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Review

Odour Nuisance at Municipal Waste Biogas Plants and the Effect of Feedstock Modification on the Circular Economy—A Review

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Abstract: The increase in the amount of municipal solid waste (MSW) generated, among other places, in households is a result of the growing population, economic development, as well as the urbanisation of areas with accompanying insufficiently effective measures to minimise waste generation. There are many methods for treating municipal waste, with the common goal of minimising environmental degradation and maximising resource recovery. Biodegradable waste, including selectively collected biowaste (BW), also plays an essential role in the concept of the circular economy (CE), which maximises the proportion of waste that can be returned to the system through organic recycling and energy recovery. Methane fermentation is a waste treatment process that is an excellent fit for the CE, both technically, economically, and environmentally. This study aims to analyse and evaluate the problem of odour nuisance in municipal waste biogas plants (MWBPs) and the impact of the feedstock (organic fraction of MSW-OFMSW and BW) on this nuisance in the context of CE assumptions. A literature review on the subject was carried out, including the results of our own studies, showing the odour nuisance and emissions from MWBPs processing both mixed MSW and selectively collected BW. The odour nuisance of MWBPs varies greatly. Odour problems should be considered regarding particular stages of the technological line. They are especially seen at the stages of waste storage, fermentation preparation, and digestate dewatering. At examined Polish MWBPs c_{od} ranged from 4 to 78 ou/m^3 for fermentation preparation and from 8 to 448 ou/m^3 for digestate dewatering. The conclusions drawn from the literature review indicate both the difficulties and benefits that can be expected with the change in the operation of MWBPs because of the implementation of CE principles.

Keywords: anaerobic digestion; biogas plant; biowaste; circular economy; feedstock; municipal waste; odorants; odour nuisance; organic fraction from municipal solid waste

Citation: Wiśniewska, M.; Kulig, A.; Lelicińska-Serafin, K. Odour Nuisance at Municipal Waste Biogas Plants and the Effect of Feedstock Modification on the Circular Economy—A Review. *Energies* **2021**, *14*, 6470. https://doi.org/10.3390/en14206470

Academic Editor: Gabriele Di Giacomo

Received: 10 September 2021
Accepted: 8 October 2021
Published: 10 October 2021

1. Introduction

The generation of municipal solid waste (MSW), mainly from households and catering and other places where the waste of a similar morphology is generated, seems to be an inherent element of intensive urban development. Minimising waste generation is the first and most important element of the waste hierarchy and an element of the CE. The CE concept is based on a "take-use-reuse" approach that consists of closing the cycle of the extended product life cycle and treating waste as valuable recyclable materials. The CE involves minimising the negative impact of the production line on the environment [1,2]. The CE has many definitions, but it is most often defined according to Ellen MacArthur Foundation [3]. The CE is a systemic approach to economic development designed to benefit businesses, society, and the environment. In contrast to the "take-make-waste" linear model, a circular economy is regenerative by design and aims to decouple growth from the consumption of finite resources gradually. An increase in the amount of waste requiring further management results from the growing population, economic development, and the urbanisation of areas with accompanying insufficiently effective waste minimisation activities [4,5]. The problems associated with the MSW economy, however widely varied, affect all countries in the world. Improperly managed waste management is reflected in the form of soil degradation, water bodies (including the organisms living in them), atmospheric pollution, and negative impacts on human health [6,7]. Legislation at the European level [8,9] indicates numerous requirements necessary to reduce the amount of waste deposited in landfills, to maximise the use of generated waste as raw materials, but above all to minimise its generation, especially that of food waste, which is in line with the Agenda for Sustainable Development 2030 adopted by the United Nations (UN) General Assembly [10]. Waste prevention is the most crucial part of the waste hierarchy [11].

There are many methods of municipal waste treatment, which can generally be divided into mechanical, biological, and thermal methods [12–14]. All these processes have one common goal: to minimise environmental degradation and maximise resource recovery [15–19]. They should be used according to the waste hierarchy [7]. An example of a biological method is organic recycling, which is limited to selectively collected BW. The main advantage of this process is the possibility of producing non-waste organic fertiliser. Mechanical methods are applied primarily to sort waste materials and prepare them for raw material recycling. Mechanical–biological methods are used mainly for mixed MSW as a disposal method. After this process, waste (so-called stabilised waste) remains and requires further processing (landfilling or thermal treatment). Waste incineration should only be used for non-recyclable, combustible waste in the form of energy recovery (waste combustion without energy recovery is against the principle of the CE) [4,11–13,20]. In the strategy for handling biodegradable waste, biological processes play a dominant role [21].

There is excellent potential in wastes undergoing biological decomposition (both under aerobic and anaerobic conditions), including biowaste, for example, food waste [9]. Studies by Das et al. [22] and Slorach et al. [23] show that a lower content of biodegradable fraction characterises municipal waste generated in highly developed countries than in medium- and low-developed countries.

There has been a growing interest in biodegradable waste due to obtaining energy from it in recent years. One of the main reasons for this increase is the change in the European Union (EU) energy policy (as of 2023, separate collection of biowaste will be obligatory for EU member states), which is dictated by the increasing demand for energy but also by the growing greenhouse effect due to the emission of greenhouse gases into the atmosphere (including methane and carbon dioxide), which is caused by, among other reasons, the use of fossil fuels, on which about 88% of the produced energy is based [24,25]. Biodegradable waste, including BW, also plays an essential role in the CE concept, which involves maximising the proportion of waste that can be returned to the system after organic recycling and energy recovery [26–30]. The origin of BW determines its composition. The amount of it is increasing every year, causing problems in regard to its disposal and management [31–37]. In the case of MSW, the organic fraction may be separated mechanically from the mixed waste stream (using a system of separators and screens connected by conveyors) or selectively collected at the source of waste generation [38–40]. Previous analyses in various countries show that the organic fraction contained in municipal solid waste (OFMSW) constitutes about 30–75% of the total content [41–45]. This content is mainly determined by factors such as the geographical location of the region, the degree of industrialisation, the socio-economic situation, lifestyle, education, or aspects of families (number and age of family members) [46,47]. Waste-to-energy technologies (WETs) are the basis for managing organic waste and converting it into valuable fuels, fertilisers, and electricity [48,49]. According to the 2030 Agenda for Sustainable Development with its Sustainable Development Goals (SDGs) [10] there is a big concern for the steady supply of affordable, renewable and clean energy sources, so solid waste is great hope among them. WETs are a crucial issue of a waste management system. Incineration dominates the WET market all over the world, and specifically in developed countries. After thermal processes, anaerobic digestion is the emerging technology in clean energy production. Reduction in greenhouse gas emissions and the generation of alternatives to fossil fuels are major goals of WETs. Among the research trends, there are also studies that focus on environmental impacts, energy technology innovations, improved energy recovery efficiency, and climate change impacts. They are supposed to contribute to the development of a low-carbon society. According to CE ideas and bioeconomy concepts, countries with the most advanced WETs should always encourage recycling and stricter policies for waste reduction [50,51]. Reports have shown that Poland is among the top countries in Europe when it comes to bioeconomies. Among the Visegrad group, Poland is leading the way with bio-based fuel, bioenergy, biomass processing and conversion, and other bio industries such as biorefinery, biochemicals, and biopharmaceuticals, whereas others have made some progress in the agro-food sector [52,53].

