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*Review*

# Food Waste Management for Biogas Production in the Context of Sustainable Development

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**Abstract:** In the context of increasing pressure regarding the sustainable utilization of food waste in a circular economy, one of the trends is their biological transformation, through anaerobic digestion, into biogas as a renewable source of energy. We presented the physical-chemical properties of the main categories of food waste from different sources: dairy, meat, and poultry, fish, fruit and vegetable, cereal and bakery, brewing and winery industries, and others. Due to the high organic load, the presence of a multitude of nutrients, and an insignificant amount of inhibitors, food waste can be successfully used in the biogas production process in co-digestion with other materials. Physical (mechanical and thermal), chemical (alkali, acid, and oxidative), and biological (enzymatic, bacterial, and fungal) techniques have been widely used for pretreatment of different substrate types, including food waste. These pretreatments facilitate the degradation of pretreated food waste during anaerobic digestion and thus lead to an enhancement in biogas production. The purpose of this study is to review the situation of food waste generated in the food industry and to formulate the main trends of progress in the use of this waste in the anaerobic digestion process.

**Keywords:** food waste; anaerobic digestion; biogas; sustainable development; co-digestion; pretreatment



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## 1. Introduction

Today, the global priority is not only to mitigate the negative impact already caused but also to meet the need to produce more food and energy for a population that is expected to exceed 10 billion people by 2050. All of this must be achieved by using as few conventional energy sources as possible, reducing polluting gas emissions and zero solid waste [1]. Globally, agriculture produces, on average, 23.7 million tons of food every day. This rise in global production has put more strain on the environment, harming soil, air, and water resources. This has a knock-on effect on population health and the ability of threatened ecosystems to survive [2].

In recent years, the development of technology has also brought with it rapid economic development, creating an improvement in living standards. At the same time, the amount of waste generated has become quite large, with the pressure on landfills reaching an alarming level [3,4].

A major threat to developing countries is food waste, which negatively influences the concept of sustainable development that most countries want to achieve. Another important issue is the incomplete food waste management systems in place in these countries, which lead to both environmental and population health problems [5]. According to studies, the amount of food waste generated in developed and developing countries is about 107 kg/capita/year and 56 kg/capita/year respectively, which clearly shows that higher living standards generate higher amounts of waste [6,7]. On the other hand, societies with a lower standard of living have lower quality requirements for food production, with the amount of waste generated by each inhabitant being in line with requirements. Unfortunately, the impact of food waste generated by these societies is higher than in developing and developing countries due to insufficient funds to improve waste management services, but the main cause is the lack of education programs to raise awareness of the importance of waste recovery [8].

Food lost or wasted contributes to climate change, with a global carbon footprint of about 8% of total global anthropogenic greenhouse emissions. It represents a waste of scarce resources, such as land, energy, and water, throughout the life cycle of products. For every kilogram of food produced, 4.5 kg of $CO_2$ are released into the atmosphere. Food waste has negative ethical effects in addition to substantial social, economic, and environmental costs. 793 million people worldwide are malnourished, in accordance with the United Nations Food and Agriculture Organization. According to Eurostat, in 2014, 55 million people (9.6% of the EU population) could not afford a quality meal every other day [9]. Although their impact on the environment is by no means negligible, they can be used in various biotransformation processes due to their rich composition in carbohydrates, lipids, and proteins [10].

Sustainable consumption and production, an emerging concept for achieving sustainable development, is attracting increasing attention for the efficient and sustainable use of resources, energy, and infrastructure to ensure a quality life for human beings. It aims to develop comprehensive development plans at a low cost to the economy, environment, and society, increase economic competitiveness, and alleviate poverty [11].

The valorization of food products produces numerous environmental benefits, such as reducing greenhouse gas emissions, reducing the space needed for storage, obtaining more environmentally friendly products, and using renewable energy. A newer method of assessing the environmental impact associated with a product is life cycle assessment (LCA), which can identify certain environmental hotspots, including recycling or final disposal of component materials. LCA can be used to accomplish several objectives, including performance comparison of competing procedures for a given product, comparison of alternative applications of FW streams, and evaluation of the environmental performance of the process and the primary output [12].

A reasonable solution, with considerable benefits for economic and social systems, is the reuse of waste through various means of treatment. Using waste as a raw material offers an alternative that avoids many of these problems while addressing the growing challenge of waste management [13]. Using food waste as a raw material offers an alternative that significantly reduces the environmental impact while addressing the growing challenge of waste management. This is also supported by the European Commission through the Waste Framework Directive, which encourages separate collection and recycling of bio-waste for better management to ensure better protection of the environment, the population, and the sustainable use of natural resources [14].

At present, there are five methods of food waste recovery used mainly in developing countries: animal feeding, composting, anaerobic digestion (AD), incineration, and landfills [5]. The use of waste for animal feed is mainly used in East Asia [15]. Composting is the most common method of using food waste. Microbes metabolize organic waste material and reduce its volume by as much as 50 percent. Currently, according to the Department of Pollution Control and the Ministry of Natural Resources and Environment, about 0.59 million tons of waste are recycled and composted to produce organic fertilizer and biogas [16].

A common but efficient process is anaerobic digestion, the main purpose of which is to obtain biogas [17,18]. Numerous studies have been carried out to improve biogas production yield and waste degradation rate by applying different pretreatment methods. It was found that the use of ultrasound [19], microwaves [20], and pretreatment of food waste under alkaline conditions resulted in high process efficiency [21]. At present, other innovative methods are used, such as the application of a freeze-thawing method [22], as well as Co $\gamma$-ray irradiation technology, a new advanced oxidation technology [23].

Food waste is an important source in the process of obtaining glucose [24] and clavulanic acid [25]. Additionally, from this category of waste, bioelectricity can be generated [26,27]. The management of food waste, which is a subcategory of bio-waste, has been the subject of several previous life cycle assessment studies [28–31].

Research conducted in this area is increasingly focused on building a circular bioeconomy and increasing the value of material flows, leading to sustainable consumption and production with reduced greenhouse gas emissions [32] to achieve zero waste (Figure 1).

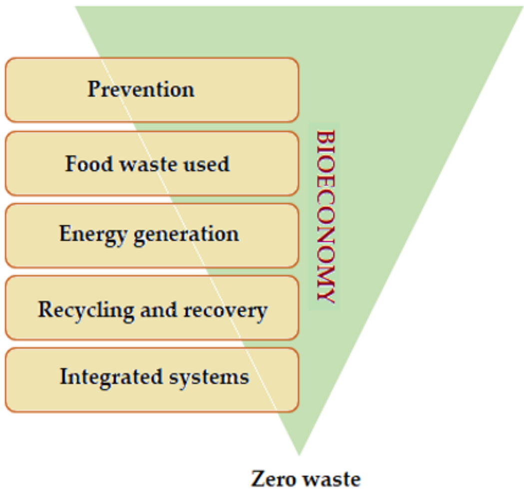


**Figure 1.** Bioeconomy system in relation to food waste (modified after [32]).

The term bioeconomy is also mentioned in the United Nations Sustainable Development Goals (SDGs) and in commitments on sustainable consumption and greenhouse gas emission reduction. Europe has thus succeeded in mitigating negative environmental impacts and reducing dependence on fossil resources, which is a critical issue in ensuring sustainability for a bio-based economy [33]. The bioeconomy is often associated with the notion of the circular economy, but although they share some objectives, the bioeconomy goes beyond the goals of the circular economy and focuses on issues that aim to replace fossil carbon with renewable biomass from agriculture, forestry, and the marine environment [34].

Achieving sustainable development goals can be facilitated by managing food waste within the framework of circular bioeconomy policy, with future developments in this area expected to focus on the integration of waste into a circular system, thereby harnessing the trade-offs between food waste and resources.

In this context, the purpose of this study is to review the situation of food waste generated in the food industry and to formulate the main trends of progress in the use of this waste in the AD process.

## 2. Waste Management and Sustainable Development

Even though societal evolution should have had a positive impact, it seems that this rapid growth has negatively affected the cities (unemployment, lack of resources, infrastructure issues, poverty, environmental problems, etc.). Thus, the need to protect the environment and society has become an issue to be addressed. The term that expressed the measures and aims that could help became known as sustainable development, a need that all countries had to deal with and that set an agenda for 2030 considered by many people as being bold—SDGs [35]. The SDGs can be attained with the help of all development sectors, and every contribution—no matter how small—has the potential to change the world.

They proposed 17 goals to be achieved by 2030, one of which refers to waste management, an activity that can help reach environmental protection. Poor waste management has had a negative influence on human health and has severely degraded the ecosystem. Lower middle-income nations are likely to see the biggest increases in trash output because waste generation is predicted to increase with economic expansion and population growth. Thus, Figure 2 shows the annual regional waste generation, which shows the amount of waste generated in million tons.

