

7 Innovative Application of Microbial Organic Waste Degradation

The management of organic waste is crucial for the sustainability of the environment and the economy, but it is influenced by socioeconomic, political and environmental factors. Since recycling is becoming more popular than landfilling, various researchers have proposed the zero waste idea, taking sustainability into account. Anaerobic digestion is regarded as an economical and environmentally responsible technology to address the imbalances in the ecosystem brought on by the accumulation of organic substantial waste due to the environmental restrictions on energy generation from biodegradable solid waste (Bouallagui et al. 2005).

The production of biogas from various biodegradable materials can be divided into four processes: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis and (4) methanogenesis. An optimistic carbon resource to be used in a more aware and renewable global economy is biodegradable organic waste (Adl et al. 2015). They are accepted to be widely used for biofuels such as biogas, biohydrogen, bioethanol and value-added products due to their abundance and diversity in terms of structural and compositional characteristics, which are related to their origins (acetic acid, lactic acid, etc.).

Anaerobic digestion has emerged as one of the most promising technologies in recent years for achieving high bioenergy yields. The hyperthermophilic bacteria are highly capable of metabolising complex substrates during the AD process (Zhang et al. 2015). Thermotoga, Thermotogaceae and Pseudothermotoga are examples of the family of hyperthermophilic bacteria that are recognised as producing hydrogen from a variety of organic substrates. *Thermotoga* and *Pseudothermotoga* species in particular have enormous potential for degrading organic wastes. Additionally, *P. elfii* and *T. neapolitana* are capable of breaking down complex substrates (Esercizio et al. 2021). The final portion of organic waste fed into digesters that could not be utilised by microorganisms during the anaerobic degradation process is known as biogas residual (digestate) (Lawal-Akinlami and Shanmugam 2017). As a result of the anaerobic digesters' residual dead microbial flora, the digestate also contains mineralised matter (Janke et al. 2015). Digestate increases soil aggregation, maintains structure and provides aeration, all of which increase crop yield (Klimiuk et al. 2010).

Microbial fuel cells (MFC) could be another option for generating power from various livestock while simultaneously reducing pollution and maintaining the potential for biofertilisers (Choi 2015). In MFC, the substrate-dwelling bacteria were capable of electrical charging, and these so-called electro active bacteria produced electricity. Utilising readily available biodegradable materials, MFC could produce 2–50% more energy. MFC would run under similar circumstances to conventional anaerobic digesters. MFC, however, performs better than anaerobic digesters at lower temperatures (30–20 C). MFC bacteria can release electrons onto the anode electrode and then react with an electron acceptor in the cathode chamber (Saheb-Alam et al. 2019). Microbial fuel cells have the ability to generate electricity, but the advantage of microorganisms on the electrodes has allowed for the development of numerous systems for various purposes.

8 Advances in Recycling of Agricultural Wastes

The agricultural wastes are considered as potential resources. Potential supplies include agricultural straw and livestock faeces. Inappropriate agricultural waste disposal not only pollutes the environment but also wastes a significant amount of important biomass resources. Recycling and utilising agricultural wastes are seen as critical steps in protection of the environment, energy structure and sustainable agriculture.

In recent decades, agricultural wastes are becoming major causes of pollution, and the problems produced by poultry and animal excrement have received worldwide attention (Liu et al. 2015). Random straw burns and livestock waste in agricultural country have resulted in a slew of environmental issues. In recent years, a considerable amount of agricultural waste has been created each year all over the world (Wang et al. 2015). Agricultural waste increased at a rate of 5–10% each year on average. Random abandonment and inappropriate exploitation would also result in air pollution, soil degradation and other negative effects. The combustion of manure and straw produces a large amount of toxic gas, smoke and dust, severely damaging our air environment (Varma et al. 2015; Karak et al. 2015). Many diseases, parasite eggs, heavy metals and other contaminants can be found in animal faeces. A portion of agricultural leftovers have even been discharged straight into water, resulting in substantial contamination of the aquatic ecosystem. The presence of agricultural waste was unique in each region. There are several options for dealing with agricultural waste material. Some of these wastes have recently been put to better use. Some of these agricultural solid wastes could be used as additions in cement, water glass, paper manufacture, ethanol production, animal feed, electricity and biogas generation, heavy metal removal, mulching, organic fertilisers and compost. Recycling agricultural solid wastes to create valuable products is an efficient way of handling them. This can be accomplished by the following:

1. Organic manure/compositing
2. Substrates for the development of edible fungus
3. Nontraditional feed ingredient
4. Traditional soap production
5. Alternative energy and biofuel production
6. Silica production

Agricultural solid wastes can be used as animal feed through sterilising, fertiliser through composting and bioenergy through anaerobic digestion. These wastes are good candidates for compositing because of their high organic matter and nutrient content, but their high salt, moisture and oil concentration may make composting difficult (Yangyang et al. 2016). As substrates, mushrooms were grown on various agricultural solid wastes (Akintola et al. 2019). Production of agricultural solid waste to feed cattle is a recycling method as well as a low-cost source of feed for generating animal-source protein. Mycomeat is a nontraditional feed component which is made from agricultural solid waste. Mycomeat fed various agricultural solid wastes to albino rats and advocated processing of the wastes to achieve a better result (Oluwaseun and Oluseun 2018). The processing of agricultural solid wastes could increase their value for pig feed (Adebiyi et al. 2019). The effect of dried sweet orange (*Citrus sinensis*) peel on humoral immune response in broiler chickens (Pourhossein et al. 2019) as well as maize replacement and its effect on growth performance in broiler chickens.

