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REVIEW ARTICLE

Different stages of microbial community during the anaerobic digestion of food waste

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Abstract Large-scale food waste (FW) disposal has resulted in severe environmental degradation and financial losses around the world. Although FW has a high biomass energy contents and a growing large number of national projects to recover energy from FW by anaerobic digestion (AD) are being developed. AD is a promising solution for FW management and energy generation when compared to typical disposal options including landfill disposal, incineration, and composting. AD of FW can be combined with an existing AD operation or linked to the manufacture of value-added products to reduce costs and increase income. AD is a metabolic process that requires four different types of microbes: hydrolyzers, acidogens, acetogens, and methanogens. Microbes use a variety of strategies to avoid difficult situations in the AD, such as competition for the same substrate between sulfate-reducing bacteria and methane-forming bacteria. An improved comprehension of the microbiology involved in the anaerobic digestion of FW will provide new insight into the circumstances needed to maximize this procedure, including its possibilities for use in co-digestion mechanisms. This paper reviewed the present scientific knowledge of microbial community during the AD and the connection between microbial diversity during the AD of FW.

Keywords Microbial structure · Organic compost · Environmental sustainability · Economic profit · Digester

Introduction

Food waste (FW) is made up of materials that were intended for human consumption but were wasted, lost, deteriorated, or polluted (Girotto et al. 2015). Due to global

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economic development and population increase, FW is being generated at a growing pace from domestic, commercial, institutional, and industrial sources. FW in the United States has increased by 50% since 1974, and around 38 million tons of FW have been discarded annually, with 76.3% of it being disposed of properly (Posmanik et al. 2017). Restaurant FW, vegetable market FW, family kitchen FW, and so on are all examples of FW. In 2025, Asia's FW yield will rise to 4.16 billion tonnes (National Bureau of Statistics of China 2020). Because of its complex composition, high moisture level, and high organic content, treating FW is a difficult task (Li et al. 2019). The two usual disposal techniques are not suitable for the management of FW because of environmental contamination and low resource recovery efficiency (Nghiem et al. 2017). In light of the detrimental environmental consequences of dumping, incineration, or composting FW (Posmanik et al. 2017). During AD, anaerobic bacteria convert various forms of biomass and organic wastes into biogas (60–70% methane, 30–40% carbon dioxide, and other gases such as hydrogen and hydrogen sulphide), leaving a nutrient-rich residue that can be used for land application (Sheets et al. 2015).

The AD system is predicated on the breakdown of organic materials by a network of microbes with a variety of nutritional and physiological requirements (Shah 2014). pH changes, temperature, substrate composition/concentration, and the presence of inhibitory or poisonous chemicals are all factors that these microbes respond to differently (Venkiteshwaran et al. 2015). Many studies have looked at the evolution of microbial communities in laboratory-scale AD bioreactors that were operated at temperatures ranging from > 35 °C to lower temperatures, with a particular focus on the methanogenic part of ecosystems (Keating et al. 2018). Considering such, very little is understood about the possible expansion of such communities at pilot and full scale, as well as how they react to external stressors depending on the operating conditions.

Several nations have enacted restrictions to keep FW out of landfills, which has aided in the progress of resource application strategies for FW, such as AD, composting, feed, insect breeding, and the transfer of elevated substances (Xiong et al. 2019). AD, composting, feeding, and rearing insects have all become popular ways to treat FW (Li et al. 2019). Chemicals with high value-added products (glucose, chitosan, lactic acid, free amino nitrogen, and so on) could be made from FW using high-value conversion technologies such as chemical, thermochemical, or fermentation methods (Xiong et al. 2019). Owing to its immature technology, rising cost, and availability of basic, reliable industrial application capabilities, good conversion of advanced technologies with promising application potential can improve the added value of FW, but it cannot be extensively marketed and employed (Li et al. 2019).

The structure and content of microbial communities in a full-scale AD are now being extensively investigated (Wu et al. 2019). Furthermore, little is known about microbial successional dynamics during the start-up period, or how microorganisms respond to changes in such systems under real-world situations (Zhang et al. 2014). In this regard, identifying a core microbiome and/or marker population in a full-scale AD can be extremely useful in estimating potential metabolic capacity and ensuring system resilience, both of which are critical aspects of the management system (De Vrieze and Verstraete 2016). Various types of microbes are engaged in the breakdown of organic materials, and tight contact between them is required for the process to remain stable (Kishneth et al. 2020). As a result, AD is more prone to failure during the start-up phase, especially when using easily biodegradable materials (Goux et al. 2016). This review discusses previous studies on microbial diversity in AD, to enhance present AD productivity constraints, and proposes investigation recommendations for future work.

FW problems and management

FW is a waste that is biodegradable that is generated by a variety of sources such as households, the hospitality sector, and the food processing industries. The quantity of FW is predictable to get higher during the next 25 years because of economic and demographic expansion, particularly in Asian countries. According to reports, the urban FW yearly volume in Asian Nations statistics demonstrates about 278 million tons in 2020 which might increase to 416 million tonnes by the year 2025 (Guruchandran et al. 2022). Aside from land and food resource loss, it is estimated that FW contributes to emissions of greenhouse gases (GHGs) by releasing CO_2 of around 3.3 billion tonnes into the atmosphere each year. Traditionally, FW is a constituent of municipal solid trash, that is burnt or discarded in open areas, which results in serious environmental and health problems. Furthermore, combustion diminishes the substrate's economic worth by obstructing the recovery of nutrient and critical chemical components from the cremated substrate. Thus, proper strategies for managing FW are essential (Kumar et al. 2022).