There are many different WETs for biodegradable fractions: thermochemical methods such as incineration, gasification, and pyrolysis, biochemical methods such as anaerobic digestion, and chemical methods such as esterification [54,55]. Aerobic methods of biological treatment also play an important role in both composting (for selectively collected waste) and aerobic stabilisation (for the organic fraction separated mechanically from the stream of mixed waste) [56–59]. Factors that determine the suitability of different types of waste for particular processes include moisture content, organic matter content, C/N ratio, calorific value (CV), and the content of non-flammable fractions [60]. When analysing the rate of organic matter degradation, factors such as the initial microbial community, oxygen availability, the physical availability to degrade, temperature, and the chemical composition of organic matter play an important role [58,61].

The most promising processing technology for OFMSW and BW is methane fermentation [62–64]. The first biogas stations were built in wastewater treatment plants in order to stabilise the sewage sludge. They were equipped with open digestate storage tanks with free digestate surfaces, without covers. In that case, limited mixing of digestate was recommended to allow a solid crust to form on the surface to limit odour emissions [65]. Many rural biogas plants in the world, especially operated by small and medium farmers, run under psychrophilic conditions—so-called psychrophilic rural digesters [66]. However, according to Environmental Protection Agency (EPA) guidelines, conventional AD biogas systems are commonly designed to operate in either the mesophilic or thermophilic temperature range [67]. Some biogas plants use open digester chambers, which is a phenomenon on the European scale. They are mainly used in sewage treatment plants. The feedstock in sewage sludge is kept in the chamber for up to 6 months under psychrophilic conditions (<20 °C), which contributes to the high mineralisation of the material. The disadvantage of this solution is the emission of gases, including odorants [68]. Thi et al. [69], in a comparative analysis of different BW processing technologies, indicated that AD is a suitable solution for developing countries with temperate climates. Among the possibilities of biogas (the main product of this process) utilisation are, e.g., heat and electricity production, use as vehicle fuel, and injection into the gas grid (after upgrading) [70]. Research conducted by Swedish scientists indicates that 1 Mg of food waste can be generated into 1200 kWh of energy, which is enough to drive 1900 km in a gas-powered car. In turn, the energy obtained from the digestion of food waste generated by 3000 households is enough to cover the annual fuel requirements of one gas-powered bus [71]. The method that fits perfectly into CE assumptions is biogas-to-biomethane upgrading. To obtain high-quality biomethane via upgrading biogas from waste anaerobic digestion there are such techniques as membrane separation, water scrubbing, chemical absorption with amine solvent, and pressure swing adsorption [72–75]. In Polish municipal waste biogas plants, biogas is most often used in cogeneration systems to produce electricity and heat, often for their own needs. In the case of surplus or insufficient parameters, biogas is burnt in flares. EPA guidelines require flares to be enclosed and operated at a minimum temperature of 1000 °C with a 0.3 s retention time to ensure adequate destruction and minimisation of emissions [67]. Other compounds, such as aliphatic and aromatic hydrocarbons, siloxanes, volatile organosulfur and organohalogen compounds, and oxygenated organic compounds, are present in small amounts in biogas [76,77]. A modern method of biogas purification is the adsorptive packed column system. Piechota presented the results of studies on the effectiveness of this method on biogas from a wastewater treatment plant [78]. The author proved the removal efficiency of 99.76% for total non-silica impurities and 100% for siloxanes. This study aims to analyse and evaluate the problem of odour nuisance of MWBPs and the impact of the input on this nuisance in the context of CE assumptions. A literature review on the subject was carried out, including the results of our own research, showing the odour nuisance and emissions from MWBPs processing both mixed MSW and selectively collected BW. The conclusions drawn from the literature review indicate both the difficulties and benefits that can be expected with the change in the operation of MWBPs due to the implementation of CE principles.

2. Municipal Waste Biogas Plants (MWBPs)

2.1. Anaerobic Digestion Process

Anaerobic stabilisation is the anaerobic decomposition of organic matter, a two-step biological process involving the conversion and stabilisation of waste [79–81]. Methane fermentation, which plays a significant role in the anaerobic stabilisation of waste, occurs with the participation of microorganisms, whose main gaseous products of decomposition of organic compounds are methane and carbon dioxide. The fermentation process consists of four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [34].

The course of the fermentation process is influenced by many factors, including the type of waste processed, which has a very significant impact on the final post-fermentation product, and many other parameters, including environmental parameters. One of them is the temperature at which the process is carried out (psychrophilic, <20 °C; mesophilic, 25 ÷ 40 °C; and thermophilic, 45 ÷ 60 °C) [82,83]. This parameter mainly affects the physicochemical properties of the treated wastes, which are essential for thermodynamic reactions and kinetic biological processes [84]. A higher process temperature has a beneficial effect on the hydrolysis of soluble substances, making them more accessible to microorganisms, increasing the kinetics of chemical and biological processes, which in turn causes a reduction in the hydraulic retention time (HRT) of the digester reactor, and improves the physicochemical properties of soluble substances as well as diffusivity [85,86]. Another benefit of using a high process temperature is the elimination of pathogenic bacteria in the fermented material [87–89].

