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Municipal waste management systems for domestic use

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ABSTRACT

Every year, the average citizen of a developed country produces about half a tonne of waste, thus waste management is an essential industry. Old waste management systems based on the collection of mixed/sorted waste and transporting it a long way to disposal sites has a significant negative impact on the environment and humans. This paper will review the available waste management systems for households. Biological methods (such as composting or anaerobic digestion) and physicochemical methods (such as burning or pyrolysis) of waste utilization will be considered from the householder's point of view. The most important features of each system will be discussed and compared. Municipal waste management systems for domestic use could eliminate or significantly reduce the stage of waste collection and transportation. Additionally, they should not require special infrastructure and at the same time should allow garbage to be changed into safe products or energy sources with no harmful emissions. The aim of the work is to identify the best available waste disposal systems for domestic use.

1. Introduction

In ancient Athens each household was responsible for collecting and transporting its wastes. Residents were required to sweep the streets daily and remove the waste from the city. Minoans (3000-1000 BCE) placed their wastes, covered periodically with layers of soil, in large pits [1]. These practices basically are fundamentals of waste management nowadays. Most waste still ends up in landfill. However, before the industrial revolution the human population was about 1 billion people, now it is 7.5 billion. Before the demographic explosion humans could afford to simply take the trash somewhere out of the abode, today it is impossible. Mankind needs new solutions immediately.

Waste management systems based on the collection of waste and transportation to disposal sites are outdated. It has been estimated that collection costs range between 40 and 60% of a community's solid waste management costs [1]. Moreover, garbage trucks are involved in more than 5 fatal accidents per 100 million miles travelled [2]. Elimination of waste collection could also prevent CO_2 emissions of 4.2–12 kg CO_2 per tonne of waste, depending on the types of vehicles employed in the various stages of waste transportation and the estimates of payload and average journey distances. It is suggested by Transport for London, that waste generated in the city travels a distance of 44 million kilometres on London's roads each year, releasing about 200,000 tonnes of CO_2 to the atmosphere. Moreover, this does not include the additional road miles incurred, and CO_2 emissions generated, through the transport of waste, principally to landfill sites outside of Greater London [3]. Furthermore, in 2013 there were 204 serious pollution incidents in UK caused by waste industry activities [4]. However, keeping raw garbage in the home before collection creates perfect conditions for infestation by rodents, insects and microorganisms that spread diseases. Hippocrates (ca. 400 BC) and Ibn Sina (980-1037 AD) already suggested a relationship between waste and infectious diseases [1].

It is estimated, that on average each citizen of European Union countries produces 475 kg of waste annually and US citizens about 730 kg [5,6]. The level globally of urban municipal solid waste generation was approximately 1.3 billion tonnes in 2010, which means about 1.2 kg per person per day [7]. Globally about 84% of MSW is collected currently and 15% is recycled. However, most of it

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Table 1
Waste management methods in different income groups [7].

Method	Income			
	High	Upper middle	Lower middle	Lower
Dumping	0%	32%	49%	13%
Landfilling	43%	59%	11%	59%
Composting	11%	1%	2%	2%
Recycling	22%	1%	5%	1%
Incineration	21%	0%	0%	1%
Others	4%	6%	33%	26%

is still dumped or landfilled, especially in countries with low income per capita [8]. This situation is depicted in Table 1. Reducing the amount of waste produced by individuals - especially if it is significantly above the global average - and the possibility of utilizing as much of the waste as possible at the household level - would provide an opportunity of solving the global problem of littering. Additionally, the costs of central waste management systems would significantly decrease.

Typical households waste consists of a range of materials that vary in composition, depending on the community and its consumers' incomes and lifestyles and its degree of industrialisation, institutionalism and commercialism. Moreover, even the season of the year and the number of persons in a household influence the amount and composition of waste. For example, more food waste and less paper is generated during summer. Additionally, the larger the household, the less waste produced per capita, but the larger community, the more garbage generated per capita [1,9]. In general, modern society produces garbage, which consist of organics and inorganics. The first group includes food, wood and garden waste, paper, plastics, textiles, rubber, leather and other materials. The second group comprises mainly glass and metals. Composition of typical municipal waste in developed and developing countries like the USA, UK, China, and Kenya are shown in Fig. 1.

For a considerable time a large variety of waste management practises have been studied and developed. Some of them were adopted as key solutions in waste management, namely: source reduction, collection, recycling, composting, incineration (burning), landfilling and simply dumping. The higher the income per capita, the more effective and safe for environment and population are the solutions used in a particular region [7]. Unfortunately, the use of some of these solutions such as dumping and waste burning in the home is disastrous. Thus, the overview of municipal waste management systems in domestic use will be carried out in order to show the most appropriate.