Food insecurity has been identified by World Trade Organization (WTO) as a primary challenge that should be addressed to attain sustainable development (WTO 2020). FW, ironically, is a major global concern. It is predicted that over half of all food produced on a global scale is wasted. The high incidence of FW combined with rising food insecurity becomes a worldwide concern. Food insecurity is caused by a variety of natural and man-made factors. Major FW man-made cause is food poverty. As a result, academics have claimed that decreasing FW can address at least a portion of the food insecurity issue (Zhang et al. 2021). The previous study has looked into a viable approach to decrease FW a newly produced kind of meal known as upcycled foods. Upcycled food is manufactured from food products that have nutritional significance and may be used but are frequently wasted (McCarthy et al. 2020). This section provides the source, problem, and management of FW.

Impact of FW

In regard to wasting resources such as nutrients, water, carbon, and energy required for food production, which are not used, badly manage FW has a negative impact on climate because of greenhouse gasses (GHGs) emission during decay, contamination of watercourses, and maybe a disease vector leading to the health hazard. The effects of FW on societies, the environment, as well as its collection and recycling might help to alleviate a number of harmful effects. Several of the possible mitigating steps necessary to accomplish this include climate change and GHGs emissions; nutrient loss; water footprint; sanitation; economic and ecological impacts. FW management, re-use, and their treatment have been provided in Fig. 1 (modified from Bigdeloo et al. 2021) and Fig. 2 (Created with BioRender.com).

Climate change and GHGs emissions

Methane (CH_4), greenhouse gases nitrous oxide (N_2O), along with carbon dioxide (CO_2), contribute to climate change and global warming. They are generated at levels of the food life cycle, resulting in emissions from manures and livestock and slurries, release stored carbon in cleared biomass; to produce energy from burning fossil fuel. When discarded food is disposed of in dumps or landfills, it decomposes and releases more pollutants into the environment (Reisch et al. 2021).

Nutrient loss

Plants are largely composed of water and carbon (C), and their growth requires phosphorus (P), nitrogen (N), and potassium (K), among various nutrients. Plant photosynthesizes C from the atmosphere, whereas PNK comes from the soil as well as inorganic and organic fertilizer applied by the farmer. The decade of unsustainable farming methods has led to nutrient deprivation and organic matter reduction in soil (O'Connor et al. 2021). Furthermore, soils have only recently been exposed to intensive agricultural methods and apply synthetic fertilizer on a worldwide scale. Breakdown in this cycle can be rectified in part by recycling these wastes from urban environments back to agriculture using compost and digester (Lansing et al. 2019).

Sanitation

Globally, around 50% of garbage is disposed of in landfills, whereas 13–33% of garbage is dumped publicly in middle and poor-income nations. Organic and FW in dumpsites and landfills can cause parasite and gastrointestinal disorders in the communities that live and work nearby, particularly children and women. Humans use the flesh and milk of grazing animals, which may be found open waste all over the world (Chen et al. 2020).

Water footprint

Water is taken from surface water bodies and groundwater aquifers for irrigation in areas having seasonal/insufficient rainfall. FW generation and unregulated disposal of FW have an influence on both groundwater and surface bodies. The use of pesticides and fertilizer, along with accompanying runoff, has a harmful influence on the quality of water in surface and groundwater bodies. Whereas untreated effluent from food processing industries pollutes leachate from the dumpsite, surface water bodies, and landfills pollute both surface and groundwater water (Mekonnen and Fulton 2018).

Economic impacts

More research is required to determine how these macro estimates may be used at the local level of particular cities. FW, for example, that is not individually collected and disposed of in landfills incurs a cost to the city in terms of transportation and entrance fees, not to mention any social or environmental implications. Cities might require accounting for the cost of GHGs emissions. GHGs accounting for untreated FW sent to landfills, the impact on the regional residents' health residing near those sites, and the cost of pollution to soil and water bodies are all quantifiable with a complete analysis. In order to get a more accurate picture of the environmental and economic costs of untreated FW, towns may choose to conduct an analysis of the economic and environmental costs of untreated FW before analyzing the cost of collection and treatment. Finally, it is vital to comprehend the revenue created by the treatment of FW in urban contexts via organic soil amendment, sale of compost, heat, transportation fuel, biogas to generate energy, and soil nutrients (Thyberg and Tonjes 2016).