Across the globe, traditional methods for turning agricultural solid waste into valuable items existed. Cocoa pods that could end up as agricultural waste are usually permitted to decompose naturally and nourish the soil, or they are used to make black soap, which can be used for dishwashing or bathing. Anaerobic digestion can turn agricultural solid waste into green energy. The high protein and fat content of these wastes may hamper anaerobic digestion stability, as well as the lack of effective technology required for biogas residue disposal (Tsai et al. 2007). However, pretreatment techniques such as mechanical (sonication), oxidative (ozone), chemical addition (acid or alkali), thermal osmotic (freezing and sodium chloride treatment) and biological (enzyme addition) can improve the physical and chemical properties of wastes, enhancing their solubilisation of organic particles, sterilisation effect and promotion of subsequent recycling (biogas production). Despite the many challenges that its production faces, biofuel and bioenergy are gaining popularity as a sustainable renewable energy source that promotes rural and regional development, reduces CO_2 emissions, creates job opportunities and replaces energy from nonrenewable fossil fuels with green energy (Nguyen et al. 2010). Silica may be found in agricultural solid waste. Using chemical, thermal and microbiological processes, silica has been extracted from agricultural solid wastes such as corn cob, rice husk, bagasse and rice straw (Shim et al. 2015). Although dietary sources are low in silicon and may need to be supplemented in diets through other means, silicon quantity decreases with age and tends to be greater in plants than animal sources (Martin 2018).

Agricultural solid wastes (high in cellulose, hemicellulose, lipids, starch and proteins) produced in huge quantities and burned on open fields or allowed to accumulate in some poor countries could be directed into biofuel production. Key stakeholders and political leaders, particularly in developing countries, should collaborate with researchers to scale up biomass conversion to alternate energy sources or biofuel output. This is projected to not only reduce the health risk posed by open-field agricultural solid waste burning or dumping but also to boost energy generation and reduce waste disposal economic losses.

9 Challenges and Future Perspective

Several researches have shown that microbial inoculants improve management of nutrients and plant diseases indicating their crucial role in future agricultural management systems. Apart from plant growth promotion, the use of bioinoculants for organic waste degradation has become a trustable solution to the modern world (Skariyachan et al. 2015). Organic wastes are generally bulky in nature; hence the time and space required for microbial degradation reduce their potential application. The search for fast-degrading strains and methods to optimise the process is crucial for improving the practicability of the technology. The complex soil-plant-microbe interactions are yet to be elucidated in detail that questions the viability of the microbial inoculants in the long run (Finkel et al. 2017; Mukhtar et al. 2018; Tabassum et al. 2017). The emission of greenhouse gases from the waste conversion facilities is recorded in humungous levels that are to be addressed by further research in the near future. Several new organic compounds are synthesised and utilised in various sectors that are mostly preservatives and have resistance to microbial degradation (John et al. 2023; Backer et al. 2018; Goss et al. 2013), which are very tough to be addressed with the existing practices and procedures for degradation of organic waste. However, biotechnological tools could offer more efficient and hardy microorganisms that could work in combination with some specific compounds or as mixed microbial cultures. The cost of genetically modified microbial inoculum and the regulations that are yet to be formulated for utilising in waste degradation hampers the path to sustainability. One of the major challenges for energy generation and product formation from municipal or other organic wastes is lack of awareness about segregation of organic and inorganic fraction. The secondary metabolites and enzymes synthesised by microbes can be explored for degradation of organic waste due to their high effectiveness and target-oriented approach. The utilisation of cost-friendly thermal-assisted composters could renovate the waste management especially municipal solid waste. However, while opting for a decentralised composting framework, a state legislation on community composting should be in place to avoid additional environmental damage. Hence, further research to identify socioeconomic characteristics and optimised location-based technology for successful processing of organic waste and exploiting in agriculture is needed.