2. Sorting

It is very difficult to find a waste management system, which can utilize all types of waste generated in a household. Most available solutions focus on organic waste such as food residues, biomass from gardens, wood and sometimes paper. Reprocessing plastics or waste tyres at a domestic level is usually both complicated and risky. In the case of glass and metal there is a lack of any effective methods for utilizing them in the household. Moreover, attempts at disposal of electrical and electronic equipment, batteries or pressurized containers, e. g. deodorants, can even be dangerous at home. Thus, a very important part of waste management at a domestic level is sorting; sorted waste can be treated further. Biological methods may be applied, which use the action of living organisms, but these are dedicated to the processing of organic waste. Alternatively, physico-chemical methods – suitable for different types of waste – may be employed. These methods will be discussed in the next sections.

2.1. Available solutions

The two most basic, and at the same time most important, types into which we can divide the waste are the biodegradable and the non-biodegradable. Sorting waste in this way can even reduce by half the amount of waste that must be taken to the recycling or incineration plants or to landfill. The resulting solid organic material can be used in further processes by the consumer. The collection of organic waste in bags made of synthetic polymers significantly hinders their subsequent utilization. Most oil-based plastics are resistant to microorganism activity, because they do not have an enzyme capable of the degradation of most artificial polymers. Moreover, the hydrophobic character of plastics additionally inhibits enzyme activity [14]. To collect organic waste, bags and containers designed precisely for this purpose should be used. However, in choosing the right equipment, it should be noted, that only materials that bio-degrade in composting environments and meet the composting time of known compostable materials can also be considered as 'compostable' [15]. *Vaverková* et al. [16–18] checked the aerobic decomposition of plastic products described as 100% degradable, BIO-D Plast or compostable. It can be concluded, that only bags made of natural materials like starch biodegrade easily in composting conditions. On the other hand, bags made of polyethylene with additives, which increase its susceptibility to bio-decomposition seem not to work properly during composting. In view of these results, conscientious consumers collecting organic waste should choose bags made of appropriate materials. This will facilitate subsequent disposal of these wastes. Fig. 2 shows three marks of compostable products.

There are many companies, which offer such as products. BioBag® proposes biodegradable bags available in different sizes, which are made from corn starch and other plant extracts. The physical and mechanical properties of these materials are similar to those of conventional plastics, but they are compostable and biodegradable, and so they enable the hygienic collection and disposal of food waste in kitchens. It is recommended that ventilated baskets be used, which reduce the weight and the volume of the waste, and they also keep the food waste "fresh", avoiding unpleasant smell and fly infestation; this solution is shown in Fig. 3. Biodegradable dog waste bags are offered, too [19].

The second stage of sorting waste at home is the separate collection of plastics, metals, glass and other materials. Bags and waste bins suitable for sorting different types of materials are widely available, and the variety of solutions is surprising. It is possible to sort waste, e.g. in kitchen cabinets or outside in larger containers. Even in a small flat waste can be successfully divided into biodegradable, plastic, glass, metal and other. Some solutions are showed in Fig. 4.

2.2. Implications

However, many consumers may have not the motivation to segregate waste, because they do not realise the importance of this practice. An interesting study was conducted by *Fahy and Davies* [21]. They organized a waste minimisation exercise lasting four weeks in 11 households located in Ireland. Researchers especially focused on householders who, for a variety of reasons, were having difficulty managing waste. Families living in apartments, rented housing, young professionals lacking time, students sharing accommodation, and households without recycling facilities were included. During the exercise the importance of composting organic waste and collecting recyclables was emphasized. In all cases the householders participating appeared keen to learn and to improve their waste management behaviour and they were open and enthusiastic about identifying both the opportunities and obstacles