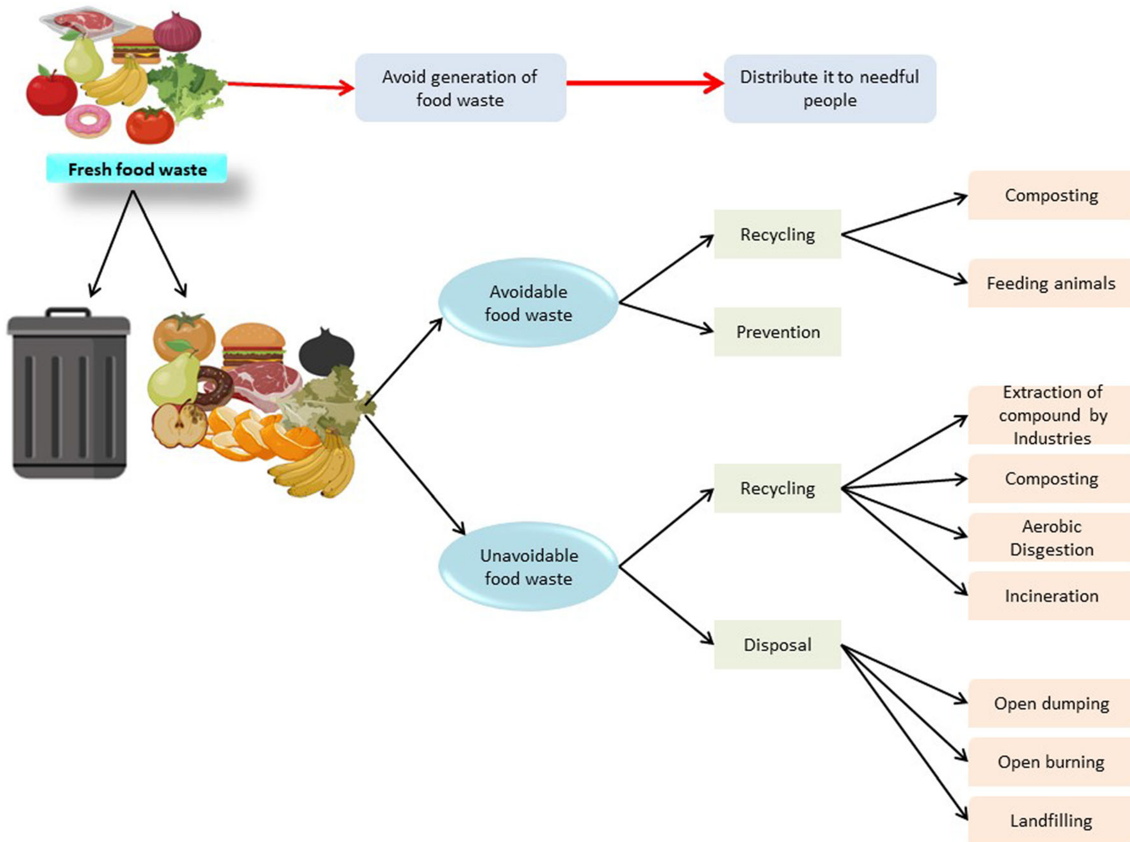

Fig. 1 Major four steps of FW management, recycle and re-use

Ecological impacts

To have an effective production of food to feed the world's growing population has resulted in massive ecological damage due to: a shift in land used from marshes, prairies, forests, and peat bogs to agriculture; species loss of biodiversity, including birds, mammals, fish, and amphibians; and overfishing of marine life. Globally, the effects of the production of food harm have been seen in the form of biodiversity loss, marine population decline, soil quality, and a variety of other indicators (Thyberg and Tonjes 2016).

Composition and odours

Proteins, carbohydrates, lipids, and inorganic materials trace of make up the majority of FW. The composition differs depending on the kind of FW along with its contents. FW including vegetables and grains is heavy in carbs, but FW containing eggs and meat is rich in lipids and proteins (Paritosh et al. 2017). The FW composition researched in various locations of the world is summarised in Table 1. Odor discharge into the surrounding environment is a big issue for many composting sites. Numerous odorous compounds have been found in gases compost as a result of several experiments screening smells from various composts. It is well understood that the quality, as well as quantity of odor produced by compost, varies depending on the composition of substrate and process variables (Agapioset al. 2020). When composting FW, at the beginning of the process there is frequently a low-pH period. Slow decomposition at extended low pH conditions is a common process concern in FW composting (Sundberg and Jönsson 2008). The two most abundant acids are acetic and lactic acid, although numerous additional acids have been discovered in lower quantities (Sundberg and Jönsson 2008). Organic acid, particularly those with longer chain lengths, is known to be odorous. Odour is assessed using dynamic olfactometry, a defined method in which a group of people estimates the gas samples' odor diluted with nitrogen at various concentrations. This technology is time-intensive and expensive, making it unsuitable for regular odor tests at a composting operation. To measure the amounts of particular compounds, an instrument based on separation procedures such as chromatography is often utilized. The low pH of wastes has been linked to lactic acid bacteria's higher concentration in incoming decomposing and trash material during the composting process's early stages