10 Conclusion

The amount of waste generated due to anthropogenic activity mostly ends up being a burden to the environment. This chapter has undoubtedly shown that microbial inoculants could improve management organic waste while improving the sustainability of agricultural sector. The anaerobic methods of conversion offer many attractive end products than aerobic methods. The prospects of energy generation through anaerobic microbial technologies could turn tables in the present energy crisis. However, several aspects of aerobic management outweigh the anaerobic means of waste conversion like duration and simplicity. The use of microbes to produce pesticide and biofertiliser can possibly reduce the use of agrochemicals. Soil degradation due to agriculture could be potentially eliminated through these technologies. Nevertheless, further research is needed to improve the efficiency and rate of waste management to reach the goal of waste-free process with environmentally enhancing microbial inoculants. Biotechnological researches for efficient microorganisms that are compatible with many types of waste and adaptable to the environment are expected in the years to come. In meeting the goal of sustainable agriculture ecosystem, the use of microbial inoculants technology could be adopted.

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References

Abdel-Rahman MA, El-Din MN, Refaat BM, Abdel-Shakour EH, Ewais EED, Alrefaey HMA (2016) Biotechnological application of thermotolerant cellulose-decomposing bacteria in composting of rice straw. Ann Agric Sci 61:135–143

Adebiyi OA, Oboli UT, Adejumo IO, Osinowo OA, Chika CU (2019) Palm oil industry waste as an animal feed and its influence on growth performance of grower pigs. J Anim Sci 97(Supple 3):386–387

Adl M, Sheng K, Gharibi A (2015) Examining a pretty simple and low cost method for modeling of biogas production from biodegradable solids. Energy Procedia 75:748–753. https://doi.org/10.1016/j.egypro.2015.07.504

Aiyelari EA, Ogunsesin A, Adeoluwa OO (2011) Effects of Terminalia Catappa leaves with Poultry Manure compost, Mulching and Seedbed preparation on the Growth and Yield of okra (Abelmoschus esculentus l. Moench). Proceedings of International Soil Tillage Research Organization, 21–24

Akinsemolu AA (2018) The role of microorganisms in achieving the sustainable development goals. J Clean Prod 182:139–155

Akintola OA, Idowu OO, Lateef SA, Adebayo GA, Shokalu AO, Akinyoola OI (2019) The use of waste management techniques to enhance household income and reduce urban water pollution, elements of bioeconomy, Krzysztof Biernat. IntechOpen, Rijeka

Albrecht R, Périssol C, Ruaudel F, Le Petit J, Terrom G (2010) Functional changes in culturable microbial communities during a co-composting process: carbon source utilization and co-metabolism. Waste Manag 30(5):764–770. https://doi.org/10.1016/J.WASMAN.2009.12.008

Asoegwu CR, Chibueze GA, Kalu N, Chimaroke GO, Oluchi UN, Uchenna CE, Chinaza GA (2020) A review on the role of biofertilizers in reducing soil pollution and increasing soil nutrients. Himalayan J Agric 1:34–38. http://inlightpublisher.com/journal/hja

Awasthi MK, Wong JW, Kumar S, Awasthi SK, Wang Q, Wang M, Ren X, Zhao J, Chen H, Zhang Z (2018) Biodegradation of food waste using microbial cultures producing thermostable ?-amylase and cellulase under different pH and temperature. Bioresour Technol 248:160–170

Backer R, Rokem JS, Ilangumaran G, Lamont J, Praslickova D, Ricci E, Subramanian S, Smith DL (2018) Plant growth-promoting rhizobacteria: context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. Front Plant Sci 871. https://doi.org/10.3389/FPLS.2018.01473/FULL

Bernal-Vicente A, Ros M, Pascual JA (2012) Inoculation of Trichoderma harzianum during maturation of vineyard waste compost to control muskmelon Fusarium wilt. Bioresources 7:1948–1960

Bernardi FH, Costa MSSD, Costa LAD, Damaceno FM, Chiarelotto M (2018) Microbiological activity during the composting of wastes from broiler productive chain. Eng Agric 38:741–750

Bianchi TS (2011) The role of terrestrially derived organic carbon in the coastal ocean: A changing paradigm and the priming effect Proceedings of the National Academy of Sciences 108(49):19473–19481. https://doi.org/10.1073/pnas.1017982108

Bonanomi G, Lorito M, Vinale F, Woo SL (2018) Organic amendments, beneficial microbes, and soil microbiota: toward a unified framework for disease suppression. Annu Rev Phytopathol 56:1–20

Bouallagui H, Touhami Y, Ben Cheikh R, Hamdi M (2005) Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. Process Biochem 40:989–995. https://doi.org/10.1016/j.procbio.2004.03.007

Brum PAR, Bellaver C, Zanotto DL, Lima GJMM (1999) Determinac¸a˜o de valores de composic¸a˜oqu´?mica e da energiametaboliza'velemfarinhas de carne e ossos para aves. EMBRAPA/CNPSA, Com Te'c 239:1–2

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman M, Sukkel W, van Groenigen JW, Brussaard L (2018) Soil quality – a critical review. Soil Biol Biochem 120:105–125. https://doi.org/10.1016/J.SOILBIO.2018.01.030

Cadena E, Colón J, Artola A, Sánchez A, Font X (2009) Environmental impact of two aerobic composting technologies using life cycle assessment. Int J Life Cycle Assess 14(5):401–410