Another critical environmental parameter for fermentation is pH, which depends on the activity of bacteria in particular stages of fermentation. In the case of methanogenic bacteria, the optimum pH level is within the range of 6.5 ÷ 7.2. A drop in pH below 6.5 rapidly inhibits the process, which stops the removal of acids from the treated raw material. Other types of bacteria are less demanding and show their activity in a broader pH range: 4.0 ÷ 8.5 [89,90]. The pH level also determines the end products of the process at low pH; acetic acid (CH_3COOH) and butyric acid ($CH_3(CH_2)_2COOH$) are formed, while at a higher pH propionic acid (CH_3CH_2COOH) is formed [91]. Digester failures are often the result of acid gathering when too many volatile solids are fed into the process (per unit reactor volume). Volatile fatty acids (VFAs) generated during anaerobic digestion of organic waste are considered a promising substrate for microbial oil production [92] and the production of renewable green chemicals. Due to this, anaerobic digestion supports the implementation of the waste management hierarchy as it enables the production of renewable green products [93]. VFAs have various applications; they are used in the production of biodiesel fuel, the synthesis of complex biopolymers, and the generation of electricity through microbial fuel cells [94]. On the other hand, a pH level above 8.0 is toxic to most anaerobic organisms, causing the inhibition of their vital functions. This increase in pH may be due to intensive methanogenesis, resulting in higher ammonia concentration, which hinders acidogenesis [95].

Another critical parameter for the fermentation process is the nutrients necessary for microorganisms' proper growth and functionality. One of the essential components is nitrogen, necessary for synthesising amino acids, which can be converted into ammonia, acting as a buffer to neutralise the acidification process of the fermented material. As reported by Rajeshwari et al. [96], the authors in their work indicate that the fermented feedstock should contain carbon, nitrogen, and phosphorus in the ratio (C:N:P) 100:3:1, which is optimal for process efficiency and a high methane yield. An imbalance in these proportions can result in a deficiency in the buffering capacity of the material or insufficient nutrients for life functions and microbial growth. Other nutrients needed by microorganisms for optimal functioning are phosphorus, sulphur, potassium, sodium, magnesium, calcium, and microelements: iron, molybdenum, manganese, copper, zinc, cobalt, nickel, selenium, or tungsten. The corresponding C/N/P/S ratio was determined by Weiland [97] to be 600/15/5/3.

Other parameters affecting the AD process include moisture content [98], particle size [99], organic loading rate (OLR) [100], solid retention time [101], sulphate reduction [102–104], denitrification [105], and ammonium concentration [106–109]. All the parameters mentioned above can play an important role in modifying the reaction rate of individual phases of the fermentation process [110–113]. The products of the fermentation process are biogas and digestate. Biogas is produced and captured during the process, and its dominant component is methane, which is the raw material required for electricity and heat generation [114]. The methane fermentation process carried out in biogas installations contributes to preventing uncontrolled methane emission into the atmosphere (e.g., during waste disposal in landfills) and increases the potential of renewable energy sources [115,116]. Besides, the encapsulation of the methane fermentation process contributes to preventing the emission of other compounds such as ammonia, NH_3, hydrogen sulphide, H_2S, or volatile organic compounds, VOCs, characterised by an unpleasant odour [117–120].

Among the methods of digestate processing, the following solutions are used: dewatering, aerobic stabilisation (in closed or open conditions), sieving and other unit operations of post-treatment, such as compost or landfilling (in the case of compost, not complying with the requirements for plant improvement products) [11,13,19].

2.2. Odour Nuisance of MWBPs

The AD process, due to the lack of air supply, is a hermetic process and therefore odourless. However, processes such as feedstock preparation and aerobic stabilisation of the digestate are associated with odour and odorant emissions [121,122].

The level of odour and odorant concentrations at MWBPs varies widely, and this variation is mainly due to the type of waste processed, technological factors and processes, air temperature, humidity, and microclimatic conditions [120,123,124].

The study by Fang et al. [125] identified 60 different compounds belonging to nine chemical groups. The compounds determined were sulphides, terpenes, ketones, alcohols, alkenes, aromatic hydrocarbons, acids, and esters. Terpenes and sulphur-containing compounds are the leading cause of odours [126]. On the other hand, in their works, Komilis et al. [127] and Scaglia et al. [128] also demonstrated the presence of BTEX compounds—benzene, toluene, ethylbenzene, and xylene—which in addition to an unpleasant odour are also characterised by harmfulness to human health. Benzene shows carcinogenic effects [129], while long-term exposure to toluene, ethylbenzene, and xylene adversely affects the respiratory system, causing asthma or asthmatic symptoms such as dyspnea, coughing, wheezing, chest tightness, and difficulty in breathing, as well as the central nervous system, causing symptoms such as headache and dizziness, nausea, fatigue, agitation, and disorientation [130–134].

Byliński et al. [135], in their work, focused on the analysis of odorant emissions (for example, dimethyl sulphide-2.43–18.67 ppb, methanethiol-2.91–12.43 ppb, benzene-0.93–10.48 ppb, toluene-0.92–26.35 ppb, and xylene-1.72–18.18 ppb) at biogas plants processing sewage sludge, which is waste from the municipal sector. The results of this work also confirmed the release of odorants from the digestate. Costa et al. [136], also investigating odorants at biogas plants but processing a different type of feedstock (microalgae), indicated a method with which to regulate the concentrations of emitted compounds by controlling the fermentation process in such a way as to maximise the transition of these compounds to the volatile fraction (biogas), which should then be treated before further use.

An analysis of the rules at the global level in terms of odour regulation shows an extensive variation in both odour and odorant concentrations as well as types of selected compounds. In countries without these regulations, the odour limit can be determined by specific and relatively easy-to-determine chemicals such as hydrogen sulphide and ammonia. Table 1 summarises odorous compounds found in the Guidelines for Air Quality produced by the WHO [137].

Table 1. Odorous compounds and average ambient air concentrations [137].