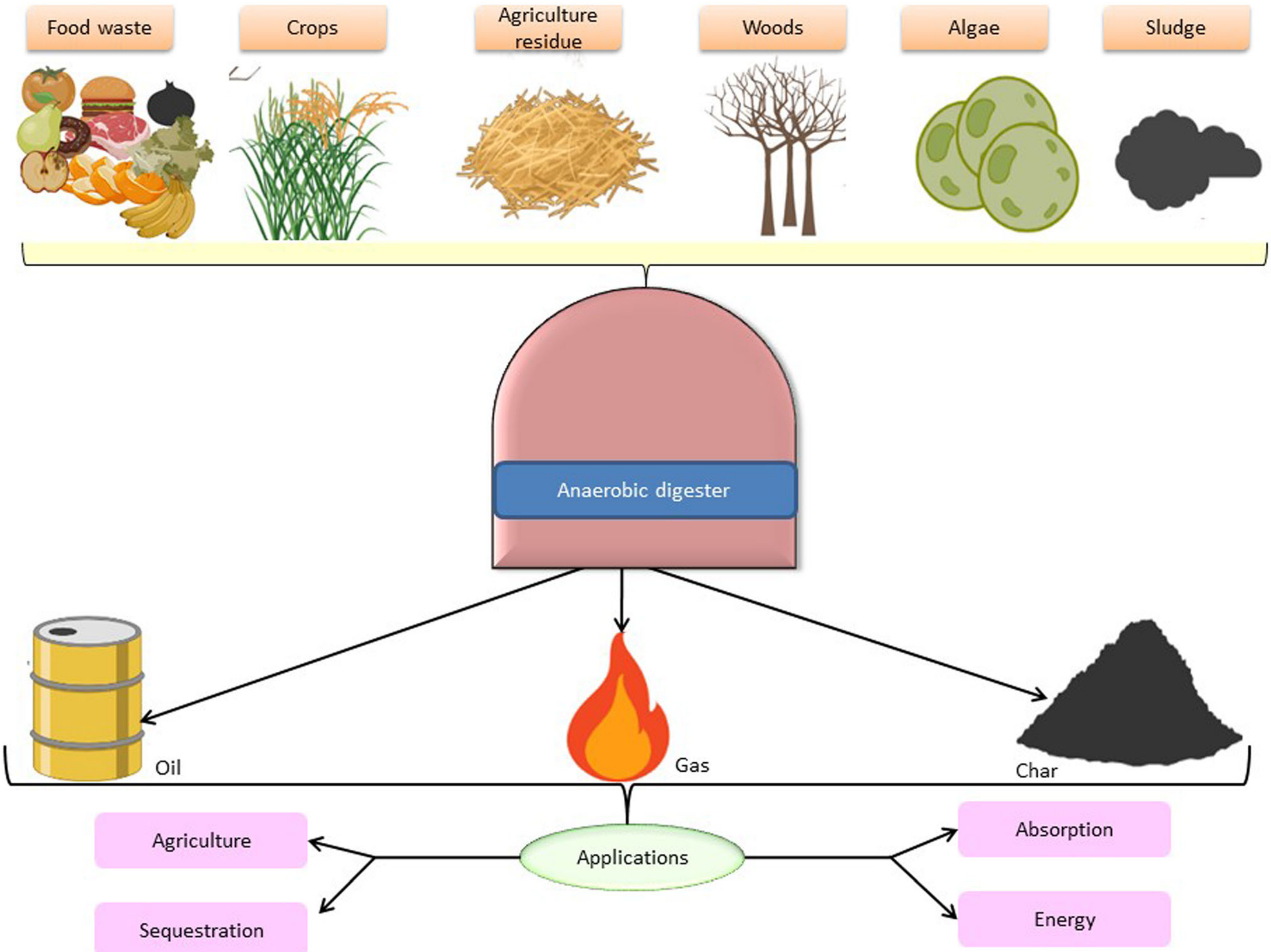

Fig. 2 FW management and its treatment using AD

Table 1 FW composition reported in several kinds of literature

Total solids	Moisture	Total sugar	Starch	Volatile solid	Cellulose	Protein	Lipids	Ash	References
24.1	75.9	42.3	29.3	–	–	3.9	–	1.3	Ohkouchi and Inoue (2006)
17.2	82.8	62.7	46.1	89.1	2.3	15.6	18.1	–	Wang et al. (2008)
19.7	80.3	59.8	–	95.4	1.6	21.8	15.7	1.9	Tang et al. (2008)
14.3	85.7	42.3	28.3	98.2	–	17.8	–	–	Zhang et al. (2005b)
24.8	75.2	50.2	46.1	–	–	15.6	18.1	2.3	Wang et al. (2008)
17.2	82.8	62.7	46.1	85.0	2.3	15.6	18.1	–	Ma et al. (2008)
14.3	81.9	48.3	42.3	98.2	–	17.8	–	–	Vavouraki et al. (2013)
18.5	81.5	55.0	24.1	94.1	16.9	16.9	14.0	5.9	Vavouraki et al. (2013)
38.7	61.3	69.0	–	–	–	4.4	6.4	1.2	Uncu and Cekmecelioglu (2011)
18.3	81.7	35.5	–	87.5	–	14.4	24.1	–	He et al. (2012)

(Partanen et al. 2010). As pH and temperature rise in well-functioning systems, the number of lactic acid bacteria quickly decreases during the initial phase (Partanen et al. 2010). Rapidly overcoming the early low-pH phase is a key method for minimizing odour from FW composting. This may be accomplished by a mix of higher aeration rate that gives cooling and oxygen, as well as additions like recycled compost (Sundberg and Jönsson 2008).