Cayuela ML, Sánchez-Monedero MA, Roig A, Sinicco T, Mondini C (2012) Biochemical changes and GHG emissions during composting of lignocellulosic residues with different N-rich by-products. Chemosphere 88(2):196–203

Chander G, Wani SP, Gopalakrishnan S, Mahapatra A, Chaudhury S, Pawar CS, Kaushal M, Rao AVR (2018) Microbial consortium culture and vermi-composting technologies for recycling on-farm wastes and food production. Int J Recycl Organ Waste Agric 7(2):99–108

Chen Z, Li Y, Peng Y, Ye C, Zhang S (2021) Effects of antibiotics on hydrolase activity and structure of microbial community during aerobic co-composting of food waste with sewage sludge. Bioresour Technol 321:124506

Chi CP, Chu SH, Wang B, Zhang D, Zhi YE, Yang XJ, Zhou P (2020) Dynamic bacterial assembly driven by Streptomyces griseorubens JSD-1 inoculants correspond to composting performance in swine manure and rice straw co-composting. Bioresour Technol 313:123692. https://doi.org/10.1016/j.biortech.2020.123692

Choi S (2015) Microscale microbial fuel cells: advances and challenges. Biosens Bioelectron 69:8–25. https://doi.org/10.1016/j.bios.2015.02.021

Cyprowski M, Stobnicka-Kupiec A, Awniczek-Waczyk A, Bakal-Kijek A, Goofit-Szymczak M, Górny RL (2018) Anaerobic bacteria in wastewater treatment plant. Int Arch Occup Environ Health 91(5):571–579. https://doi.org/10.1007/s00420-018-1307-6. Epub 2018 Mar 28. PMID: 29594341; PMCID: PMC6002452

Damtie MM, Shin J, Jang HM, Cho HU, Wang J, Kim YM (2021) Effects of biological pretreatments of microalgae on hydrolysis, biomethane potential and microbial community. Bioresour Technol 329:124905

Dar GH, Mehmood MA, Bhat RA, Hakeem KR (2022) Microbiota and biofertilizers, Vol 2: ecofriendly tools for reclamation of degraded soil environs. Springer, Singapore. https://doi.org/10.1007/978-3-030-61010-4

Dhanya BS, Mishra A, Chandel AK, Verma ML (2020) Development of sustainable approaches for converting organic waste to bioenergy. Sci Total Environ 723. https://doi.org/10.1016/j.scitotenv.2020.138109

Duan ML, Zhang YH, Zhou BB, Qin ZL, Wu JH, Wang QJ, Yin YA (2020) Effects of Bacillus subtilis on carbon components and microbial functional metabolism during cow manure–straw composting. Bioresour Technol 303:122868

Echeverria MC, Cardelli R, Bedini S, Colombini A, Incrocci L, Castagna A, Agnolucci M, Cristani C, Ranieri A, Saviozzi A, Nuti M (2012) Microbially enhanced composting of wet olive husks. Bioresour Technol 104:509–517. https://doi.org/10.1016/J.BIORTECH.2011.11.042

ElMekawy A, Srikanth S, Bajracharya S, Hegab HM, Nigam PS, Singh A et al (2015) Food and agricultural wastes as substrates for bioelectrochemical system (BES): the synchronized recovery of sustainable energy and waste treatment. Food Res Int 73:213–225

Esercizio N, Lanzilli M, Vastano M, Landi S, Xu Z, Gallo C, Nuzzo G, Manzo E, Fontana A, D'Ippolito G (2021) Fermentation of biodegradable organic waste by the family Thermotogaceae. Resources 10:1–26. https://doi.org/10.3390/resources10040034

Eskander S, Saleh HE (2017) Biodegradation: process mechanism. Environ Sci Engg 8(8):1–37. https://www.researchgate.net/profile/Hosam-Saleh-3/publication/312491332_Biodegradation_Process_Mechanism/links/58ff410c45851565029f1647/Biodegradation-Process-Mechanism.pdf

Fang Y, Jia XB, Chen LJ, Lin CQ, Zhang H, Chen JC (2019) Effect of thermotolerant bacterial inoculation on the microbial community during sludge composting. Can J Microbiol 65:750–761

Fernandez VI, Stocker R, Juarez G (2022) A tradeoff between physical encounters and consumption determines an optimal droplet size for microbial degradation of dispersed oil. Sci Rep 12(1):1–10

Finkel OM, Castrillo G, Paredes SH (2017) ScienceDirect Understanding and exploiting plant beneficial microbes. Curr Opin Plant Biol. https://doi.org/10.1016/j.pbi.2017.04.018

Garcia C, Hernandez T, Coll MD, Ondoño S (2017) Organic amendments for soil restoration in arid and semiarid areas. AimspressCom 4(5):640–676. https://doi.org/10.3934/environsci.2017.5.640