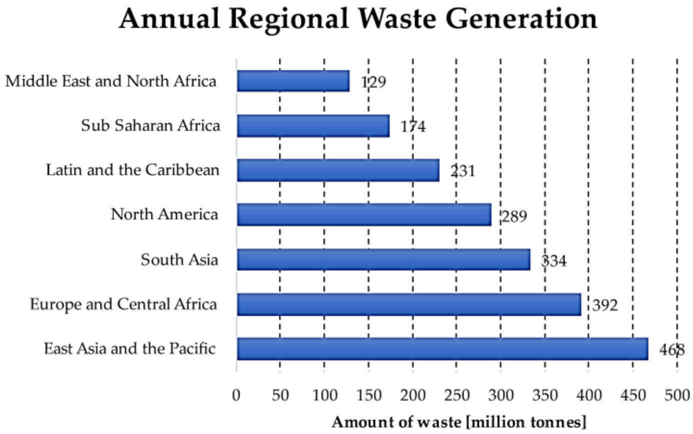


**Figure 2.** European Union Food Waste Generation (modified after [36]).

When local governments have a clear understanding of how much and where waste is generated, as well as the types of waste that are being produced, they can realistically allocate funds and infrastructure, evaluate pertinent technologies, and take into account strategic service providers (NGOs or private sector). With an emphasis on waste statistics, it is necessary to assist governments in making critical financial, policy, and planning decisions for the management of solid waste.

According to the European Commission for Waste Management, there are three main directions:

a. Waste prevention;
b. Recycling and reuse;
c. Improving final disposal and control of waste.

### *2.1. Food Waste and SDGs*

As mentioned before, there are any types of waste that need to be considered; thus, in the 12th Goal, we encounter issues related to 'Responsible Production and Consumption,' which is closely related to food loss and waste management.

For some time now, favorable circumstances for energy and material recovery have been identified by waste management operators [37]. Thus, food issues became the focal point for UN SDG 12, which refers to the environmental impact that all three stages (production, processing, and distribution) have on the environment.

To reduce food losses along the production and supply chains, including post-harvest losses, and to reduce global per capita food waste by half by 2030, a 10-year framework of circular economy initiatives will be put into place as part of SDG 12.

The FAO (Food and Agriculture Organization) of the UN contributes several significant facts to the total situation of food waste. Along with other things, the distinctions between developed and developing economies are particularly intriguing. Food loss and waste primarily occur at the beginning of the food chain and are caused by management, technological, and financial limitations on harvesting methods, as well as holding and cooling infrastructure. Food is wasted and lost primarily in the final stages of the supply chain in developed economies, with customers' reckless behavior actively participating.

Currency is more widely available, and foods are aggressively marketed at both the amount of media marketing and the large-scale retail sector, which encourages consumers to make impulsive purchases that end up costing them money for a variety of reasons [37]. According to different studies, global food loss and waste is around 1.3 billion tons/year [38,39]. More than 95% of this amount ends up in landfills, where it is converted into biogas or other greenhouse gases [40], and because of high volatile solids and moisture content, it is an important source of decomposition, odor, and leachate [41]. Additionally, approximately 72% of the total food waste generated in the EU comes from the household and processing sector, with the remainder coming from the food service sector, followed by the production, retail, and wholesale stages, which contribute 12%, 11%, and 5%, respectively [42], as can be seen in the Figure 3.

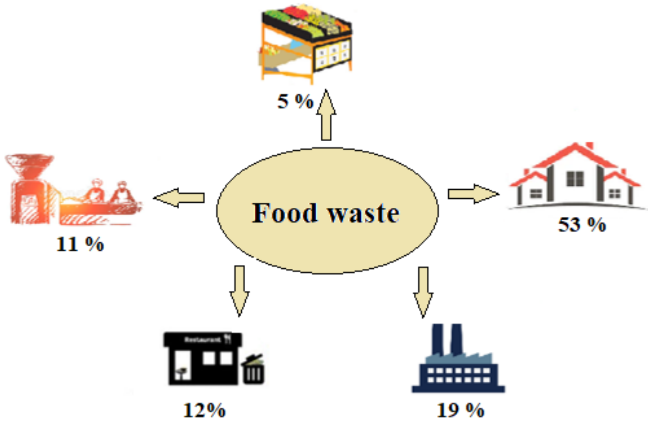


**Figure 3.** European Union Food Waste Generation (modified after [42]).

The research area related to food waste is constantly developing new ways, technologies, techniques, and management systems to make procedures simpler. Additionally, the need for integrated and sustainable methods for food waste is desired to have an improved way of disposing the food and achieving technology innovation, life cycle assessment, and sustainable development [43–45]. Not achieving the objective of SDGs related to food waste means consequences related to health, the environment, and society, all with a significant impact for the future. To tackle this issue properly, food loss and waste should first be classified. Researchers have proposed a classification of food waste as avoidable, partly avoidable, and unavoidable [46].

According to studies, most of the food waste is generated by the consumer, with more than 50% of the waste at a European level [47]. This can signify that educating consumers and making them aware of the implications of food waste on sustainable development are one step closer to SDG's objectives. Without proper waste management (reduce, reuse, and recycle), no strategy to reduce waste will work. Some scientists have revealed the need for proper channels to transform waste into raw material for another step in the process of reducing losses [48].

### *2.2. Anaerobic Digestion for Food Waste*

A waste management technique called AD is used to recycle organic waste materials and create biogas that is rich in methane.

To handle and recycle rising solid waste streams, biogas from AD, a sustainable biofuel produced from a range of organic substrates (feedstocks), is a leading technology. Natural gas, an increasingly essential fossil fuel for the world's energy supply, can be replaced with refined biogas as a drop-in fuel [49].

Since most studies examining the effects of fluctuation concentrate on defining efficiency under sets of steady conditions, researchers know today even less about the viability and estimated variations of biogas production using combined, non-uniform, and temporally parameter feedstocks in experimental structures and temperate climates [50,51]. By adjusting the digester designs, temperature range, substrate, co-digestion pre-treatments, organic loading rate, and sludge retention durations, among other factors, it is possible to increase the transformation of organic materials during AD [52,53]. However, each transformation must consider the key bacterial activity engaged, and some adjustments are difficult to make in existing systems. Additionally, it is typically costly and complex to supervise any effects.

The structural composition of food waste, whether pre/post, is biologically acceptable with the microorganisms that promote AD [54], making it a major-grade organic feedstock for biogas production. The increased nitrogen concentration of most food waste compounds predisposes digesters to nitrogen inhibitory activity, ammonia concentration, low pH, and souring, requiring low organic mass flow, are corrective strategies to overcome the carbon to nitrogen (C:N) discrepancy inside digesters, according to previous studies on food-based AD [55]. The wide C:N ratio in food waste shows the need to refine the optimum C:N ratio.

There are issues such as heterogeneity of food waste that have implications for the AD process, and thus implications for the final digestate quality [56]. Additionally, in this process, about 40% become biogas. Through research, it was demonstrated that to obtain an increase in process efficiency, a two-stage AD system needs to be used at the same time having various ratios for food waste [57,58].

Other data obtained by scientists revealed that using additives such as metal additives proved the important effect that metal has on the digestion process [59]. The entire process system is presented in Figure 4, where the process from start to finish is presented. As can be seen, there are various outputs by using AD on the raw material, which in this case is food waste. As can be observed in the end, we can obtain natural gas, which can be used as different types of energies.