FW anaerobic digestion

FW is major significant component of global waste (Santagata et al. 2021; Bian et al. 2022). It is predicted that methane (CH_4) production rate varies between 0.4 and 0.5 L CH_4 g VS^1 (Nagao et al. 2012; Li et al. 2016, 2019), indicating energy recovery has higher potential. As a result, interest in FW AD has grown during the last few years. Capson-Tojo et al. (2016) published and evaluated FW therapy in laboratory-scale trials with AD. AD has been extensively used for FW treatment on an industrial basis in several European and affluent Asian nations. England, Germany, Korea, and Spain have established AD factories having capacities of 2500 tonnes/year or higher (Thi et al. 2015). Developing countries have developed diverse types of AD digesters in commercial and household sizes for FW treatment using AD technology (Thi et al. 2015). AD is regarded as the primarily appealing approach for processing and organic solid waste recycling in order to create energy-rich gases like methane and hydrogen while also reducing the volume of waste (Wang et al. 2018).

Because of its higher organic content, FW has a strong potential for AD to create methane (CH_4). Table 1 depicts the biogas potential output from several kinds of FW. Although, FW AD is a complicated procedure. Several inhibitors, including volatile fatty acids and ammonia build-up, frequently result in poor performance and even failure of the process (Benyahya et al. 2022). To ensure a consistent operation, typically digesters are run at a low organic loading rate (Tampio et al. 2014). A number of studies concentrate on monitoring purposes in order to improve process reliability and efficiency (Li et al. 2016). As seen in Fig. 3 (Created with BioRender.com), AD is a biochemical process in which all complex organic molecules go through a series of multiple-step that includes hydrolysis, acidogenesis, acetogenesis, as well as methanogenesis. At different stages of hydrolysis and acidification, hydrogen synthesis, and methane production in the AD process, the microbial populations change (Hou et al. 2021). As AD is a biochemical process having microbial groups, microorganisms' wide range, are at the base of digesters. Many attempts on microorganisms have been made in this sector to improve the stability and efficiency of AD (Abbas et al. 2021). Anaerobic methane production is an effective alternative for FW management. The process produces fewer residual trashes, is affordable, and uses FW as a renewable energy source (Nasir et al. 2012). AD is divided into three stages: hydrolysis of enzymatic, generation of acid, and production of gases.

Enzymatic hydrolysis

Microorganisms that cannot transfer large polymer molecules to cell membranes are broken down in the primary phase by hydrolases released by obligate or facultative hydrolytic anaerobic bacteria. Hydrolysis converts polymers into monomeric or oligomer molecules. Polysaccharide is further subdivided into oligo-saccharides followed by mono-saccharides; for example, (1) depicts the formation of molecules of glucose by hydrolysis of starch. Proteins are degraded into amino acids and peptides, whereas lipids are transformed into fatty acids and glycerol.

$$nC_6H_{10}O_5 + nH_2O \rightarrow nC6H1_2O_6 \quad (1)$$

Strauber et al. (2012) reported that under anaerobic circumstances, the rate of hydrolysis is slower as compared to acid production rate and is affected by the type of the bacterial concentration, bioreactor temperature, substrate, and pH. Other factors influencing the rate of hydrolysis are enzyme synthesis, size of substrate particle, pH, and adsorption of enzyme on particles of the substrate. According to Wainaina et al. (2019), *Enterobacter* and *Streptococcus* are anaerobe genera that are accountable for hydrolysis.

Acidogenesis phase

This occurs in the second phase, through which hydrolytic products are fermented to volatile fatty acids like propionate, acetate, isobutyrate, valerate, butyrate, ammonia, carbon dioxide, and hydrogen. In acidification, anaerobic facultative bacteria utilize carbon and oxygen, leading to an anaerobic environment appropriate for methanogenesis. In this step, obtained monomers in the first phase turn into substrates for microbes, who transform the substrate into organic acid via a bacterial group. Methane (CH_4) may be produced straight from hydrogen, carbon dioxide, and acetate. On the other hand, butyrate, propionate, isobutyrate, and valerate, are introduced for additional breakdown by syntrophic acetogenic bacteria, resulting in hydrogen and acetate (Zhang et al. 2005a).

Acetogenesis

Bacteria that are Acetogenic belong to the genera *Syntrophobacter* and *Syntrophomonas* degrade acid phase products into hydrogen and acetates. Molecules of acetate are also produced when carbon dioxide is reduced with hydrogen as a source of the electron. Acetate will be utilized further by methanogens in later phases. The H generated during the process, on the other hand, has an inhibiting impact on microbes. As a result, in AD, acetogenic bacteria coexist with hydrogenotrophic methanogens,