Gaši S, Tanovi B (2013) Biopesticide formulations, possibility of application and future trends. Pestic Phytomed (Belgrade) 28(2):97–102. https://doi.org/10.2298/PIF1302097G

Gilmore SP, Lankiewicz TS, Wilken SE, Brown JL, Sexton JA, Henske JK, Theodorou MK, Valentine DL, O'Malley MA (2019) Top-down enrichment guides in formation of synthetic microbial consortia for biomass degradation. ACS Synth Biol 8:2174–2185

Gómez MA, Baldini M, Marcos M, Martínez A, Fernández S, Reyes S (2012) Aerobic microbial activity and solid waste biodegradation in a landfill located in a semi-arid region of Argentina. Ann Microbiol 62(2):745–752

Goss MJ, Tubeileh A, Goorahoo D (2013) A review of the use of organic amendments and the risk to human health. Adv Agron 120:275–379. https://doi.org/10.1016/B978-0-12-407686-0.00005-1

Gou CL, Wang YQ, Zhang XQ, Lou YJ, Gao YH (2017) Inoculation with a psychrotrophic–thermophilic complex microbial agent accelerates onset and promotes maturity of dairy manure–rice straw composting under cold climate conditions. Bioresour Technol 243:339–346

Greff B, Szigeti J, Nagy A, Lakatos E, Varga L (2022) Influence of microbial inoculants on co-composting of lignocellulosic crop residues with farm animal manure: A review Journal of Environmental Management 302:114088. https://doi.org/10.1016/j.jenvman.2021.114088

Hakeem KR, Dar GH, Mehmood MA, Bhat RA (2021) Microbiota and biofertilizers: a sustainable continuum for plant and soil health. Springer, Singapore. https://doi.org/10.1007/978-3-030-48771-3

Hassan S, Sabreena. (2022) Microbes as requisite additives for organic waste management: a brief review. Curr World Environ 17(1):32–40

Heimann M, Reichstein M (2008) Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature 451(7176):289–292. https://www.nature.com/articles/nature06591

Holman DB, Hao XY, Topp E, Yang HETW (2016) Alexander effect of co-composting cattle manure with construction and demolition waste on the archaeal, bacterial, and fungal microbiota, and on antimicrobial resistance determinants. PLoS One 11:Article e0157539

Hou T, Zhao J, Lei Z, Shimizu K, Zhang Z (2022) Supplementation of KOH to improve salt tolerance of methanogenesis in the two-stage anaerobic digestion of food waste using pre-acclimated anaerobically digested sludge by air-nanobubble water. Bioresour Technol 346:126360

Hussein SDA, Sawan OM (2010) The utilization of agricultural waste as one of the environmental issues in Egypt (a case study). J Appl Sci Res 6(8):1116–1124

Janke L, Leite A, Nikolausz M, Schmidt T, Liebetrau J, Nelles M, Stinner W (2015) Biogas production from sugarcane waste: assessment on kinetic challenges for process designing. Int J Mol Sci 16:20685–20703. https://doi.org/10.3390/ijms160920685

Jia X, Qin X, Tian X, Zhao Y, Yang T, Huang J (2021) Inoculating with the microbial agents to start up the aerobic composting of mushroom residue and wood chips at low temperature. J Environ Chem Eng 9(4):105294

Jiang Y, Lv Y, Wu R, Lu J, Dong W, Zhou J, Zhang W, Xin F, Jiang M (2020) Consolidated bioprocessing performance of a two-species microbial consortium for butanol production from lignocellulosic biomass. Biotechnol Bioeng 117:2985–2995

Jin X, Ai W, Dong W (2022) Lignocellulose degradation, biogas production and characteristics of the microbial community in solid-state anaerobic digestion of wheat straw waste. Life Sci Space Res 32:1–7

John JZ, Maheswari M, Kalaiselvi T, Prasanthrajan M, Poornachandhra C, Rakesh SS, Gopalakrishnan B, Davamani V, Kokiladevi E, Ranjith S (2023) Biomining Sesuvium portulacastrum for halotolerant PGPR and endophytes for promotion of salt tolerance in Vigna mungo L. Frontiers in Microbiology 14. https://doi.org/10.3389/fmicb.2023.1085787

Joshi VK, Sandhu DK (1996) Preparation and evaluation of an animal feed byproduct produced by solid-state fermentation of apple pomace. Bioresour Technol 56:251–255

Karak T, Sonar I, Nath JR, Paul RK, Das S, Boruah RK, Dutta AK, Das K (2015) Struvite for composting of agricultural wastes with termite mound: utilizing the unutilized. BioresourTechnol 187:49–59

Karnchanawong S, Nissaikla S (2014) Effects of microbial inoculation on composting of household organic waste using passive aeration bin. Int J Recycl Org Waste Agric 3:113–119

Kiran EU, Trzcinski AP, Ng WJ, Liu Y (2014) Bioconversion of food waste to energy: a review. Fuel 134:389–399