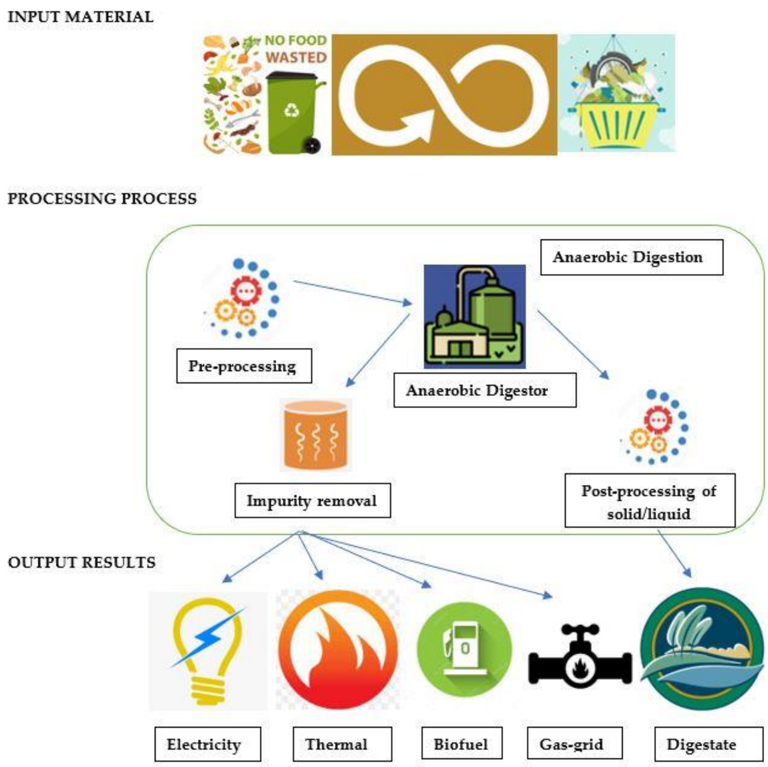


**Figure 4.** Anaerobic Digestion System (modified after [60]).

## 3. Categories of Food Waste

Nowadays, the types of food waste are characterized by great diversity in terms of their origin, as well as their chemical composition, physical properties, and the presence of microorganisms. There are many ways to classify this waste based on which optimal recovery and valorization technology is chosen. The simplest method of classifying food waste is based on the type of industry sector that generates it. The advantage of this classification method is the easy and immediate establishment of the recovery route and the handling of waste that comes from a common area, has common characteristics, and the costs are significantly reduced [61].

Therefore, waste is classified into waste from the dairy, meat and poultry, fish, fruit and vegetable, cereal and bakery, brewing and winery industries, among others (Figure 5).


**Figure 5.** Categories of food waste.

Other criteria for classifying food waste could be food source, edibility, animal-product presence, complexity, treatment, unpackaged/packaged (important for sorting and subsequent treatment), packaging biodegradability, stage of the supply chain, and others [62,63] (Figure 6).

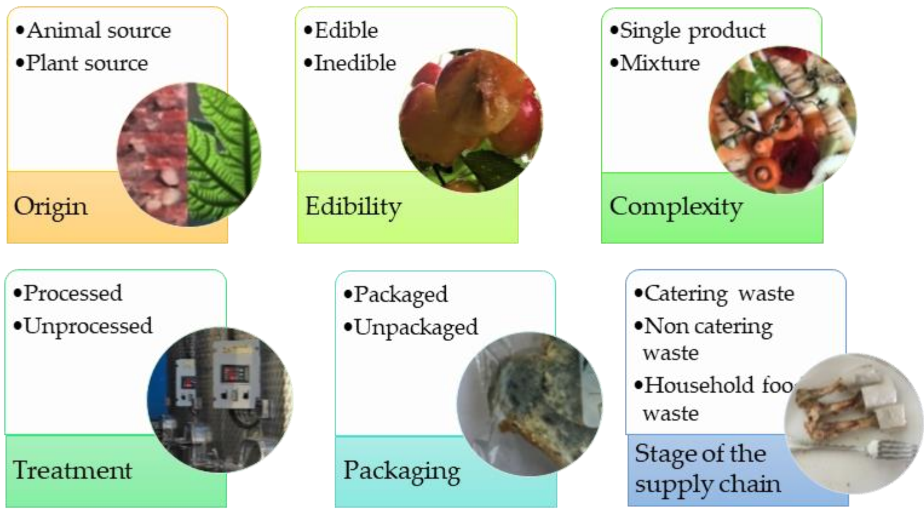


**Figure 6.** Classification of food waste (modified after [63]).

The quantification of food waste is explained in the Food Loss and Waste Accounting and Reporting Standard (2016), which recommends the use of modular definitions and various quantification methods and classifies waste according to the food category from which it comes, having as the classification source the categories from either the Codex General Standard for Food Additives (GSFA) system or the United Nations Central Production Classification (CPC) system [64].

These classification criteria are only partially useful for the utilization of food waste through AD and biogas production. The most important characteristic, however, refers to the chemical composition of the waste, which represents fermentable substrates for the microorganisms involved in the AD process. In addition, the absence of inhibitory substances for the activity of substrate decomposition enzymes and microorganisms in the digestor is of significant importance. Other factors with a high impact on the AD process and biogas production are humidity (although this can be adjusted along the process), substrate particle sizes, pH, $E_h$, the presence of useful or pathogenic microorganisms.

In the AD process, a major role in the multiplication and activity of microorganisms involved in the 4 known stages (hydrolysis, acidogenesis, acetogenesis, and methanogenesis) is fulfilled by the composition and physical-chemical properties of food waste: C:N ratio, total solids (TS), volatile solids (VS), pH, chemical oxygen demand (COD), ash, moisture, and others.

The quality and availability of the substrate and nutrients in the AD process have a significant impact on the biochemical reactions and multiplication of bacteria. It is known that the optimal C:N values are between 10 and 30. In food waste, this ratio is in the range of 9.3–24.5, but it varies significantly depending on the type of food waste.

Compared to other types of substrates used in AD, food waste is generally characterized by a diversity of nutrients favorable to microbial growth and acidic pH (generally from 3.9 to 6.7), unlike other organic waste such as animal manure, green waste, and sewage sludge. In the first stage of anaerobic digestion, hydrolysis, studies have shown that the decomposition of proteins is favored by pH values between 7.0 and 8.0, while the decomposition of carbohydrates is favored by pH 6.0–9.0. At the same time, it has been demonstrated that methanogenic microorganisms are particularly sensitive to pH values, being active at pH values in the range of 6.5–7.2 [65].

COD is used in the analyses during the AD process to estimate the amount of available organic matter in the digester and in the effluent, as well as the yield of the biogas production process. Along with the other chemical properties of food waste, during AD, the COD value is often used to determine the quantity of feed in the reactor. In addition, the COD of the influent and effluent materials is used to calculate digestion efficiency.

Other measures of the chemical properties of the AD process include total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and the concentrations of some essential bioelements, such as C, N, P, S, and K.

Food waste contains, as expected, a wide range of micronutrients that include metal ions, such as K, Na, Ca, Mg, Fe, Zn, etc., which are necessary bioelements in small concentrations for the development of microorganisms. In addition, in most wastes from the food industry, heavy metals that are toxic to humans and microorganisms are in minimal concentrations or absent [66].

The presence of sulfur in some food waste can lead to the production of H2S in quantities greater than 2000 ppm, which makes it necessary to remove this compound from the biogas obtained in the AD process. The presence of hydrogen sulphide in biogas has major unwanted effects; at concentrations of 1000 to 2000 ppm, it produces serious respiratory problems. Even at 100 to 200 ppm, it can cause blurred vision and even death after several hours of inhalation. At concentrations up to 50 ppm, dissolved H2S is toxic to the bacteria in the AD process. It is a corrosive gas that degrades the metal parts of the equipment and produces sulfur dioxide by combustion, which is corrosive and harmful to the environment [67].

Nitrogen in protein form or other types existing in food waste is considered beneficial for the AD process; this element plays an important role both as a nutrient and in buffering the environment in the digester.

Although they are necessary as trace minerals in the AD environment, in large amounts $Ca^{2+}$ and $Mg^{2+}$ can accentuate the toxicity of the ammonium ion in the reactor. Na in combination with K or Mg has beneficial effects on biogas production. However, Na values higher than 8 g/L existing in more and more food waste (especially from fast food) are considered inhibitory for the methanogen group [66].

Regarding the content of proteins and carbohydrates in food waste, they are directly related to the type of food from which this waste comes. It is known that the level of carbohydrates of all types (mono and di polysaccharides) is significantly higher in food waste of plant origin, even if the degree of accessibility of the different sugars is not similarly high. Food waste can have a high content of cellulosic or lignocellulosic material (waste from cereal processing, vegetable and fruit peels, seeds, kernels, etc.) and, in this case, requires pre-treatment to destroy the lignocellulosic material. Oligosaccharides are more accessible to microorganisms that act in the first stage of AD, producing a hydrolysis reaction of the substrate. In many types of processed or unprocessed food waste from restaurants or households, the presence of starch is almost inevitable. Microorganisms that intervene in the first stage of AD can produce various enzymes from the hydrolases class, which break down carbohydrates into smaller sugars or monomeric units. Additionally, food waste, especially of animal origin, contains large amounts of proteins that will be hydrolyzed to peptides and amino acids, sources of nitrogen for the microorganisms in the digester. Protein degradation produces ammonium during AD; large amounts of ammonia can become toxic to microorganisms. The fats present in food waste will also be hydrolyzed with the production of glycerin and fatty acids, the presence of the latter having an important role in the development of the AD process. However, a large amount of lipids can unbalance the process, leading to low biogas yields. In addition, food waste contains a significant amount of vitamins and other growth factors that favor the development of even pretentious microorganisms. The moisture content of food waste is in most cases quite high; in the waste from the raw materials, before processing, the water content specific to the plant or animal cell is found, with values between 60% and 80%, which ensures a range of water activity favorable to the multiplication of most groups of bacteria and fungi. The moisture content of food waste depends on the source and type of waste and can have values ranging from 48% to 95%, with an average value of 77%. For example, according to Selvam et al., source-segregated food waste, organic fraction of MSW (municipal solid waste), and samples from households have a moisture content of around 70%, while food waste from canteens and restaurants has a moisture content of 75–85% [66].