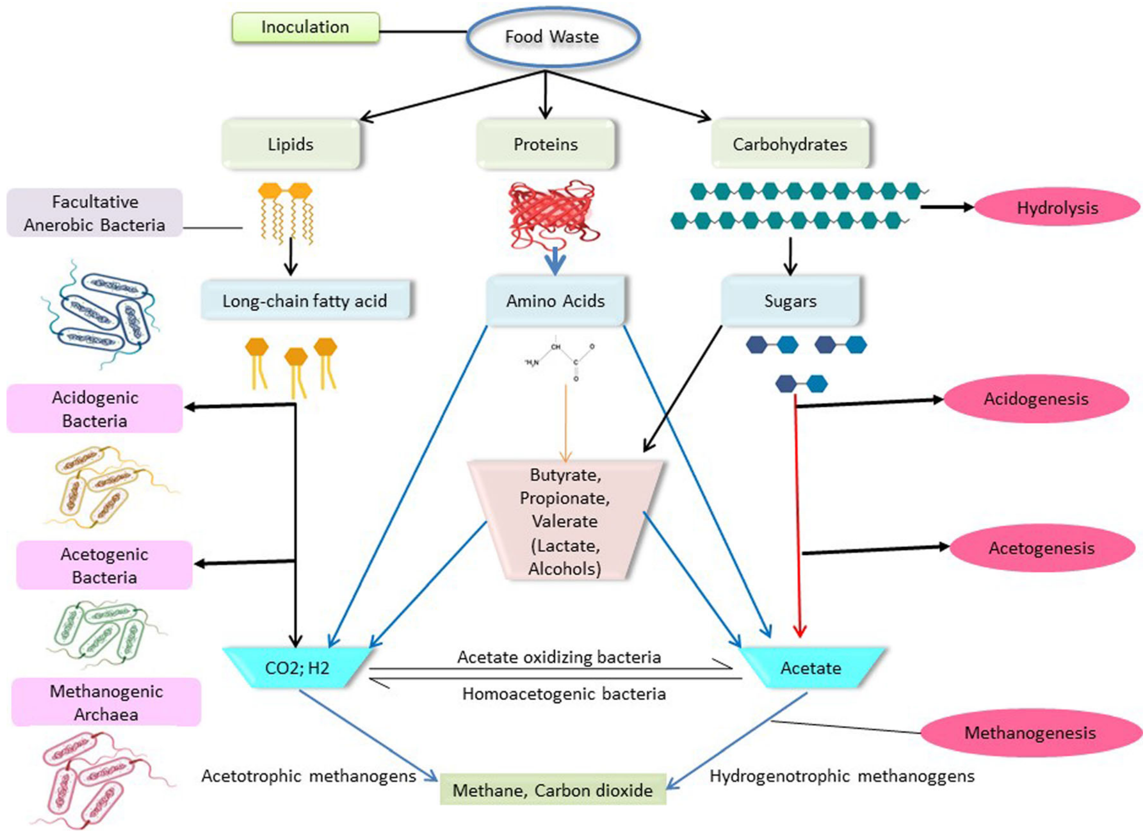

Fig. 3 The essential stages and routes of the AD process for FW

which eliminate H by using it for CH_4 synthesis. Furthermore, acetogenesis is the phase that represents the biogas efficiency generation since acetate decreases to produce 70% of methane. Simultaneously, hydrogen 11% is produced throughout the process (Qian et al. 2019).

$$nC_6H_{12}O6 \rightarrow 3nCH_3COOH. \quad (2)$$

Methanogenesis

Archaea methanogens carried out Methanogenesis which occurs in the last phase. CH_4 can be produced either by decreasing carbon dioxide or by fermentation of acetic acid. As a result, preceding phase components, hydrogen, carbon dioxide, and acetic acid, operate as a precursor for methane synthesis. Only 30% of the CH_4 generated in this process is due to the reduction of carbon dioxide by methanogens (Karakashev et al. 2005).

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (3)$$

CH_4 may be produced by 2 types of methanogens: hydrogenotrophic methanogens, which use hydrogen to decrease carbon dioxide, and acetoclastic methanogens, which make CH_4 from acetic acid.

$$CO_2 + 4H_2 \rightarrow CH_4 + 3H_2O. \quad (4)$$

Microbial community structure during composting

Composting is characterized by microbial community successions that enthusiastically decomposes putrescent and degradable organic waste in self-heating, wet, as well as aerobic condition. Both bacteria and fungus, reflect the microbial community structure of the environmental composting. The existence of certain bacteria or fungi can have an impact on the entire composting process, either positively or adversely. Physical characteristics are critical to understanding the activity of various microorganisms' groups, which reflect the quality of the composting process's end result (Bohacz 2019). During the early phases of the composting process, most collected wastes have low pH, which coincides with a higher concentration of lactic acid bacteria (Partanen et al. 2010). Another ideal approach for composting is anaerobic digestion, which uses FW to create biogas by addressing the management of waste and recycling nutrients (Stürmer 2020). The microbial population works by dissolving complex organic material into lipids, proteins, and carbohydrates, which are then hydrolyzed by enzymes like cellulase, lipases, amylase, and protease into steady, simpler forms of carbohydrate, long-chain fatty acid, and amino acid (Lauwers et al. 2013). Calculating enzyme activity during composting may offer knowledge about composted materials' maturity by decomposing organic matter and nitrogen transformations (Bohacz 2019). The biochemical changes that occur at each step of composting, as well as the usage and type of microorganisms that arise during the decomposition process include different stages of composting.

Stages of AD

The process of composting is divided into 3 main phases: the mesophilic phase, the thermophilic phase, and the maturation or cooling phase, where varied microflora like thermophilic and mesophilic fungi, *actinomycetes*, and bacteria are there which convert and stabilize organic waste into humus (Morenoet al. 2011). Various communities of microbes prevail at different stages of composting. Mesophiles execute the first breakdown of organic materials owing to the easily accessible sources of carbon at the start of the process. The thermophilic microorganisms, that are heat resistant, will take over and dominate the mesophiles during the thermophilic phase. Because rising temperature increases the breakdown of components and hence the exhaustion of nutrients, the temperature progressively decreases and returns to the mesophilic phase before the compost develops (Yu et al. 2019). In the chilling period, the mesophiles return to the compost and begin the digestion of leftover organic waste. Figure 1 depicts the all-over temperature profile that dictates the beginning and finish of every stage. Overall, the composting process is linked to a diverse set of communities of microbes. Literature reports have recognized the existence of bacteria from the genera *Streptomyces, Bacillus, Anthrobacter, Escherichia, Enterobacter, Micrococcus, Staphylococcus, Alternaria, Nitrobacter, Morganella, Nitrosomonas, Paucimonas, Proteus, Pseudomonas,* and fungal genera *Cephaliophora, Aspergillus, Cladosporium,* and *Humicola*, Table 2 summarises the microorganisms that have been described in several recent scientific papers based on the composting phases.