Klimiuk E, Pokoj T, Budzynski W, Dubis B (2010) Theoretical and observed biogas production from plant biomass of different fibre contents. Bioresour Technol 101:9527–9535. https://doi.org/10.1016/j.biortech.2010.06.130

Kong D, Zhang K, Liang J, Gao W, Du L (2019) Methanogenic community during the anaerobic digestion of different substrates and organic loading rates. Microbiol Open 8(5):e00709. https://doi.org/10.1002/MBO3.709

Kumar S, Bhattacharyya JK, Vaidya AN, Chakrabarti T, Devotta S, Akolkar AB (2009) Assessment of the status of municipal solid waste management in metro cities, state capitals, class I cities, and class II towns in India: an insight. Waste Manag 29(2):883–895

Kumar V, Shahi SK, Singh S (2018) Bioremediation: an eco-sustainable approach for restoration of contaminated sites. In: Microbial bioprospecting for sustainable development. Springer, Singapore, pp 115–136

Kutu FR, Mokase TJ, Dada OA, Rhode OHJ (2019) Assessing microbial population dynamics, enzyme activities and phosphorus availability indices during phospho-compost production. Int J Recycl Org Waste Agric 8:87–97. https://doi.org/10.1007/s40093-018-0231-9

Lawal-Akinlami HA, Shanmugam P (2017) Comparison of biochemical methane potential and methanogen morphology of different organic solid wastes co-digested anaerobically with treatment plant sludge. Process Saf Environ Protect 107:216–226. https://doi.org/10.1016/j.psep.2017.02.001

Lee J, Koo T, Yulisa A, Hwang S (2019) Magnetite as an enhancer in methanogenic degradation of volatile fatty acids under ammonia-stressed condition. J Environ Manag 241:418–426

Li J, Cooper JM, Lin Z, Li Y, Yang X, Zhao B (2015) Soil microbial community structure and function are significantly affected by long-term organic and mineral fertilization regimes in the North China Plain. Appl Soil Ecol 96:75–87. https://doi.org/10.1016/J.APSOIL.2015.07.001

Lima GJMM, Martins RR, Zanotto DL, Brum PAR (2000) Composic¸a˜oqu´?mica e valores de energia de subprodutos do beneficiamento de arroz. EMBRAPA/CNPSA, Com. Te'c. 244:1–2

Liu Y, Dong JX, Liu GJ, Yang HN, Liu W, Wang L, Kong CX, Zheng D, Yang JG, Deng LW, Wang SS (2015) Co-digestion of tobacco waste with different agricultural biomass feedstocks and the inhibition of tobacco viruses by anaerobic digestion. Bioresour Technol 189:210–216

Liu P, Ji J, Wu Q, Ren J, Wu G, Yu Z, Xiong J, Tian F, Zafar Y, Li X (2018) Klebsiella pneumoniae sp. LZU10 degrades oil in food waste and enhances methane production from co-digestion of food waste and straw. Int Biodeterior Biodegradation 126:28–36

Liwarska-Bizukojc E, Ledakowicz S (2003) Stoichiometry of the aerobic biodegradation of the organic fraction of municipal solid waste (MSW). Biodegradation 14(1):51–56. https://doi.org/10.1023/A1023538123655

Lokeshwari M, Swamy CN (2010) Waste to wealth-agriculture solid waste management study. Pollut Res 29(3):513–517

Luo X, Yuan X, Wang S, Sun F, Hou Z, Hu Q, Zhai L, Cui Z, Zou Y (2018) Methane production and characteristics of the microbial community in the co-digestion of the spent mushroom substrate with dairy manure. Bioresour Technol 250:611–620. https://doi.org/10.1016/j.biortech.2017.11.088

Martin KR (2018) Dietary silicon: is biofortification essential? J Nutr Food Sci Forecast 1:1006

Mehta CM, Sirari K (2018) Comparative study of aerobic and anaerobic composting for better understanding of organic waste management: a mini review. Plant Arch 18(1):44–48

Msarah MJ, Ibrahim I, Hamid AA, Aqma WS (2020) Optimisation and production of alpha amylase from thermophilic Bacillus spp. and its application in food waste biodegradation. Heliyon 6(6):e04183

Mukhtar S, Saeed B, Samina M, Muhammad M, Mirza S, Mclean J (2018) Impact of soil salinity on the microbial structure of halophyte rhizosphere microbiome. World J Microbiol Biotechnol 0(0):0. https://doi.org/10.1007/s11274-018-2509-5

Naeem S, Loreau M, Inchausti P (2002) Biodiversity and ecosystem functioning: the emergence of a synthetic ecological framework. In: Biodiversity and ecosystem functioning: synthesis and perspectives, pp 3–11

Nguyen TL, Gheewala SH, Sagisaka M (2010) Greenhouse gas savings potential of sugar cane bio-energy systems. J Clean Prod 18(5):412–418