Also, most of the waste resulting from processed food or wastewater from the food industry has fairly high aw values, which allows the development of microorganisms at aw values higher than 0.65.

It must be considered that the composition of food waste can differ depending on the sector of the food industry, the eating habits of a population group, and the season. It was found that [66] the percentage of carbohydrates is higher in winter, while the percentage of proteins is increased in summer, a phenomenon explained by diets or other uses of food waste (composting). Of course, these differences depend on the area and the behavior of groups of people.

Apart from the chemical composition, a large part of food waste contains a high number of types of microorganisms, considering that food represents excellent culture media for bacteria and fungi. Whether the waste comes from unprocessed food or from processed food from restaurants and households, contamination with spoilage microorganisms is almost inevitable. Therefore, especially under favorable conditions of temperature and humidity, microorganisms can reach the exponential growth phase, producing a series of primary and secondary metabolites because of the decomposition and metabolism of the substrate represented by food waste. Therefore, there is an initiation of the hydrolysis of the substrate, which continues in the AD reactor.

### *3.1. Waste from Dairy Industry*

Waste from the dairy industry comes from the production of drinking milk, cheese, yogurt, and other fermented lactic products, which are characterized by common properties: high protein concentration, high moisture, relatively low pH, and a large number of lactic bacteria. These wastes can come from normal technological losses, as well as from the occurrence of problems in the production process during storage or transport [68]. The by-products normally resulting from milk processing (whey, milk residues, cheese residues) are usually used to obtain some food ingredients or additives, as well as for animal feed. Additionally, due to the high degree of perishability, certain quantities of expired or altered products are obtained, which is inappropriate for human consumption. When this is unprofitable, waste from the dairy industry becomes dangerous to the environment and can be used in the AD process.

These wastes become quite complicated to treat due to the high organic load and favor the development of microorganisms. In addition, wastewater resulting from the dairy industry process has a high amount of organic compounds that can have negative effects on the sewage drainage system.

From the point of view of composition, dairy industry waste has a high content of saturated fats, lactose, and proteins (casein, albumins, and whey globulins), which leads to high values of BOD (biochemical oxygen demand) and COD. For example, according to [69], sweet whey (with a pH of 5.2–5.4) contains 5.8–8.5% TS, 0.6–1% proteins, and 0.2–0.5% fats. Some properties of the waste from the dairy industry, such as the decrease in pH over time, the low values of bicarbonate alkalinity, and increased COD, represent problems in the AD process [70]. In addition, the high concentration of lactose from waste and effluents resulting from dairy industry processes favors the bacteria involved in lactic fermentation and has an inhibitory effect on the methanogens in the AD reactor.

These problems due to the composition of dairy industry waste could be solved by co-digestion with other substrates used in AD, such as manure, straw, lignocellulosic waste, and waste from other food sectors. In addition, in order to balance the AD process and increase biogas production, the two-stage AD technique can be used, which allows the separation of the acetogenesis and methanogenesis stages under the conditions of lower hydraulic retention time (HRT) values compared to the classical method of AD [71]. In the conditions of some regions where there are both agricultural and livestock farms, as well as milk processing units, the advantages of using dairy waste in the AD process to obtain biogas should be taken into consideration.

### *3.2. Waste from Meat and Poultry Processing Industry*

The meat industry produces an impressive amount of food waste from cattle, hogs, sheep, lambs, and other animals that are not poultry. Waste from semi-prepared or finished meat products, such as smoked, seasoned, cooked, and other products, are also included.

The waste is composed of waste animal tissue, non-processable materials, fat from different wastes, after-processing bones, intestine content and haslets, bristles, blood, post-flotation waste, feed content, slaughter by-products, legs, horns, nails, and other [72]. In addition, the wastewater from the meat plant has a high load of manure, grease, and proteins with high values of BOD (usually between 900–2500 mg/L), COD (1000–3000 mg/L), SS (suspended solids) (900–3000 mg/L), nitrogen (100–300 mg/L) and phosphorus (between 5 and 150 mg/L) [73].

In the slaughterhouse, a series of wastes, such as inedible organs, hair, and skeletal material, are generated, for which the recovery or reuse of some parts is economically difficult due to their content. They can be used to extract fat and obtain the protein flour used in animal feed. In addition, manure, gut manure, and generated wastewater that have a very high pollutant load and solid content could be used in AD [73]. Most of the waste and by-products generated by the meat industry still have a high content of essential nutrients, and that is why they are used for the separation by different techniques of some commercially useful products: amino acids, hormones, minerals, vitamins, fatty acids, glue and gelatin, and many others. Waste resulting from these processing operations can also be used in the production of biogas.

The poultry industry generates waste similar to that of the meat industry, producing significant amounts of solid waste and wastewater. The most important poultry processing wastes are those generated in slaughterhouses: feathers, blood, feet, head, bone, trimmings, and organs [74,75]. All these wastes have a high content of proteins (around 32%) and lipids (54%) and can be used as a substrate in biogas production, with high yields and short digestion times (especially for blood and bone meal). However, as in the case of waste from the meat industry, poultry waste contains a large amount of protein nitrogen, which decreases the value of the C/N ratio between 7 and 10 (the optimal ratio for a stable process is 25–30). Additionally, an inhibition of methanogenesis may occur due to the long-chain fatty acid in the substrate; therefore, co-digestion with other substrates, such as cattle manure and crop waste, should be considered [76].

### *3.3. Waste from Fish Processing*

The waste and by-products from the processing and consumption of fish with a high nutritional content are used to obtain high-value products from scales, skin, cartilage, and skeletal material (collagen, peptides, chitin/chitosan, oil, etc.), as well as animal feed, compost, and biogas production [77].

The percentage of by-products and waste from fish processing can be quite high, depending on the anatomy of the fish species and the final product obtained, varying between 20 and 80% and containing bones, scales, viscera, heads, skin, and fins in different proportions. This waste contains a large amount of proteins and lipids and can be used as a co-substrate to increase the yield of biogas in anaerobic co-digestion [77].

Until now, there have not been many studies on fish waste digestion. Lanari and Franci [4] used a substrate rainbow trout biomass (fecal sludge) using an up-flow anaerobic recirculating digester. McDermott et al. produced biogas while investigating the effect of ultrasonication as a pre-treatment of aquaculture waste for anaerobic digestion. Marchaim et al. applied a combined method of digestion by thermophilic anaerobic bacteria and flesh flies on solid waste from the Yona Tuna and Sardines fish processing factory. Gebaur used a method of stabilizing and hygienizing sludge from saline fish farm effluents to produce biogas. Gebaur demonstrated that the mesophilic treatment of sludge of total solids (TS) 8.2–10.2 (wt.%) in 15 L continuous stirred tank reactors at 35 °C led to methane yields between 0.114 and 0.184 L/g COD. Batchwise digestion of fish waste and sisal pulp was studied by Mshandete et al., both with the wastes separately and with mixtures in various proportions in 1000 mL bioreactors. Gebaur and Eikebrokk investigated the treatment of concentrated sludge (10–12 wt.% TS) collected from Atlantic Salmon smolt hatchery with biogas production to reduce the high energy demands of smolt hatcheries [78–83].

### *3.4. Waste from the Fruit and Vegetable Industry*

The fruit and vegetable industries produce large amounts of waste, both during the processing of materials and at the consumer level. These wastes are mostly represented by the inedible parts of fruits and vegetables (peels, seeds, kernels, tails, pomace) but also by a significant amount of raw materials altered during transport and storage, especially in the case of highly perishable materials, because fruits and vegetables have the highest wastage percentage (40–50%) [23–25]. To this, wastewater resulting from the production process of various foods from fruits and vegetables, which contain a fairly high amount of organic compounds, is added. The largest amounts of waste are generated in the production of juices, in the conservation process, in winemaking, and in the extraction of oils and sugar from different plant materials.

These wastes are characterized by a specific composition of plant material: high humidity, large amounts of carbohydrates (cellulose, starch, hemicellulose, easily assimilable sugars), lignin, proteins, lipids (saturated, unsaturated, waxes, etc.), vitamins, and ash. They have a high degree of biodegradability and are a favorable substrate for the growth of fungi in particular. The C/N ratio is different depending on the species and plant organs, but it is, on average, between 20 and 30 [84]. Research has shown that the biogas production potential of FVW is quite low due to the low value of TS and high VS content, which is hydrolyzed at high speed and increases the acidification of the substrate in the reactor. For this reason, the method of co-digestion with other organic substrates is practiced [85].