First stage (Mesophilic)

In the composting process early-stage mesophilic temperature, as well as carbon-rich substrate availability, favor the mesophiles growth with a mixture of actinomycetes, bacteria, and fungi, which grows at temperatures ranging from 15 to 45 °C and achieve optimum growth at temperatures ranging from 30 to 39 °C (Majhi et al. 2021). Mesophilic fungi like yeast, mold, and acid-producing bacteria such as *Acetobacter* spp. and *Lactobacillus* spp., are the dominating species at this stage in the decomposition of organic waste materials (Partanen et al. 2010). As organic acids are created, the pH normally drops. These microbes subsequently convert the easily digested carbon sources into organic acid, leading to a pH reduction in the compost (Kausar et al. 2013). Fungi like mold and yeast are in charge of breaking stiff debris, allowing bacteria to continue the process of decomposition, which explains the breakdown of various chemicals like sugars, amino acids, and other simple components during this phase.

Second stage (Thermophilic)

Destruction of organic materials by thermophilic microorganisms, specifically fungus and bacteria occurs. Thermophiles are used in place of mesophiles at this stage of composting, which thrive at temperatures ranging from 40 to 80 °C, favoring thermophilic and actinomycetes bacteria including *Bacillus* spp. (Arya et al. 2021). When carbon supply in the overall compost depletes at the conclusion of the thermophilic stage, the temperature steadily lowers as it prepares to enter the maturation or cooling stage (Gajalakshmi and Abbasi 2008). Actinobacteria and *Bacillus* spp. are the most prevalent strain in the compost at this stage.

Third stage (Cooling)

The maturation phase is distinguished by a temperature that is even lower than 25 °C. The microbial activity of thermophiles ceases due to substrate depletion, and mesophiles are now returning to recolonize organic matter from spores that survive at higher temperatures and revive when the temperature drops, or by inoculation from the environment or the compost pile's edge. Because of the metabolism of phytotoxic chemicals, the microbiota at this stage has an important role in the maturation of compost and controlling diseases of plants. Some soil fungi can degrade lignin in a way that *actinomycetes* and bacteria cannot (Maaroufi et al. 2019).

Importance of food for sustainability

Composting has several advantages, particularly for nature and the environment. As a result, FW composting should become a viable alternative to chemical fertilizers, obviating the need for chemicals. By breaking down organic debris, these bacteria and fungus produce humus, a nutritious and nutrient-rich material. Composting also enriches the soils with nitrogen, potassium, and phosphorus. Certain

Table 2 Microbial population diversity varies depending on composting stage

Group	Compost stage	Genus	Microbial species	References
Bacteria	Mesophilic	*Amycolicicoccus*	*Amycolicicoccus subflavus*	Partanen et al. (2010), Hefnawy et al. (2013), Chandna et al. (2013), Antunes et al. (2016), Li et al. (2019) and Paneet al. (2020)
		Brevibacillus	*Brevibacillus brevis*	
		Bacillus	*Bacillus cereus,. Bacillus badius, Bacillus polymyxa, Bacillus flexus, Bacillus pumilus, Bacillus subtilis, Bacillus* sp.	
		Mycobacterium	*Mycobacterium xenopi, M. thermoresistibile*	
		Enterobacter	*Enterobacter sakazakii*	
		Klebsiella	*Klebsiella pneumonia*	
		Staphylococcus	*Staphylococcus sciuri, S. aureus, S. xyloseus, Staphylococcus* sp.	
		Serratia	*Serratia marcescens*	
Fungi		*Fusarium*	*Fusarium oxysporum, F. moniliforme, Fusarium* sp.	Hefnawy et al. (2013)
		Aspergillus	*Aspergillus niger, A. flavus*	
		Rhizopus	*Rhizopus nigricans*	
		Streptomyces	*Streptomyces cinnaborinus, Streptomyces antibioticus, Streptomyces roseus, Streptomyces griseuss*	
		Penicillium	*Penicillium citrinum*	
Bacteria	Thermophilic	*Anoxybacillus*	*Anoxybacillus flavithermus*	Partanen et al. (2010), Hefnawy et al. (2013), Chandna et al. (2013), Antunes et al. (2016), Li et al. (2019) and Paneet al. (2020)
		Amycolicicoccus	*Amycolicicoccus subflavus*	
		Acidorax	*Acidovorax* sp.	
		Brevibacillus	*Brevibacillus brevis*	
		Comamonas	*Comamonas kerstersii*	
		Geobacillus	*Geobacillus sp. Y4.1MC1, Geobacillus sp. WCH70, G. thermodenitrificans*	
		Bacillus	*Bacillus subtilis, Bacillus coagulans, Bacillus benzoevorans, Bacillus megaterium, Bacillus flexus, Bacillus nealsonii, Bacillus stearothermophilus, Bacillus pumilus, Bacillus* sp.	
		Gemmatimonas	*Gemmatimonas aurantiaca*	
		Klebsiella	*Klebsiella pneumonia*	
		Clostridium	*Clostridium thermocellum, Clostridium acidurici, Clostridium* sp.	
		Lysinibacillus	*Lysinibacillus sphaericus, Lysinibacillus fusiformis*	
		Mahella	*Mahella australiensis*	
		Paenibacillus	*Paenibacillus mucilaginosus, Paenibacillus* sp. *JDR-2*	
		Kocuria	*Kocuria flavus*	
		Mycobacterium	*Mycobacterium xenopi, Mycobacterium thermoresistibile*	
		Rhodothermus	*Rhodothermus marinus*	
		Solibacillus	*Solibacillus silvestris*	