Oluwaseun AC, Oluseun AI (2018) Efficacy of crude and immobilized enzymes from Bacillus licheniformis for production of biodegraded feather meal and their assessment on chickens. Environ Technol Innov 11:116–124

Park J, Lee B, Tian D, Jun H (2018) Bioelectrochemical enhancement of methane production from highly concentrated food waste in a combined anaerobic digester and microbial electrolysis cell. Bioresour Technol 247:226–233

Pathak D, Kumar M, Rani K (2017) Biofertilizer application in horticultural crops. In: Microorganisms for green revolution, pp 215–227. https://doi.org/10.1007/978-981-10-6241-4_11

Pourhossein Z, Qotbi AAA, Seidavi A, Laudadio V, Mazzei D, Tufarelli V (2019) Feeding of dried sweet orange (Citrus sinensis) peel on humoral immune response of broiler chickens. Int J Recycl Organic Waste Agric 8:361–367

Preston TR, Leng RA (1989) The greenhouse effect and its implication for world agriculture. The need for environmentally friendly development. Livestock Res Rural Dev 1(1):1–4

Ramana KV, Singh L (2000) Microbial degradation of organic wastes at low temperatures. Def Sci J 4:371–382

Rao DLN, Patra AK (2009) Soil microbial diversity and sustainable agriculture. J Indian Soc Soil Sci 57(4):513

Rastegari AA, Yadav AN, Yadav N (eds) (2020) New and future developments in microbial biotechnology and bioengineering: trends of microbial biotechnology for sustainable agriculture and biomedicine systems: diversity and functional perspectives. Elsevier

Ravindran B, Sekaran G (2010) Bacterial composting of animal fleshing generated from tannery industries. Waste Manag 30(12):2622–2630. https://doi.org/10.1016/J.WASMAN.2010.07.013

Ren J, Fan B, Niu D, Gu Y, Li C (2021) Biodegradation of waste cooking oils by Klebsiella quasivariicola IUMR-B53 and characteristics of its oil-degrading enzyme. Waste Biomass Valoriz 12(3):1243–1252

Rodale Institute (2011) Report: 30 years of the farming systems trial

Roslan MAM, Jefri NQUA, Ramlee N, Rahman NAA, Chong NHH, Bunawan H, Bharudin I, Kadir MHA, Mohammad M, Razali H (2021) Enhancing food waste biodegradation rate in a food waste biodigester with the synergistic action of hydrolase-producing Bacillus paralicheniformis GRA2 and Bacillus velezensis TAP5 co-culture inoculation. Saudi J Biol Sci 28(5):3001–3012

Sabater C, Ruiz L, Delgado S, Ruas-Madiedo P, Margolles A (2020) Valorization of vegetable food waste and by-products through fermentation processes. Front Microbiol 11:581997

Saheb-Alam S, Persson F, Wilen BM, Hermansson M, Modin O (2019) Response to starvation and microbial community composition in microbial fuel cells enriched on different electron donors. Microb Biotechnol 12:962–975. https://doi.org/10.1111/1751-7915.13449

Sayara T, Basheer-Salimia R, Hawamde F, Sánchez A (2020) Recycling of organic wastes through composting: process performance and compost application in agriculture. In: Agronomy (Vol. 10, Issue 11). MDPI AG. https://doi.org/10.3390/agronomy10111838

Sharma S, Verma R, Dhull S, Maiti SK, Pandey LM (2022) Biodegradation of waste cooking oil and simultaneous production of rhamnolipid biosurfactant by Pseudomonas aeruginosa P7815 in batch and fed-batch bioreactor. Bioprocess Biosyst Eng 45(2):309–319

Shim J, Velmurugan P, Oh BT (2015) Extraction and physical characterization of amorphous silica made from corn cob ash at variable pH conditions via sol gel processing. J Ind Eng Chem 30:249–253

Shojaosadati SA, Faraidouni R, Madadi-Nouel A, Mohamadpour I (1999) Protein enrichment of lignocellulosic substrates by solid state fermentation using Neurospora sitophila. Resour Conserv Recycl 27:73–87

Skariyachan S, Megha M, Kini MN, Mukund KM, Rizvi A, Vasist K (2015) Selection and screening of microbial consortia for efficient and ecofriendly degradation of plastic garbage collected from urban and rural areas of Bangalore, India. Environ Monit Assess 187(1):1–14

Tabassum B, Khan A, Tariq M, Ramzan M, Saleem M, Khan I, Shahid N, Aaliya K (2017) Bottlenecks in commercialisation and future prospects of PGPR. Appl Soil Ecol 121(November 2016):102–117. https://doi.org/10.1016/j.apsoil.2017.09.030

Thakre M, Thakur M, Malik N, Ganger S (2011) Mass scale cultivation of entomopathogenic fungus Nomuraea rileyi using agricultural products and agro wastes. J Biopest 4(2):176–179