Chemical Compound	Average Ambient Air Concentration (µg/m^3)
Acetone	0.5–125
Acrolein	15
Carbon disulphide	10–1500
Hydrogen sulphide	0–15
Isophorone	no data
Styrene	1.0–20
Tetrachloroethylene	1–5
Toluene	5–150

Wiśniewska et al. [138], in their work, defined five primary categories of odorant sources at MWBPs: waste storage, preRDF storage, mechanical waste treatment and fermentation preparation, digestate dewatering, and oxygen stabilisation of digestate. The research conducted at two Polish MWBPs shows the mean VOC, and NH_3 concentrations vary depending on the stage of the technological line and are in the following ranges: 0–38.64 ppm (0–0.169 mg/m^3) and 0–100 ppm (0–69.653 mg/m^3), respectively, while according to the best available technique (BAT) conclusions, for waste treatment channelled [139] VOC and NH_3 emissions to air from biological waste treatment should not exceed values of 40 mg/m^3 and 20 mg/m^3 [120]. Pilot studies carried out at six Polish MWBPs have shown that the most significant odour nuisance and odour emissions are caused by such elements of the process line as fermentation preparation, digestate dewatering, waste storage, etc., at a technological wastewater pumping station [5,124]. Tables 2 and 3 summarise the odour and odorant concentrations and odorant emissions at MWBPs in Poland for various elements of the process line.

On the other hand, studies presented in paper [5], conducted in 2020 at three Polish MWBPs, indicate that the highest odour nuisance and the highest VOC and NH_3 concentrations concern the oxygen stabilisation of digestate and technological wastewater pumping stations. In the VOC mixture emitted, the dominance of toluene is very clear, followed by phenol and styrene.

Table 2. Odour and odourant concentrations at MWBPs in Poland [124,138].

Location/Odour Source	Fermentation Preparation				Digestate Dewatering			
	c_{od} (ou/m^3)	C_{VOC} (ppm)	C_{H2S} (ppm)	C_{DMS} (ppm)	c_{od} (ou/m^3)	C_{VOC} (ppm)	C_{H2S} (ppm)	C_{DMS} (ppm)
Jarocin	16 ÷ 78	0.20 ÷ 0.53	0.279	0.360	142 ÷ 448	0.82 ÷ 1.30	0.406	1.317
Tychy	4 ÷ 22	1.37 ÷ 1.94	0.860	<0.001	31 ÷ 42	1.20 ÷ 1.83	0.114	<0.001
Promnik	5 ÷ 11	1.06 ÷ 5.71	0.007	0.624	8 ÷ 42	2.65 ÷ 6.41	0.267	0.997
Stalowa Wola	16 ÷ 31	2.35 ÷ 2.38	<0.001	0.009	16 ÷ 31	0.20 ÷ 2.13	<0.001	0.022
Wólka Rokicka	22 ÷ 42	1.30 ÷ 1.40	<0.001	0.026	-	-	-	-
Biała Podlaska	4 ÷ 5	0.50 ÷ 0.63	<0.001	0.002	-	-	-	-

–a technological process that does not occur at a biogas plant. c_{od}—odour concentration. C_{VOC}—volatile organic compounds concentration. C_{H2S}—hydrogen sulphide concentration. C_{DMS}—dimethyl sulphide concentration.

Table 3. Odourant concentrations and emissions from mixed MWBPs in Poland [123].

Waste Storage		Emission from the Hall of Waste Storage			Digestate Dewatering		Emission from the Hall of Digestate Dewatering		Oxygen Stabilisation of Digestate	
C_{NH3} (ppm)	C_{VOC} (ppm)	E_{NH3} (kg/h)	E_{VOC} (kg/h)	E_{H2S} (kg/h)	C_{NH3} (ppm)	C_{VOC} (ppm)	E_{NH3} (kg/h)	E_{VOC} (kg/h)	C_{NH3} (ppm)	C_{VOC} (ppm)
2–8	4.42–19.79	0.23–0.44	0.15–0.42	0.02–0.25	1–12	2.07–6.27	0.004–0.04	0.03–0.17	0–7	0.08–2.47

C_{NH3}—ammonia concentration. C_{VOC}—volatile organic compounds concentration. E_{NH3}—ammonia emission. E_{VOC}—volatile organic compounds emission. E_{H2S}–hydrogen sulphide emission.

2.3. MWBPs in the CE

There are many indicators of sustainable development in the literature, which are essential from the point of view of investments in CE assumptions [56,113,140–148]. In general, they can be divided into three main categories: economic, environmental, and social. From the point of view of this work, the environmental indicators presented in Table 4 seem to be the most relevant since the literature review shows that "odour", analysed in this paper, is most commonly classified as an environmental indicator. The indicators presented in this table are selected based on the literature review as those most frequently identified by the authors.

Table 4. The sustainable environmental indicators [56,110,140–148].

No	Environmental Indicators
1	Land use
2	Water use
3	Pollutant generation
4	Life cycle of CO_2 emission
5	Overall emissions
6	SO_x emissions
7	NO_x emissions
8	Particulate matters
9	Ash
10	Noise
11	Dust
12	Odour
13	Litter

When considering MWBPs in terms of sustainable development and the CE, the mentioned indicators supporting the investment assessment are essential for the analysis [149–152]. The vision of the CE should also support the implementation of the SDGs [153]. Important indicators characterising biogas plants are, first, minimising the emission of greenhouse gases to the atmosphere (CO_2, SO_x, and NO_x) [154–156], but also reducing the emission of odours, which in turn positively affects the well-being of residents living near the analysed investments [157–159]. Social indicators such as quality of life, health, and well-being are also important in terms of the nuisance associated with the operation of waste treatment facilities [160,161]. The concept of the CE should contribute to the well-being of individuals and communities, but many authors note that the CE focuses on the economic value of products while neglecting the social dimension. In the specific case presented, the emission of odours is important from both an environmental and a social viewpoint.

2.4. Feedstock for MWBPs

The methane fermentation process of waste can be qualified in different ways from the hierarchy of waste treatment methods defined in the Waste Directive [9]. This is determined primarily by the type of input in the process and, consequently, the type of products produced. The methane fermentation of waste may be implemented as a recovery process (organic recycling), where the input in the process is separately collected post-consumer waste and the product (besides biogas) is compost, or as a disposal process, where the input is mixed MSW and the mechanically sorted white-water fraction (OFMSW) is directed to the biological process. In this case, the aim of the process is primarily to reduce the volume of waste and reduce the activity of microorganisms, including pathogens dangerous to human and animal organisms. After this process, there remains (besides biogas) stabilised waste (stabilised digestate), which, when deposited in a landfill, has a much lower biogas production [162–165]. During AD, not all biodegradable substances are broken down [166,167]. However, if properly managed, the processed organic feedstock can achieve a high degree of stabilisation [168,169]—whether the product is a non-waste organic fertiliser (in the case of organic recycling) or stabilised waste (in the case of disposal).