Table 2 continued

Group	Compost stage	Genus	Microbial species	References
		Pseudomonas	*Pseudomonas putida, Pseudomonas mendocina, Peseudomonas* sp.	
		Thermobacillus	*Thermobacillus composti*	
		Thermus	*Thermus sp*	
		Thermaerobacter	*Thermaerobacter marianensis*	
		Thermosediminibacter	*Thermosediminibacter oceani*	
		Sorangium	*Sorangium cellulosum*	
		Sphaerobacter	*Sphaerobacter thermophilus*	
		Thermobispora	*Thermobispora bispora*	
		Terribacillus	*Terribacillus halophilus*	
		Streptosporangium	*Streptosporangium roseum*	
		Thermobifida	*Thermobifida fusca*	
		Symbiobacterium	*Symbiobacterium thermophilum*	
Fungi		*Talaromyces*	*Talaromyces thermophilus, Talaromyces* sp.	Partanen et al. (2010) and Hefnawy et al. (2013)
		Thermatinomyces	*Thermactinomyces* sp.	
		Aspergillus	*Aspergillus fumigates var. elpticus, Aspergillus fumigatus*	
		Thermocyces	*Thermomyces* sp.	
		Thermo	*Thermo vulgaris, Thermo dichotomicus, Thermo* sp.	
Bacteria	Cooling or maturation	*Bacillus*	*Bacillus subtilis, Bacillus composteris, Bacillus circulans, Bacillus licheniformis, Bacillus southcampusis, Bacillus pumilus*	Li et al. (2019), Hefnawy et al. (2013) and Chandna et al. (2013)
		Amycolicicoccus	*Amycolicicoccus subflavus*	
		Mycobacterium	*Mycobacterium thermoresistibile, Mycobacterium xenopi*	

nutrients aid in the buffering of severely acidic or alkaline soil, allowing crops to grow and yield more. Composting also aids in the retention of nutrients and the preservation of the soil's pH equilibrium. FW may be decreased and repurposed, which is the most obvious benefit of composting. As a result, the life of landfills is extended because less waste is disposed of there (Awomeso et al. 2010). Composting improves polluted, compacted, and marginal soils, resulting in forest and wetlands restoration and habitat renewal. Without the use of heavy machinery, soil contaminated by hazardous waste is remedied and water retention is improved cost-effectively.

The commitment of stakeholders in the management process is critical to the success of FW management. As essential stakeholders in the food value chain, retailers, grocery stores, hotels, and restaurants can work with farmers to form a long-term sustainable partnership (Kor et al. 2017). Composting, for example, can help increase crop yields in agriculture. Organically cultivated vegetables and products may also command a premium price. Composting can be used to remediate hazardous waste-contaminated soils and save money. When compared to traditional soil, water, and air pollution remediation technologies, composting is a more cost-effective solution (Somerville et al. 2020). The fertility of soil can be improved by composting waste items, which produce plant nutrients in the soil. As a result, water, pesticides, and fertilizer usage can be minimized, resulting in significant cost benefits (Al-Rumaihi et al. 2020). Moreover, composting allows farmers to diversify their farm goods and so boost their income. The partnership can save producers money on fertilizers while also saving the other party money on waste disposal because it can use the same distribution capabilities that supply fresh produce to collect FW.

Conclusions

Recycling and bio-energy from FW through AD is a reliable approach for sustainable development. Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are all microbial processes that are involved in AD of FW. The operational anaerobic species are important in the AD of organics, and the spread of the microbial population is affected by a combination of factors, such as operating parameters, interfering substances, and co-digestion substances. Microbes can serve as markers of whether the AD process is steady or falling. Under high oil, high salt, and high heterogeneity conditions, the dynamic succession, microbial growth characteristics, and effects of various elements on microecology need to be studied in depth at different stages of AD. FW is high in biomass energy, and an increasing number of national projects to recover energy from FW utilizing AD are being implemented. Process control and monitoring, as well as microbiological remediation, can be used to control AD instability and increase energy conversion efficiency. The authors discuss the current state of research on these approaches and identify known constraints to effective AD, as well as make suggestions for future studies. More extensive studies on the principles of microorganism evolvement under complicated circumstances, as well as genome-resolved metagenomic and data-driven methodologies, must be conducted to pave the way for AD microbial regulation strategies.

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Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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