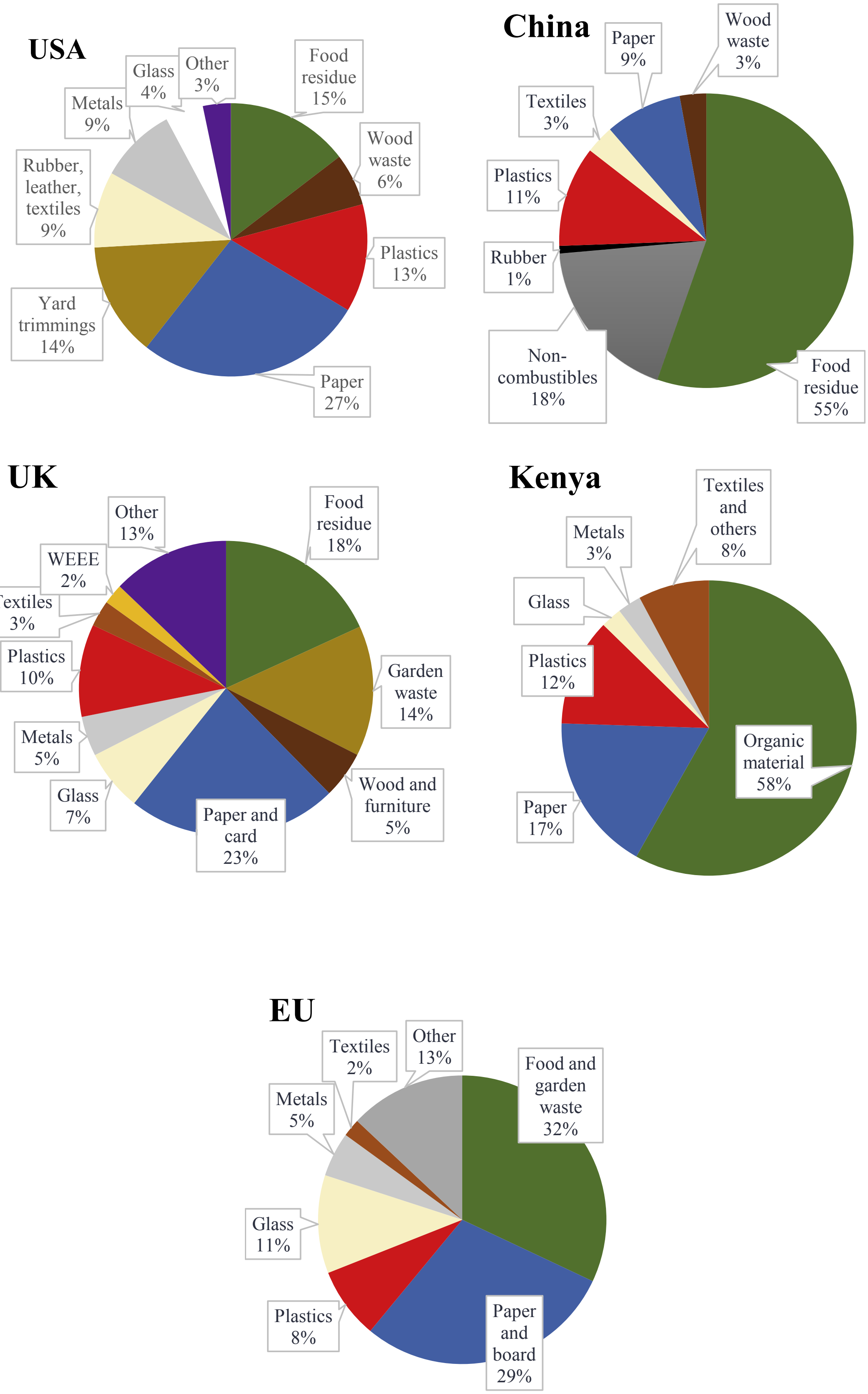


Fig. 1. Waste composition in different countries [6,10–13].

to improved waste management during the exercise. The results suggested, that the first step to a successful implementation of a domestic waste management system is an increase in knowledge. Showing in practice that something is possible makes people more

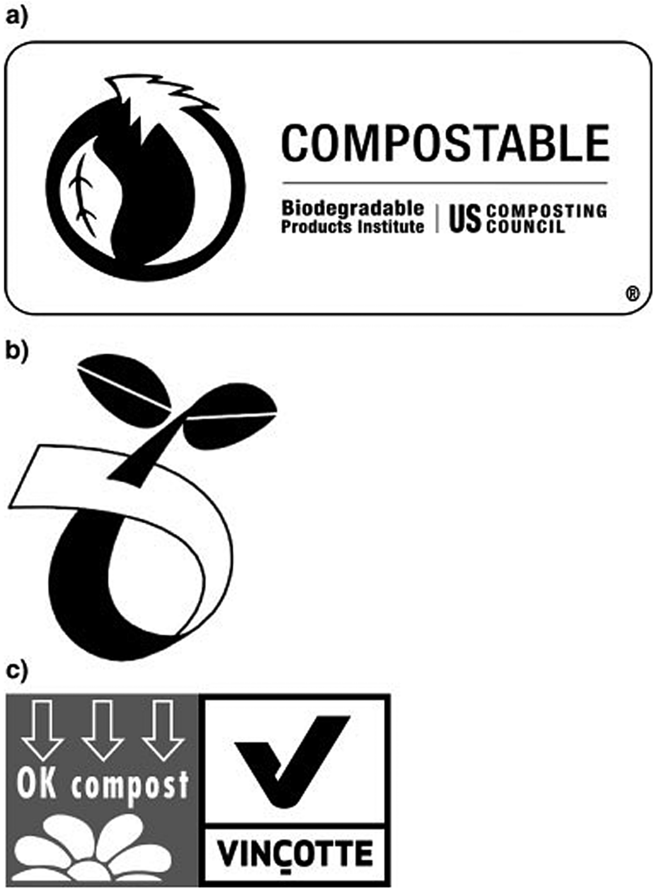


Fig. 2. Logos for compostable materials: a) BPI, b) DIN CERTCO, c) OK compost [15].