Regarding the differentiation resulting from the hierarchy of waste handling methods, the basic types of raw materials intended for MWBPs may be the waste separated mechanically from the stream of mixed MSW (the undersized fraction after passing through sieves sized 50–100 mm [162,170]), as well as BW collected selectively (mainly kitchen waste) [171–173]. An unquestionable benefit of the BW fermentation process for BW collected selectively, and an added value from the CE's point of view, is the possibility to use not only the biogas produced in the process but also the digestate as an organic fertiliser, which used correctly, increases soil fertility [174–176]. On the other hand, O-Thong et al. [177] state that co-digestion, i.e., the joint processing of several types of raw materials, is most used at biogas plants in the world. The advantages of co-digestion are mainly: an increase in the amount of rapidly biodegradable matter [178,179], improvement in the buffer capacity of the material, which in turn helps to maintain an adequate pH level necessary for methanogenesis [180,181], an increase in the carbon-to-nitrogen ratio (C:N—optimum range 20 $\div$ 30 [182–187]) [187,188], a decrease in the effect of inhibitors on the process by their dilution [187–189], an increase in the volumetric production of methane [190–192], and others. However, this applies to agricultural biogas plants. According to the report Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste in Europe, other products to the organic fraction of MSW used to be rather the exception, mainly due to the adjustment of the pre-treatment at biogas plants to the municipal waste stream. The use of co-digestion at MWBPs in Europe concerns about 13% of the installed capacity, where the number of co-products is at the level of about 10% to 15% [193]. However, under Polish conditions, at MWBPs, one specific type of waste is usually directed to digesters [40,124].

The benefit of using selectively collected BW as feedstock is its higher biogas potential in terms of the amount of biogas produced per unit weight of waste and the methane content of the biogas (biogas yield and stability), which is also crucial in the context of the CE. The literature analysis indicates an approximately 10% increase in the amount of biogas produced when it is produced from BW collected selectively compared to OFMSW separated mechanically from the stream of mixed MSW [40,62,194–197]. The MWBPs operating in Poland are based mainly on the fermentation of OFMSW, mechanically separated from the stream of mixed MSW, characterised by a biogas yield of 105 m^3/Mg of charge and methane concentration in biogas of 51 ÷ 53% [40,124]. Due to the changes introduced to the country in the system of selective collection of MSW (mainly because of the introduction and development of the selective collection of BW), biogas plants equipped with two digestion lines allocate one of them to BW. This fraction is characterised by a higher biogas yield—about 111 m^3/Mg charge—and methane concentration in biogas on the level of 58 ÷ 60% [40].

Between 2018 and 2020, studies have been conducted at six MWBPs in Poland, published in [5,120,123,124,138]. This study primarily considered odorant and odour emissions as well as technological aspects (including the type of feedstock) accompanying the waste treatment process. Table 5 presents a summary of the capacity and feedstock of MWBPs in Poland, while Figure 1a,b presents simplified schemes of typical process lines for mixed MSW (1a) and selectively collected BW (1b).

Table 5. The feedstock and capacity of MWBPs in Poland (own elaboration).

Location	**Feedstock**	**Annual Biogas Plant Capacity (Mg/a)**	**Fermentation**	**Digestate Stabilisation**
Jarocin	OFMSW	15,000	Horizontal reactor with one paddle agitator; thermophilic, semi-dry dynamic fermentation	Digestate dewatering followed by two-step oxygen stabilisation
Tychy	OFMSW	30,000	Two separate horizontal reactors, each with four agitators; mesophilic, dry dynamic fermentation	Digestate dewatering followed by two-step oxygen stabilisation
Promnik	OFMSW	30,000	Two separate horizontal reactors, each with four agitators; mesophilic, dry dynamic fermentation	Digestate dewatering followed by two-step oxygen stabilisation
Stalowa Wola	OFMSW	15,000	Horizontal reactor with four agitators; mesophilic, dry dynamic fermentation	Digestate dewatering followed by two-step oxygen stabilisation
Wólka Rokicka	OFMSW	20,000	Seven open-feed reactors; thermophilic, dry static (garage) fermentation	One-step oxygen stabilisation
Biała Podlaska	BW	20,000	Two separate horizontal reactors, each with one paddle agitator; thermophilic, semi-dry dynamic fermentation	One-step oxygen stabilisation

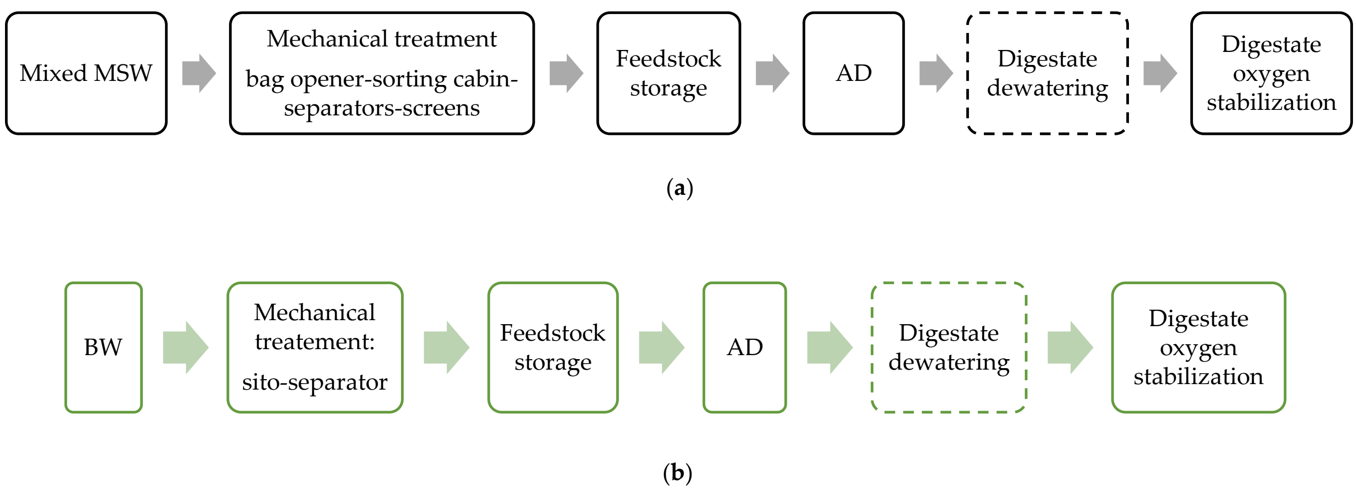

Figure 1. Typical process flowcharts of mixed MSW (**a**) and BW (**b**) at Polish MWBPs.