In [86], the main components of this waste from the market of Milan are described: dry matter 10.82, crude protein 12.37 (% DM), NDF 22.43 (% DM), ash 8.12 (% DM), water-soluble vitamins (ascorbic acid, B1, B2, B3, B5), lipo-soluble vitamins (beta-carotene, E), minerals (Ca, Fe, Mg, K, etc.), and polyphenols. These nutritional properties of fruit and vegetable waste make them usable not only for the extraction of valuable compounds, animal feed, and composting, but also as a substrate in the AD process, singly or in co-digestion with other types of substrate. The economic efficiency of biogas production is higher if the AD reactor can be placed near the fruit and vegetable processing unit.

Fruit and vegetable waste (FVW) can be used as a substrate for the production of biogas or bio-ethanol following physical, chemical, or biological treatments [87–89]. More and more studies have been carried out to evaluate this type of waste as a source of nutrients in the AD process. Dubrovskis et al. [90] showed that pumpkin, marrow, and apple wastes can be used as substrates for biogas production. Plazzotta et al. demonstrated that FVWs are characterized by a high content of volatile solids, which can readily be hydrolyzed, leading to low pH levels and inhibition of anaerobic digestion [88].

Chemical analyses showed that the organic fraction of fruit and vegetable wastes consists of 75% sugars and hemicelluloses, 9% cellulose, and 5% lignin [85]. Due to the FVW composition, they can be used both as a single substrate and especially in the co-digestion process [85]. There have been several studies on the successful application of co-digestion. Shen et al. [91] carried out research on the co-digestion of fruit & vegetable waste (FVW) and food waste (FW) at various organic loading ratios (OLRs) in single-phase and two-phase systems and obtained the highest amounts of $CH_4$ (0.351 –0.455 L (g VS) − 1 d − 1) in the case of a higher level of OLR ($\geq$2.0 g (VS) L − 1 d − 1), two-phase digestion. Lin et al. [92] reported the co-digestion of FVW with food waste. The results showed that co-digestion of FVW and FW, with their proper ratio, improved the stability of anaerobic digestion and achieved higher biogas production. At the optimum mixture ratio of 1:1 for co-digestion of FVW with FW, the methane production yield was 0.49 $m^3$ $CH_4$/kg VS.

### *3.5. Waste from Cereals Processing Industry*

During the industrialization of wheat, rye, barley, oat, rice, millet, corn, sorghum, and triticale, through transport, processing, storage, distribution, and consumption, significant amounts of waste are generated that can be transformed into added-value products, animal feed, compost, bio-fuels, and others. The largest amount of waste from cereals is generated from the milling industry, namely "grain screenings" containing seeds that do not correspond qualitatively, germs, and cereal bran, which is the main by-product [93]. Other cereal by-products are bran from rice (result after polishing brown rice), bran from rye oat, triticale, and cake from maize (result after oil extraction). These wastes contain cellulose, hemicellulose, lignin, starch, glucans, and other carbohydrates with smaller molecules, proteins, and lipids that can be used in the AD process.

### *3.6. Waste from the Brewing Industry*

The waste resulting from the beer industry comes mainly from the operations of mashing, fermentation, maturation, and filtration and is mainly represented by spent grains, hot trub, residual yeast, and diatomaceous earth slurry [94,95].

Brewing spent grain is generated after separating the sweet wort formed during the mashing operation. Spent grain (exhausted malt) constitutes the largest percentage of the waste of the brewing industry (to about 85% of the total waste generated in the brewing process [95], with a composition rich in carbohydrates, cellulose (15–25%), hemicellulose (28–35%), lignin (28%), proteins (15 to 26.2%), free amino acids (lipids 10%), phenolic compounds, vitamins, and minerals (Ca, Se, P, Mg), and a high moisture content (75–80%) [94,95]. The composition of the spent grain depends on both the type of barley used and the conditions during the technological process.

Brew spent grain is used especially for animal feed, the production of lactic acid, culture media for different biosynthesis, obtaining phenolic compounds, and others. The use of spent grain in AD for the production of biogas poses some problems regarding components such as cellulose, hemicellulose, and lignin, which are difficult to hydrolyze by microorganisms and their enzymes. The synthesis of cellulases, hemicellulases, and laccases by bacteria and molds is not sufficient to destroy the structure of these polysaccharides; therefore, biogas production must be improved by applying physical, chemical, or biological pretreatments.

The alcoholic fermentation process takes place in the presence of yeasts of the genus Saccharomyces, which, after fermentation and maturation, are separated from the liquid by centrifugation or filtration and represent a biomass with high nutritional value, with a high content of carbohydrates (35–45% of DM), proteins (35–60% of DM), free amino acids, lipids, minerals (95–7.5% of DM), vitamins, and fatty acids, and high values of BOD [95,96]. Through the phenomenon of autolysis, the cytoplasmic content consisting of water and the mentioned nutritional compounds, rich in growth factors, is released and can be used by microorganisms in the AD process. Part of the yeast produced in the brew fermentation process is reused in the following process, and the rest can be mixed in animal feed or constitute part of the substrate in anaerobic fermentation to produce biogas [97].

A hot tub is formed during the boiling operation when it separates in the form of a precipitate resulting mainly from the coagulation of proteins with a large mass that undergo thermal denaturation. Along with these proteins, other low-mass proteins are precipitated that form bonds with other compounds through the amino acid proline.

Another by-product resulting from the germination of barley or other grains during the malting stage in the beer industry is represented by germ/rootlets, which are separated and can be used especially in animal feed.

### *3.7. Waste from Wine Industry*

A large amount of by-products that can be used primarily for the recovery and extraction of high-value compounds for the food industry, pharmacy, cosmetics, and others is generated by the wine industry. The main by-products from winemaking consist of pomace, lees, and yeast sediment. The pomace represents approximately 20% of the raw material and contains the inedible parts of the grape (skin, stem, pulp, seeds). The wine lees contain the sediment left after fermentation (yeast, tartaric acid, and ethyl alcohol). After separating the valuable compounds from the resulting by-products, what remains could also be used in the production of biogas through the AD process, especially in co-digestion with other waste [98].

Although anaerobic treatment of winery wastes is not very common, probably because of high capital costs, some studies have referred to the utilization of these wastes to obtain energy [99].

Moletta et al. [100] showed that winery, distillery waste, and wastewater can be successfully used in the AD process to produce biogas, and the digester effluent can be an agricultural fertilizer. For organic loads between 5 and 15 kgCOD/m$^3$ of digester/day, the authors obtained biogas production between 400 and 600 L per kg COD. Other studies have investigated the production of biogas through the co-digestion of winery waste with manure, or with waste-activated sludge [101] in mesophilic conditions, obtaining high biogas production, because the winery waste supplies the system with missing nutrients and stabilizes the whole process [102].

Waste containing spent yeast from the brewing and wine industries represents a valuable source of nutrients and growth factors for the microorganisms involved in AD. In addition to autolysis and enzymatic hydrolysis, a recently exploited technique is hydrothermal decomposition. Lamoolphak et al. [103] demonstrated that after a 20 min reaction in water at 250 °C, 78% of Baker's yeast was decomposed, obtaining a protein amount of 0.16 mg/mg dry yeast, which was used as a nutrient for yeast growth. In another study, Takkar et al. studied the recovery of proteins from spent yeast as a by-product of the fermentation industry using the 'flash hydrolysis' technique, through a continuous-flow hydrothermal treatment, at temperatures between 160 and 280 °C for 10 ± 2 s, and the liquid hydrolysate rich in proteins and amino acids was tested as a nutrient for the cultivation of E. coli in the bioreactor [104].

### 3.8. Catering Waste

In restaurants, pubs, canteens, hospitals, school units, etc., appreciable amounts of food waste are generated, the use of which is restricted either by the lack of organization, by the necessary logistics, by the mixed composition of food waste, or other reasons. They contain a large amount of organic compounds with a high degree of digestibility and availability for microorganisms and are used mainly in animal feed or to obtain biogas. This type of food waste mainly contains sugar-based wastes, meat (meat and chicken, fish, bones) and lipid waste (fats, oils, and greases), starch and flour wastes (bakery waste), fruit and vegetable waste, brewery waste, and others.

## 4. Utilization of Food Waste as Substrate in the AD Process

Food waste causes a significant amount of socio-economic and environmental costs, and the recovery and valorization of these resources could have a positive impact on the environment and society [105]. Food waste not only has a negative economic impact but also increases greenhouse gas emissions (mainly methane). Increasing the efficiency of the food chain and decreasing food loss and waste are essential ways to lower production costs and support environmental sustainability [106].