Townsend RJ, Nelson TL, Jackson TA (2010) Beauveria brongniartii a potential biocontrol agent for use against manuka beetle larvae damaging dairy pastures on Cape Foulwind. New Zealand Plant Prot 63:224–228. https://doi.org/10.30843/NZPP.2010.63.6572

Trivedi P, Mattupalli C, Eversole K, Leach JE (2021) Enabling sustainable agriculture through understanding and enhancement of microbiomes. New Phytol 230(6):2129–2147

Tsai WT, Lin CC, Yeh CW (2007) An analysis of biodiesel fuel from waste edible oil in Taiwan. Renew Sust Energ Rev 11:838–857

Umesha S, Singh PK, Singh RP (2018) Microbial biotechnology and sustainable agriculture. In: Biotechnology for sustainable agriculture. Woodhead Publishing, pp 185–205

Vanotti MB, Szogi AA, Vives CA (2008) Greenhouse gas emission reduction and environmental quality improvement from implementation of aerobic waste treatment systems in swine farms. Waste Manag 28(4):759–766

Varma VS, Yadav J, Das S, Kalamdhad AS (2015) Potential of waste carbide sludge addition on earthworm growth and organic matter degradation during vermicomposting of agricultural wastes. Ecol Eng 83:90–95

Ventorino V, Romano I, Pagliano G, Robertiello A, Pepe O (2018) Pre-treatment and inoculum affect the microbial community structure and enhance the biogas reactor performance in a pilot-scale biodigestion of municipal solid waste. Waste Manag 73:69–77. https://doi.org/10.1016/J.WASMAN.2017.12.005

Wang J, Wang S (2018) Microbial degradation of sulfamethoxazole in the environment. Appl Microbiol Biotechnol 102(8):3573–3582

Wang SR, Ru B, Dai GX, Sun WX, Qiu KZ, Zhou JS (2015) Pyrolysis mechanism study of minimally damaged hemicellulose polymers isolated from agricultural waste straw samples. Bioresour Technol 190:211–218

Wang JQ, Liu ZP, Xia JS, Chen YP (2019) Effect of microbial inoculation on physicochemical properties and bacterial community structure of citrus peel composting. Bioresour Technol 291:121843

Wei Y, Liang Z, Zhang Y (2022) Evolution of physicochemical properties and bacterial community in aerobic composting of swine manure based on a patent compost tray. Bioresour Technol 343:126136

Wu S, Zhang L, Chen J (2012) Paracetamol in the environment and its degradation by microorganisms. Appl Microbiol Biotechnol 96(4):875–884

Xue S, Wang C, Zhang Z, Song Y, Liu Q (2016) Photodegradation of dissolved organic matter in ice under solar irradiation. Chemosphere 144:816–826. https://www.sciencedirect.com/science/article/pii/S0045653515301466

Yadav M, Vivekanand V (2021) Combined fungal and bacterial pretreatment of wheat and pearl millet straw for biogas production – a study from batch to continuous stirred tank reactors. Bioresour Technol 321. https://doi.org/10.1016/j.biortech.2020.124523

Yadav M, Joshi C, Paritosh K, Thakur J, Pareek N, Masakapalli SK, Vivekanand V (2022) Organic waste conversion through anaerobic digestion: a critical insight into the metabolic pathways and microbial interactions. In: Metabolic engineering, vol 69. Academic Press Inc., pp 323–337. https://doi.org/10.1016/j.ymben.2021.11.014

Yang S, Xiong H, Yang H, Yan Q, Jiang Z (2015) High-level production of ?-1, 3-1, 4-glucanase by Rhizomucor miehei under solid-state fermentation and its potential application in the brewing industry. J Appl Microbiol 118:84–91

Yangyang L, Jin Y, Li J, Chen Y, Gong Y, Li Y et al (2016) Current situation and development of kitchen waste treatment in China. In: The tenth international conference on waste management and technology (ICWMT), Procedia environmental sciences, vol 31, pp 40–49

Zhang L, Sun X (2014) Effects of rhamnolipid and initial compost particle size on the two-stage composting of green waste. Bioresour Technol 163:112–122. https://doi.org/10.1016/J.BIORTECH.2014.04.041

Zhang W, Wu S, Guo J, Zhou J, Dong R (2015) Performance and kinetic evaluation of semi-continuously fed anaerobic digesters treating food waste: role of trace elements. Bioresour Technol 178:297–305. https://doi.org/10.1016/j.biortech.2014.08.046

Zhao Y, Lu Q, Wei YQ, Cui HY, Zhang X, Wang XQ, Shan S, Wei ZM (2016) Effect of actinobacteria agent inoculation methods on cellulose degradation during composting based on redundancy analysis. Bioresour Technol 219:196–203

Zhou M, Yan B, Wong JWC, Zhang Y (2018) Enhanced volatile fatty acids production from anaerobic fermentation of food waste: a mini-review focusing on acidogenic metabolic pathways. Bioresour Technol 248:68–78. https://doi.org/10.1016/J.BIORTECH.2017.06.121