According to [191], by 2014 about 55% of the installed capacity in Europe (of MWBPs) was destined to treat BW.

3. The Feedstock Modification to Reduce Odour Nuisance at MWBPs–Analysis, Discussion, Recommendations

At MWBPs, the input in the process may be mixed MSW, from which OFMSW or selectively collected BW is then mechanically separated. Different morphological compositions characterise both these raw materials. Studies conducted by Seruga et al. [40] in one of the Polish biogas plants on the group composition of BW fractions from selective collection intended for the fermentation process indicate that the biofraction content is 68.1% ± 5.2% on average. The remaining input materials are wood—8.1% ± 0.5%, paper—2.4% ± 0.7%, plastics—1.1% ± 0.4%, glass—0.8% ± 0.4%, inert waste—1.4% ± 0.9%, textiles—0.1% ± 0.4%, metals—0.1% ± 0.1%, hazardous—0.1% ± 0.1%, tetra pack—0.3% ± 0.1%, others—0.4% ± 0.1%, and fine fraction 0 ÷ 15 mm—17.1% ± 2.3%. At the same time, the OFMSW mechanically sorted from the mixed MSW at this biogas plant has a food and green waste content of only 48.3% ± 2.7%. However, municipal biowaste is not always characterised by high "purity" and homogeneity. This is particularly the case in countries where the separate collection system has recently been introduced and is undergoing implementation and development. Unpublished morphological studies of BW diverted to one of the biogas plants studied between September 2017 and October 2020 show that the food waste content is highly variable throughout the year, ranging from 22.6% to 62.2%, with a mean value of 36.8% and a standard deviation of 7.6%. The rest consists of glass and stone (min. 3.7%, max. 39.3%, avg. 19.4%, standard deviation 7.6%), plastics and aluminium (min. 1.2%, max. 22.4%, avg. 6.7%, standard deviation 4.8%), and paper and textiles (min. 15.0%, max. 57.3%, avg. 37.1%, standard deviation 9.2%). The presented BW quality results from the fact that the selective collection system for biowaste is currently at the initial stage of development in Poland. Many hard fractions in the form of glass and stones, which are impurities of BW, can cause the failure of digesters through their accumulation in the lower part of reactors, resulting in the blockage of mixers. Each such failure is not only a technological problem (the necessity of emptying the chambers) but also an environmental problem (increased emission of odorants, in particular, ammonia), which was proved in the paper [123]. The above comparison also shows that the effectiveness of selective collection systems for MSW, particularly BW, varies considerably in different countries where this system has only just been introduced and is at the implementation stage. During this transition period, differences in feedstocks (OFMSW from the mixed MSW/BW stream) may be small and less significant, but this significance and variation will increase over time.

Our own research conducted in Poland in the period 2018–2020, the results of which have been published in a series of articles [5,120,123,124,138], allow us to state that the lower emissions of odorous compounds from biogas plants processing BW have been observed in comparison to installations where the input material for the fermentation process is OFMSW mechanically separated from the stream of mixed MSW, especially in some stages of the technological sequence—namely mechanical treatment and fermentation preparation. A comparison of odour and odorant concentrations at these process stages for BW and OFMSW at several biogas plants is presented in Figures 2 and 3.