Considering the rapidly increasing costs associated with energy supply, waste disposal, and increasing public concerns regarding environmental quality, converting food waste to energy is becoming an environmentally beneficial and economically attractive solution.

Using food waste for bioenergy has many advantages, such as climate change mitigation, supporting the circular economy, and sustainable development. Various types of biofuels can be produced from food waste, namely biomethane through anaerobic digestion, biohydrogen through dark fermentation, biohythane (combination of biohydrogen and biomethane gas) through two-stage anaerobic fermentation, and biodiesel through transesterification [107–111].

AD is a biological process of organic substrate decomposition in the presence of several species of bacteria under controlled environmental conditions in the absence of oxygen. In this process, microorganisms (bacteria) break down organic matter, releasing a series of metabolites, including methane and carbon dioxide. Recently, the anaerobic fermentation process has gained special attention due to environmental protection by reducing greenhouse gas emissions, as well as the generation of biogas, which is a promising source of renewable energy. The benefits of anaerobic fermentation technology are also reflected in the stability and agronomic quality of the obtained (digested) fertilizer. This treatment method is in accordance with the provisions of the European Union, which assume the reduction and recovery of waste, as well as the promotion of clean technologies [112].

The metabolic reactions during the AD process involve four main stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first stage, hydrolysis, the organic compounds are hydrolyzed into smaller units, such as sugar, amino acids, and fatty acids. In the acidogenesis phase, acidogenic bacteria break down the monomers resulting from the hydrolysis phase into organic acids (acetic, propionic, and butyric acids), volatile fatty acids, alcohols, hydrogen ($H_2$), carbon dioxide ($CO_2$) and ammonium ($NH_4$).

Acid phase products are converted by acetogenic bacteria into acetate, $H_2$ and $CO_2$, which represents the substrate for the last stage of the process, methanogenesis. In the final stage of the AD process, methanogenesis, microorganisms convert previously formed hydrogen and acetic acid into methane ($CH_4$) and carbon dioxide ($CO_2$) [112,113]. The two main components resulted from AD process, $CO_2$ and $CH_4$, are upgraded to biomethane and used for various purposes, such as the production of electricity, cooking fuel or transportation fuel [114].

Figure 7 presents the AD stages.

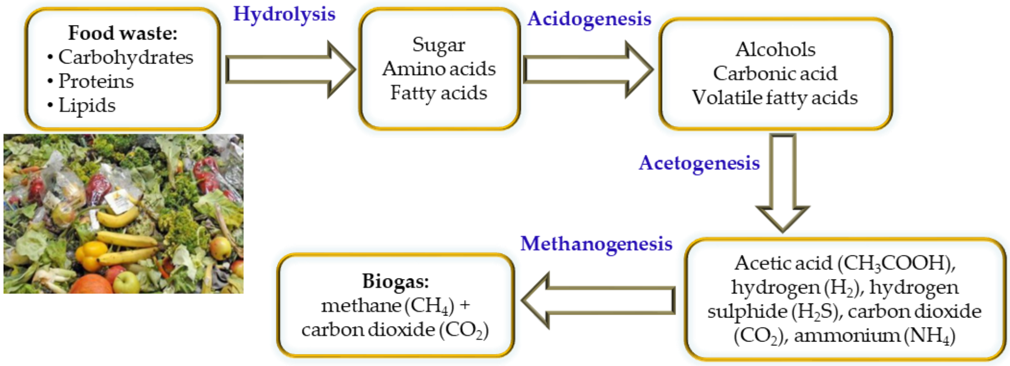


**Figure 7.** AD stages (modified after [115,116]).

In general, raw materials for biogas plants derived from the food industry are produced in both solid and liquid forms: organic waste from the production process, technological losses, wastewater, and sludge. For example, in the fruit and vegetable industries, the remaining parts such as leaves, peel, pomace, rind, stem, seeds, and spoiled fruit and vegetables are considered waste. The production of milk, milk powder, cheese, butter, and other dairy products results in large amounts of liquid waste. Waste resulting from the oil industry that can be used in anaerobic digesters includes wastewater and organic solid waste (seeds and husks) [117].

Many studies have been conducted on the AD process of food waste for biogas production. However, because of the presence of cations such as sodium, potassium, calcium, and magnesium, high salt concentrations in food waste can inhibit the decomposition of organic substrates. To solve this problem, the co-digestion of food waste with low-nitrogen and lipid waste is used. Thus, the problems associated with the accumulation of intermediate volatile compounds and high concentrations of ammonia ($NH_3$) are reduced [118]. Co-digestion is an energy-efficient process that can improve the performance of anaerobic fermentation by adding a nutrient-rich secondary substrate to which the initial feedstock is lacking. It has been shown that the fermentation of several raw materials in the same bioreactor can establish a positive synergism, activating the microbial growth necessary to carry out the biogas production process under optimal conditions. Anaerobic co-digestion of food waste with other substrates is recommended to overcome the problems associated with food waste mono-digestion [112].

Studies have shown that mixing sewage sludge with food waste by anaerobic co-digestion increases the yield of $CH_4$ in biogas. In a recent study conducted by Cheong et al. [119], a simulation model of anaerobic co-digestion of food waste with sewage sludge for biogas production was developed. The simulation and optimization models for biogas production were developed by the authors using SuperPro Designer v9.0 and Design Expert v13. The optimum hydraulic retention time (HRT), water to feed ratio (kg/kg), sludge recycle ratio, and sewage sludge to food waste ratio (kg/kg) is determined using Design Expert v13 to give maximum methane flow, COD, and VS removal efficiencies at the anaerobic digester. The optimization results showed that the methane yield of 0.29 L $CH_4$/g COD removed, COD removal efficiency of 81.5%, and VS removal efficiency of 69.2% were obtained with an HRT of 38.8 days, water to feed ratio (kg/kg) of 0.048, sludge recycle ratio of 0.438, and sewage sludge to food waste ratio (kg/kg) of 0.044. The authors reported that the methane yield was 16% higher in the optimized case.

In a similar work, Aguilar et al. [120] investigated the feasibility of producing power and heat from anaerobic co-digestion of food waste and primary sludge under thermophilic (55 °C) and mesophilic (35 °C) conditions in one assembled model simulation for biogas production and a combined heat and power system using Aspen Plus simulation software. The results showed that biogas production is higher under thermophilic conditions (137.4 $m^3\ h^{-1}$) compared to the mesophilic scenario (67.74 $m^3\ h^{-1}$). The authors reported that the methane content of mesophilic conditions is 25% higher than that produced by the thermophilic process. This is obtained as a food waste: primary sludge ratio of 1:2.

Other research has shown that the co-digestion of food waste and municipal waste helps to improve the biogas yield by up to 40–50% compared to the mono-digestion of food waste [118,121].

The yield of methane obtained by AD of food waste varies depending on the hydraulic retention time, operating conditions, type of reactor, and composition of the food waste. According to Kuo and Dow [122], the yield of methane from the AD of one ton of food waste can be as high as 90.6 $m^3$.

Dairy industry by-products, such as cheese whey, represent a great opportunity for biogas production. Antonopoulou et al. [123] investigated the suitability of cheese whey for biohydrogen and methane production in a two-stage anaerobic process at 35 °C. The authors concluded that the highest biogas and methane production rates were 105.9 L of biogas/day and 75.6 L of $CH_4$/day, respectively, and were obtained at an HRT of 4.4 days.

In another study, Montalvo et al. [124] tested the production of biogas from organic residues generated from winemaking waste. The substrates used were stalks, pomace, vine shoots, and waste-activated sludge from the liquid waste treatment plant and wine lees. According to the authors, the digesters using wine lees and waste-activated sludge from the aerobic treatment plant produced the highest methane yields, with values of 876 $\pm$ 45 L $CH_4$/kg VS.

Miller et al. [125] studied the feasibility of using mono- and co-digestion mixtures of food waste, brewery waste, grease waste, and agricultural residues of *Miscanthus x giganteus* feedstocks in a small-scale AD system with low-energy inputs. According to the results, *Miscanthus x giganteus* in the co-digestion process had the greatest impact on the production of biomethane, whereas monodigestion of brewery waste produced the most biogas content (0.76 $gCH_4$ $gVS^{-1}$ $d^{-1}$).

Szaja et al. [126] investigated the effect of introducing dried brewery spent grain in co-digestion with sewage sludge on biogas yield. The authors conducted the experiment in semi-continuous anaerobic reactors operating under mesophilic conditions (35 °C) at different hydraulic retention times (HRT) of 18 and 20 days. The authors reported that at an HRT of 18 days, the average methane content in the co-digestion experiment was 0.27 $m^3$ kg/VS added, compared to 0.29 $m^3$ kg/VS added obtained in the control test.