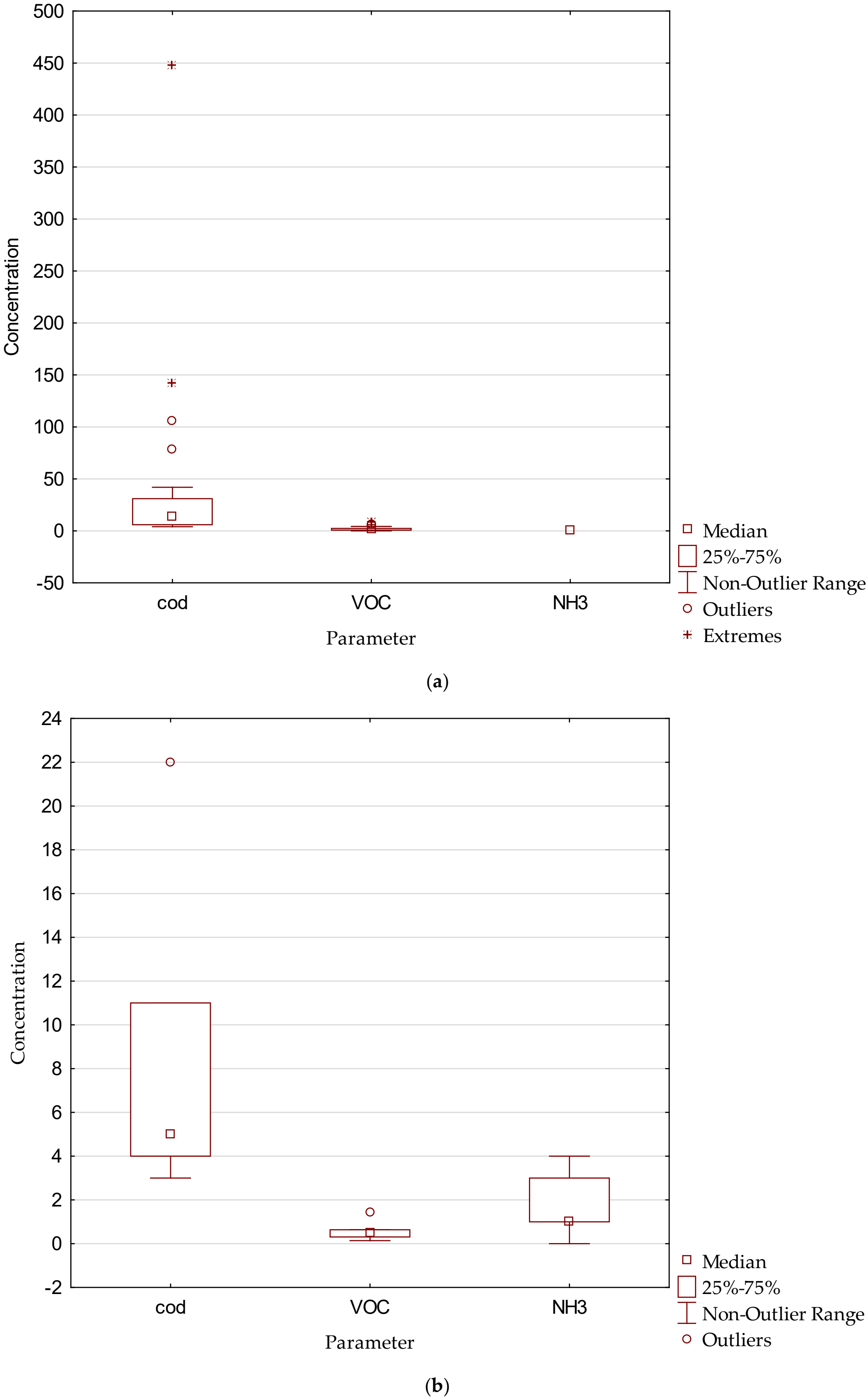

Figure 2. The range of odour and odorant concentration for OFMSW (**a**) and BW (**b**) at Polish MWBPs (own elaboration based on [122,136]).

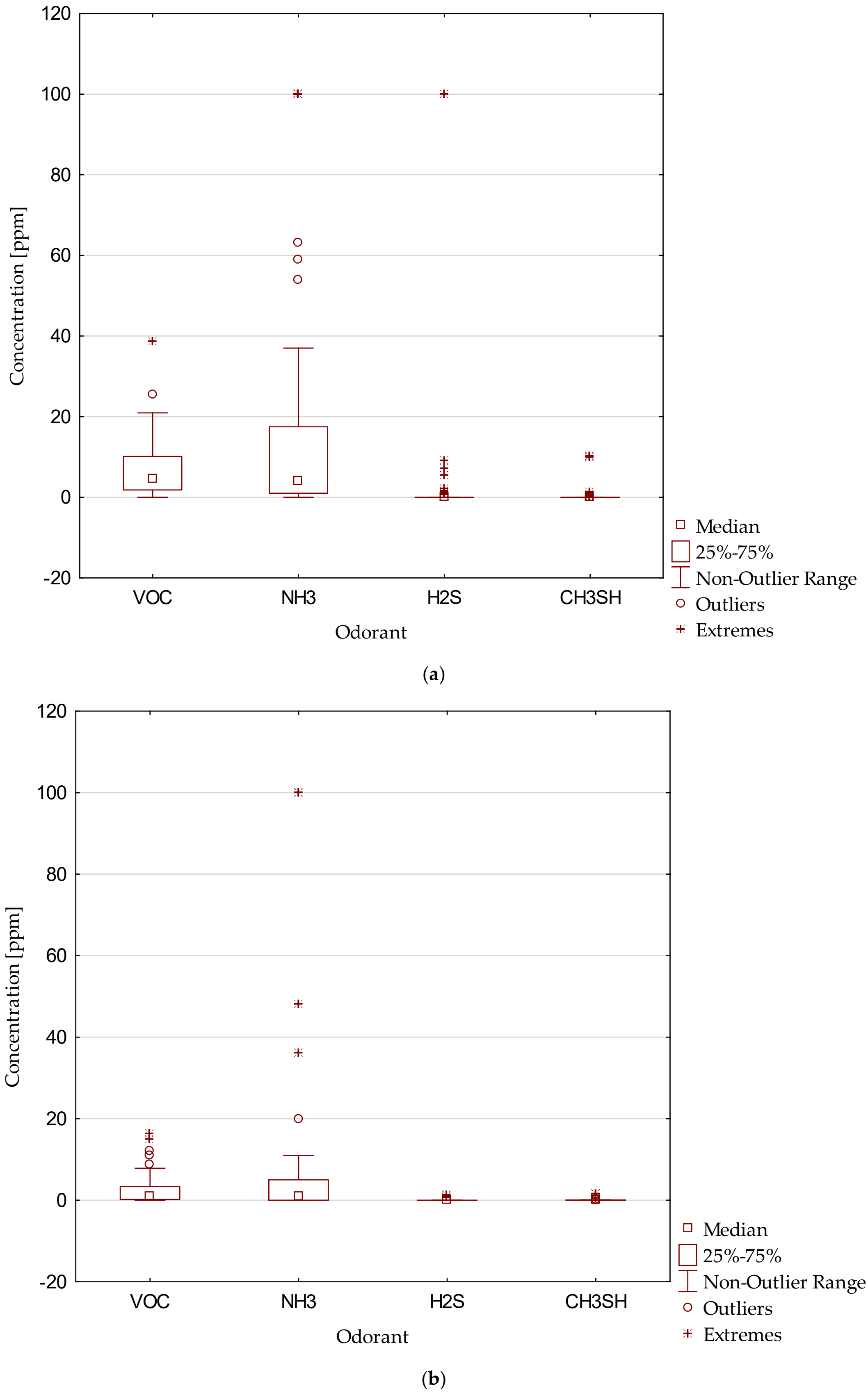

Figure 3. The range of odorant concentration for OFMSW (**a**) and BW (**b**) at Polish MWBPs (own elaboration based on [118]).

The odour concentration for the methane digestion feedstock preparation in a biogas plant processing selectively collected BW is significantly lower than biogas plants processing mixed MSW. Pre-treatment of mixed MSW is accompanied by varying concentrations of ash—the ranges of this parameter in the six biogas plants studied are presented in Table 1. Additionally, the concentration of odorants when BW is prepared for fermentation is much lower. Even about 6-fold lower CH_3SH concentrations and 1.5- to 9-fold lower VOC concentrations were observed compared to pre-treatment of mixed MSW. When selectively collected BW was processed, either no H_2S emissions were recorded or they were 100 times lower. However, no differences in NH_3 concentrations were evident. Similar relationships were not observed for the oxygen stabilisation of digestate, regardless of whether the digestate was from BW (1–4 ppm) or OFMSW (1–3 ppm) [120,124]. There are similar results in papers [198–201], where it was stated that waste treatment odours depend on the type of raw material.