Waste resulting from poultry processing can also be used for biogas generation through the AD process [127].

## 5. Food Waste Pretreatments

Researchers in the field have shown that food waste represents an important problem that requires solutions to reduce the environmental pollution caused by it. Additionally, AD is presented as one of the most effective methods of food waste recovery and will have excellent benefits for the environment and society [128–130].

The AD process is affected by food waste characteristics (physicochemical and biological). To accelerate the process and enhance biomethane production, food waste is subjected to different pretreatments prior to AD [131]. The aim of these pretreatments is to increase the solubilization of organic components and refractory compounds, which leads to the reduction of organic matter. This is equivalent to an increase in biogas production [132].

The pretreatment techniques used prior to AD can be classified into three major categories (Figure 8): physical, chemical, and biological. Food waste can also be subjected to a combination of various pretreatments. The pretreatment mechanism and substrate composition influence the effect of various pretreatment methods on food waste [133]. Numerous studies conducted on food waste AD have improved biogas production and degradation rates by utilizing different pretreatments.

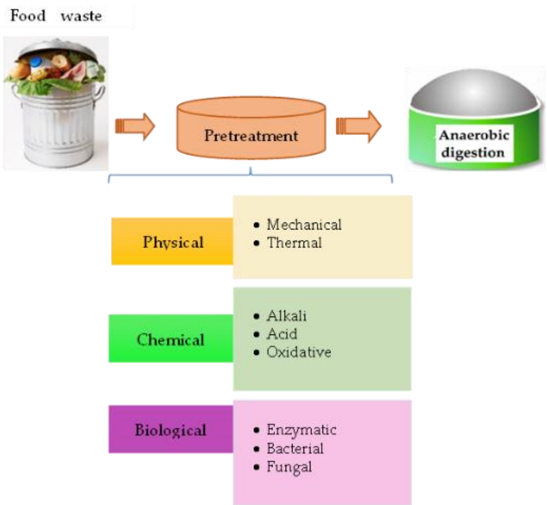


**Figure 8.** Food waste pretreatments (modified after [134,135]).

### *5.1. Physical Pretreatment*

#### 5.1.1. Mechanical Pretreatment

During the mechanical pretreatment, the solid particles of the substrate are disintegrated and/or grinded, to release the cell compounds and to increase the specific surface area. AD is enhanced due to the improved contact between the substrate and anaerobic bacteria [133]. Thus, the size reduction of food waste is an often-recommended pretreatment before AD [136]. In the mechanical pretreatment category, the most common methods used are: comminution/grinding, disintegration sonication, high-pressure homogenizer, maceration, and liquefaction.

Biomass comminution can be achieved by using specific equipment, including hammer mills, knife mills, millstones, beads mills, etc. The selection of certain equipment is made according to the moisture percentage of the material to be subjected to the comminution process [112].

Izumi et al. [137] studied the effect of particle size on the AD of food waste. Size reduction (decrease of mean particle size from 0.843 to 0.391 mm) through a beads mill resulted in a 40% higher COD (chemical oxygen demand) solubilization. This pretreatment improved the biogas production yield by 28%. Nevertheless, the authors showed that the excessive size reduction of food waste leads to a decrease in methane yields.

Quiroga et al. [138] showed that ultrasound-assisted pretreatment has a good influence on methane yields during the co-digestion of food wastes, sludge, and cattle manure.

A physical pretreatment of food waste toward bio-methane production enhancement is represented by the high-voltage pulse discharge. The Zou et al. [139] study reflected that, by HVPD pretreatment, 54.3% of solid organics were converted to soluble organics, while the bio-methane production obtained was 134% higher compared to the results of untreated samples.

#### 5.1.2. Thermal Pretreatment

The thermal pretreatment of food waste leads to the disintegration of cell membranes, which means the solubilization of the organic components.

Thermal pretreatment at high temperatures (>170 °C) can have a negative effect on anaerobic digestion, creating complex substrates that are difficult to degrade. Liu et al. [140] studied the influence of thermal pretreatment on kitchen waste and vegetable/fruit waste. The pretreatment at 175 °C for 60 min resulted in a 7.9% and 11.7% decrease in biomethane production, respectively, because of the melanoidin production. Ma et al. [22] obtained a 24% increase in biomethane yield when the food waste was thermally pretreated at 120 °C for 30 min by autoclave.

Ariunbaatar et al. [141] conducted a series of batch experiments with thermophilic pretreatment (prior to mesophilic digestion, the entire reactor was heated) and conventional thermal pretreatment (the substrate was heated) to obtain an improvement in the AD process of food waste. The results showed an increase of methane yield by 40% in the case of 6–12 h pretreatment at 50 °C and for 1.5 h pretreatment at 80 °C.

The influence of thermal pretreatment on food waste prior to anaerobic digestion was studied by Gnaoui et al. [142]. It was observed that for pretreatment conditions of 100 °C and 30 min, the methane yield reached higher values, which were 23.68% higher than the control sample of food waste.

Another study on the thermal pretreatment of food waste was conducted by Gianico et al. [143]. The conditions of thermal pretreatment were T = 134 °C, $p$ = 3.2 bar, and the retention time was 20 min. After thermal pretreatment, the pretreated FW was centrifuged, and the solid fraction was subjected to anaerobic digestion. The results showed process stability and a higher conversion rate for the thermal pretreated fraction, which was more than 0.26 $Nm^3$ $CH_4$ $kg^{-1}$VS in the case of the untreated samples.

The enhancement of thermal and ozonation pretreatments on AD of food waste was also studied by Ariunbaatar et al. [144]. It was shown that thermal pretreatment at 80 °C for 1.5 h led to the highest biomethane production of 647.5 ± 10.6 mL $CH_4$/gVS, which is 52% higher than the results obtained for untreated samples. Additionally, it was observed that AD was diminished (because of the formation of melanoidins) in the case of thermal pretreatment at temperatures over 120 °C for more than 4 h.

The influence of thermal pretreatment on the AD of floatable oil-recovered food waste was studied by Qi et al. [145]. The authors concluded that thermal pretreatment at 120 °C of floatable oil recovered food waste represents the optimum for enhanced methane yield, while pretreatment at 160 °C will have a negative influence on the AD process.

Ultrasound and microwave pretreatments are two methods that have been studied recently by researchers in the field, and they concluded that these pretreatments have an efficient influence on the AD of food waste (the biomethane production is increased) due to the dissolution of organic matter [146,147].

Fei et al. [18] analyzed the use of radiation technology as a pretreatment for food waste during anaerobic digestion. A Co-60 gamma source was used for the experiments. The results showed that in the case of 8.28-kGy irradiation pretreatment, the soluble chemical oxygen demand (SCOD) was higher, with 70.6% reaching 239.1 g/L, while the biogas production increased by 14.3%. Therefore, the ionizing radiation process is an efficient pretreatment for the AD of food waste.

Hydrothermal pretreatment is divided into two categories: steam explosion pretreatment and liquid hot water pretreatment. The liquid hot water pretreatment assumes that the biomass is pretreated without the use of any chemicals at greater pressure. In a steam explosion, the material is heated briefly under high pressure using saturated steam, followed by a rapid pressure reduction that causes material destruction [148].

In another study conducted by Fei et al. [131], the traditional hydrothermal and ionizing radiation pretreatment of food waste before AD was analyzed. The results concluded that ionizing radiation pretreatment had the lowest environmental impact. In addition, ionizing radiation pretreatment consumes the highest amount of energy, reaching 71–75% of the total energy consumption.

Liu et al. [149] conducted research on the microwave pretreatment effect applied to food waste and sludge prior to the anaerobic co-digestion process. The best results were obtained after 35 days of co-digestion of microwave-pretreated food waste and sludge, reaching the highest methane production of 3446.3 ± 172.3 mL, which was 19.93% higher than the results obtained for the control sample.

Yue et al. [150] studied the influence of ultrasound and microwave heating on lipid and food wastes, which were used as substrates for anaerobic digestion. Lipid mixing, solid dissolving, and macromolecular degradation are improved by ultrasound and microwave pretreatments due to shock wave and heating effects. The increase in input energy from 0 to 50,000 kJ/kg-TVS (total volatile solids) during the ultrasound pretreatment led to an increase in methane production, which had the highest values of 927.97 ± 3.84 mL/g-TVS for lipid waste and 586.96 ± 10.84 mL/g-TVS for food waste. The same trend was observed after microwave pretreatment when the highest methane production was 738.63 ± 12.61 mL/g-TVS for lipid waste and 637.35 ± 6.97 mL/g-TVS for food waste.

The effect of different pretreatments on AD was studied by Deepanraj et al. [132]. For the experiments, food waste was co-digested with poultry manure, and the autoclave, microwave, and ultrasonication were the pretreatments applied. The results showed that the autoclave, microwave, and ultrasonication pretreatments induced an increase in biogas production of 4.67, 6.43, and 10.12%, respectively. The ultrasonication pretreatment achieved the best result from the study, with a 9926 mL biogas yield.

### 5.2. Chemical Pretreatment

Acids, alkalis, and oxidants are used for the chemical pretreatment of food waste to enhance the biogas production of anaerobic digestion. This is possible due to the disintegration of organic components during chemical pretreatment. The substrate composition and the type of method utilized influence the effect of chemical pretreatment on the AD process. In the case of substrates with important amounts of carbohydrates, chemical pretreatment is not recommended, but substrates rich in lignin present good results after chemical pretreatment [151,152].

Dilute acid hydrolysis is the most commonly applied chemical pretreatment method for food waste. For example, pretreatment of bagasse (residual fibers remaining after sugarcane is pressed in sugar production) and coconut fiber with HCl improved biogas production by 31% and 74%, respectively [112].

Monlau et al. [153] improved methane yield from sunflower oil cake using dilute acid pretreatment and reported that methane yield increased from 195 to 289 mL/g VS by pretreatment at 170 °C and 1% $H_2SO_4$. Although they continued to increase the temperature and acid concentration (>1%), the methane yield did not improve.

Linyi et al. [128] analyzed the effect of alkali pretreatment on food waste during anaerobic digestion. The experiments showed that alkali pretreatment has a beneficial influence on the solubilization of organic matter. The best results were obtained for pretreatment with 1% CaO when the biogas production was 829 mL/g VS with a methane content of 65.48%.

Some studies in the field have shown that AD is improved by the addition of trace metals such as iron, selenium, cobalt, copper, nickel, molybdenum, and tungsten. Thus, Facchin et al. [154] used a trace metal combination (molybdenum, tungsten, cobalt, nickel, selenium) on food waste chemical pretreatment, and the results showed an increase of 45–65% for the biogas yields.

Ozonation is another chemical pretreatment method that presents some advantages compared to other chemical pretreatments: no chemical residues, no increases of the salt concentration, and disinfecting the pathogens.

Cesaro et al. [155] studied the efficiency of sonolysis and ozonation pretreatments in enhancing biogas production. The substrate used in the experiments was the sorted organic fraction of municipal solid waste. It was observed that both pretreatments improved the solubilization of organic solid waste. In addition, the results showed that biogas production can decrease after ozonation pretreatment because the higher ozone doses applied were conducted to by-products that were less biodegradable.

In the study conducted by Ariunbaatar et al. [144], the enhancement of thermal and ozonation pretreatments on the AD of food waste was investigated. The conclusion of this study was that ozonation is not an efficient pretreatment of food waste prior to anaerobic digestion.

### 5.3. Biological Pretreatment

Compared to other pretreatment methods, biological pretreatment usually requires much lower energy consumption and does not involve the use of chemicals; this represents an economic advantage and a minimal impact on the environment [156].

The biological pretreatment applied to the organic substrate to increase biogas production has recently focused mainly on methods of pretreatment with fungi, pretreatment with certain microbial strains, and enzymatic pretreatment.

Wu et al. [157] studied the influence of ethanol pre-fermentation (EP) with various inoculum-to-substrate ratios (ISRs) on the AD of food waste and distillers' grains. The results showed that in the case of EP, the maximum methane yield was 581.2 mL/g-VS at 2.5 ISR, while for ISR 1 and ISR 0.4, methane production was 41.8% and 71.7% lower than the maximum yield. The methane yield without EP was 143.2 mL/g-VS, 57.7% lower than the value obtained with EP, at the same ISR value. In conclusion, ethanol pre-fermentation reduced the inhibition by acidification, minimized the lag period, and increased the growth of methanogens.

The effects of ethanol and lactic acid pre-fermentation on the AD of food waste were studied by Zhao et al. [158]. The experiments concluded that the methane production in the ethanol pre-fermentation was higher (43.9 and 49.6%) than in the lactic acid pre-fermentation and untreated samples, respectively. Therefore, ethanol pre-fermentation represents an efficient method for improving the methane production of anaerobic digestion.

To enhance AD performance, Meng et al. [159] investigated the effect of lipase pretreatment on floatable grease in food waste. For the experiments, three lipases were used to hydrolyze floatable grease from food waste to eliminate the inhibition of floatable grease. Animal fat and vegetable oil were used as substrates for anaerobic digestion. The best results were obtained in the conditions of 24 h, 1000–1500 µL and 40–50 °C. The biomethane production rates for animal fat, vegetable oil, and floatable grease were enhanced by 80.8–157.7%, 26.9–53.8%, and 37.0–40.7%, respectively, while the digestion time was reduced by 10–40 days.

The enzymatic pretreatment of activated sludge, food waste, and their mixture was studied by Yin et al. [160]. For the experiments, fungal mash produced in situ was used. It was observed that for the mixture waste pretreated with fungal mash, the bio-methane yield was 2.5 times higher than the results for untreated activated sludge. In addition, the total VS reduction was 54.3% for the anaerobic system pretreated with fungal mash.

To complete the food waste analysis and to offer a short overview, Table 1 provides a short outline of the research presented in this chapter regarding the food waste pretreatment methods and the enhancement of biomethane yield after pretreatment.

**Table 1.** Food waste pretreatments overview—Selection of food waste pretreatments.

| Pretreatment | Substrate | Effect on Methane Yield (%) | References |
|---|---|---|---|
| Mechanical pretreatment (beads mill) | Food waste | +28% | [137] |
| Mechanical pretreatment (high voltage pulse discharge) | Food waste | +134% | [139] |
| Thermal pretreatment | Food waste | +24% | [22] |
| Irradiation pretreatment (Co-60 gamma-ray) | Food waste | +14.3% | [18] |
| Microwave pretreatment | Food waste + sludge | +19.93% | [149] |
| Microwave pretreatment | Food waste + poultry manure | +6.43 | [132] |
| Ultrasonication pretreatment | Food waste + poultry manure | +10.12 | [132] |
| Chemical pretreatment (dilute acid hydrolysis) | Bagasse | +31% | [112] |
| Chemical pretreatment (trace metal combination) | Food waste | +45–65% | [154] |
| Biological pretreatment (enzymatic) | Food waste + activated sludge | +2.5 times | [160] |
| Biological pretreatment (lipase) | Floatable grease of food waste | +37.0–40.7% | [159] |

## 6. Conclusions

Biogas from AD, a sustainable biofuel made from a variety of organic substrates (feedstocks), is a prominent technique for managing and recycling growing solid byproducts. Natural gas, a fossil fuel that is becoming increasingly necessary for the world's energy supply, can be swapped out for refined biogas as fuel.

Food waste is a key qualitative organic feedstock for the generation of biogas because it has a structural composition that is biologically suitable for the bacteria that promote AD, whether it is pre- or post-consumer waste. Although measuring food loss and waste, whether it is at the national, regional, or international level, it is challenging, and approaches and instruments are being created to help us track our progress.

The main categories of food waste are generated from different sources, namely dairy, meat and poultry, fish, fruit and vegetable, cereal and bakery, brewing and winery industries, and others, and differ through a series of properties such as C:N ratio, TS, VS, moisture, pH, COD, and ash.

These physical-chemical characteristics determine the type of treatment that will be applied to release the nutrients needed by microorganisms from the stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis in AD.

To increase the efficiency of biogas production, a multitude of pretreatments are applied. Mechanical and physical pretreatments are represented by thermal, ultrasound, microwave, irradiation, hydrothermal, and ionizing radiation; chemical pretreatments used are acid hydrolysis, alkali, and ozonation; and biological pretreatments refer to the use of active bacterial and fungal strains and specific enzymes. All of these pretreatments can be used single or in combination, depending on the structure and composition of the substrate and the parameters of the AD process.

Recent trends to maximize energy recovery from food waste refer to using the most appropriate pretreatment, co-digestion process, after the separation and extraction of high-value compounds from this waste.

Thus, the food waste trend shows the necessity of concentrating on key actions such as harvesting optimization, enhancing product distribution, maximizing product utilization, strengthening food recovery, refining product management and customer behavior, and recycling everything so that, in the end, the amount of food wasted along the entire food supply chain can be significantly decreased. Since they often have the biggest financial and environmental effects relative to the capital invested yet have historically received less attention than rescue and recycling, we focused on education and awareness action areas.

Increasingly, the sustainable use of food waste is concentrated on creating a circular bioeconomy, raising the value of material flows, and achieving zero waste through sustainable production and consumption with lower greenhouse gas emissions.

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