The relationships presented are highly relevant to the CE indicators (Table 1). In attempting to determine the reason for these differences, one should first note the significantly shorter pre-treatment process sequence in the case of selectively collected BW, comprising of particular screening and sometimes pre-treatment with the use of a single separator in most cases (Figure 1b) in comparison to mixed MSW, for which bag tearing, manual segregation, as well as a system of screens and many different separators connected by conveyors are used (Figure 1a). Longer process lines mean longer waste processing times, resulting in longer odour and odorant impacts and more locations where malodorous emissions can occur. Additionally, in research conducted in a biogas plant processing BW, a short storage time for this fraction was observed (waste was collected from the inhabitants more frequently and in smaller amounts, and immediately directed to the fermentation on the same-day process). This is also a significant reason for lower odour nuisance, even despite temporary high concentrations of odours and odorants.

Odour nuisance of biogas plants is also connected with the production of process effluents, especially in the process of wet and semi-dry fermentation requiring appropriate management due to the high pollutant loads, mainly organic and nitrogenous. This wastewater, in Polish conditions, is treated and then directed to a wastewater treatment plant, treated on-site, or directly directed to the treatment plant by pipeline or using a slurry fleet [202–205]. Studies conducted so far in the analysed biogas plants indicate that the process wastewater from BW processing is characterised by a lower pollutant load and is a source of lower odour and odourant emissions (c_{od} = 4 ou/m^3; C_{VOC} = 0 ÷ 1.53 ppm) in comparison to wastewater from the treatment of OFMSW (undersized) mechanically separated from mixed MSW (c_{od} = 142 ÷ 394 ou/m^3; C_{VOC} = 1.11 ÷ 25.41 ppm) [204–206].

The guidelines and recommendations of waste treatment plant odours are indicated in the previously mentioned BAT conclusions for waste treatment [139]. This document lists, among other things, the recommended techniques to reduce emissions of organic compounds into the air (e.g., biological filter, fabric filter, thermal oxidation, and wet scrubbing) and the emission levels associated with the best available techniques for organised emissions. These levels follow for an odour concentration of 200–1000 ou/m^3, ammonia of 0.3–20 mg/Nm^3, and total VOC 5–40 mg/Nm^3 (the values indicated are the average over the sampling period).

4. Summary and Future Research Work

Environmental and social aspects are an essential part of the CE concept and monitoring progress in its implementation and delivery. In CE strategies, social indicators such as quality of life, health, and well-being of inhabitants, and environmental indicators such as pollutant generation, overall emissions, and odour are mentioned. Methane fermentation as a waste treatment process is an excellent fit for the CE, both technically, economically, and environmentally. Co-fermentation, i.e., using at least two complementary substrates in one digester, can be an exciting and promising way to achieve CE goals. Biogas installations have multiple functions in the CE, and feedstock modification at MWBPs and effective selective collection of BW is essential from the point of view of higher biogas yield, renewable energy production, minimising greenhouse gas emissions, and improving the efficiency of soil fertility (using the digestate as an organic fertiliser). In addition, it is shown that the modification of feedstock towards BW contributes to a reduction in odour and odorant emissions, which are the cause of odour nuisance among residents living in the vicinity of biogas plants, and thus additionally fits into the CE environmental and social objectives.

With the change of feedstock in municipal waste biogas plants due to the implementation of CE rules, both benefits and difficulties in the operation of these plants can be expected, especially during the initial period of change. During the implementation of a separate collection system, the differences in input (in the form of OFMSW mechanically separated from mixed MSW and BW) are smaller and of less importance. However, this importance will increase with time as the efficiency of separate collection improves.

Nevertheless, lower odour and odorant emissions at biogas plants processing BW compared to mixed MSW are observed especially due to the shorter processing time of BW. The time of waste processing is significant, especially at the stage of storage and pre-treatment. For mixed municipal waste, it is much longer (due to the greater complexity of the process). The situation is different for BW, for which the pre-treatment is simplified, and its time is shorter, thus reducing the inconvenience for the user. BW processing usually involves a less extensive pre-treatment process line and, therefore, fewer locations from which odour sources can be emitted.

This study has limitations that point to future works and research avenues due to changing requirements regarding waste collection systems and the implementation of new technological solutions. It would be interesting to carry out a study comparing two kinds of feedstock in one biogas plant. Moreover, survey research can be recommended to assess the impact of such installations on residents. Further studies should include an assessment of the biogas plant influence and proposals for measures to improve deodorisation and minimise odour nuisance. Similar studies can also be carried out in other countries to find the best technological and technic solutions, which are the nearest to the CE.

5. Conclusions

Odour nuisance of MWBPs varies greatly, and this variation is caused by technological factors and processes, air temperature, humidity, microclimatic conditions, and the type of waste processed. The problems of odour nuisance should be considered regarding particular phases of the MWBP technological line. They are especially seen at the stage of waste storage, fermentation preparation, and digestate dewatering. Research results indicate lower odour and odorant emissions at biogas plants processing BW compared to mixed MSW. This is particularly evident at the stage of mechanical treatment, fermentation preparation and technological wastewater management. In countries where a separate BW collection system is at an early stage of development BW biogas plants may initially be characterised by a similar odour nuisance as mixed MSW plants, because of the heterogeneity and low degree of BW "purity". However, the beneficial influence of BW feedstock on the odour effect will increase with time, as the efficiency of separate collection improves. Further research on odour nuisance of MSW treatment plants should be conducted for the sake of the health, comfort, and well-being of residents living in their vicinity—elements that are significant CE indicators.

Author Contributions: Conceptualisation, investigation, writing—original draft preparation, and visualisation, M.W.; supervision, A.K.; conceptualisation, writing—review and editing, and validation, K.L.-S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Warsaw University of Technology.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AD	Anaerobic digestion
BAT	Best available techniques
BW	Selectively collected biowaste
CE	Circular economy
c_{od}	Odour concentration (ou/m^3)
MSW	Municipal solid waste
MWBP	Municipal waste biogas plant
OFMSW	Organic fraction of municipal solid waste
SDGs	Sustainable development goals
VFAs	Volatile fatty acids
VOCs	Volatile organic compounds
WETs	Waste-to-energy technologies

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