Fig. 3. Ventilated container with biodegradable bag for organic waste collection [19].

willing to cooperate, but only if they believe it is worth doing. People are more willing to recycle if they are concerned about the problems of waste and have enough space and the required facilities. On the other hand, householders may not prioritize activities such as recycling very highly and as a result they may not prioritize space in their kitchen or living area for the storage of recyclable goods [22].

However, in the case of sorting recyclables and other materials, e.g. hazardous or bulky waste, there always appears the issue of a well-organized system of collecting this waste and efficient methods of further utilization. As was mentioned before, waste collection has implications both for humans and the environment. Additionally, some types of recycling processes consume more energy/water/other resources and emit more pollutants than production from raw materials. Here is an example. In many cities people were instructed to rinse plastic containers before putting them in the recycling bin. *Goodall* [23] calculated that if the plastics are washed in water which was heated by coal-derived electricity, then the net effect of recycling could be more carbon in the atmosphere. This is only one stage of recycling. It has been estimated that recycling one tonne of plastics can finally generate about 3 tonnes of CO_2.

3. Biological methods of waste utilization

All biological waste utilization methods involve the decomposition of biodegradable wastes by living microbes (bacteria and fungi), which use biodegradable organic matter as a food source for growth and reproduction. Microbes excrete specialised enzymes that digest biodegradable waste components (e.g. cellulose, lignin, starch and other complex polysaccharides, proteins and fats) into simple nutrients - sugars, amino acids and fatty acids, which they absorb. As the microbes grow and reproduce a significant proportion of these nutrients is converted into heat, carbon gases and water. This results in a large loss in weight during the process. Sometimes slightly larger organisms are also used such as invertebrates.

There are two main types of environments in which such microbes live. Therefore, there are two main types of biological processes used to treat biodegradable waste: aerobic – in the presence of oxygen and anaerobic – in the absence of oxygen.

Biological methods of waste utilization technologies are carried out in a way, which allows the control and enhancement of natural biological processes. Thus they can only act on biodegradable organic materials. Biological methods can treat either mechanically separated organic waste from a mixed MSW or source-sorted biodegradable materials, which provide a cleaner organic stream. Food and green wastes are suitable feedstock materials for these technologies. Other biodegradable materials, such as paper, card and wood also can be treated. However they take a longer time to degrade [24].

3.1. Composting

Composting is a natural aerobic process of the biological stabilization of organic waste that allows a weight and volume reduction and produces a compost, which provides the nutrients required for new plants. It can be also defined as the decomposition of organic

Fig. 4. Recycling bins for in-door and out-door use [20].

matter by microorganisms under aerobic conditions. This end product can be used for agricultural purposes since its incorporation in soil in suitable conditions increases fertility [25]. The composting process can be shown in a simple equation such as

$$\text{Organic waste} + O_2 \xrightarrow{\text{Microorganisms}\left\{\begin{array}{l} heat \\ CO_2 \\ H_2O \end{array}\right.} \text{Compost}$$

Home composting is interesting waste management option because the waste producer is also the processor and end-user of the product [26].

3.1.1. Composting conditions

Composting can be done at different scales: at a household level, on a community scale and at large-scale in a composting plant. Home-composting can be done very easily provided there is enough space outside to install the composter. The composter can be installed in the garden or even on a balcony. A traditional home-composter is a simple box, made of wood or plastic that can even be home-made. It is in contact with soil to enhance biological activity, and should have a lid to prevent rodents and other animals from eating the compost feedstock. Another efficient technique in home composting is the rotary drum. This solution provides agitation, aeration and mixing of the compost, to produce uniform organic fertilizer without any odour or leachate related problems [27]. Some factors have been identified as important for aerobic microorganisms to work properly. The speed of compost generation is the result of attention paid to these factors. However, it is up to householders to decide how much time and effort they want to put into composter maintenance, how much space they can use, as well as how fast they require the finished compost. Investment and operating costs can vary over a large range, from almost zero compost pile maintenance costs to several thousands of dollars for a fully automatic composting machine.

In general, food waste and yard trimmings, preferably shredded, can be added to the composter. Nevertheless, meat, fish, dairy products and sanitary material are to be avoided because they are likely to attract vermin. The temperature in the compost heap can be too low to kill potential pathogens present in such waste and contamination should be avoided [28]. However, in 2016 *Storino* et al. [29] checked the influence of meat waste on the composting process and the quality of final product. They found that the addition of meat waste as feedstock for composting in bins increased the temperature during aerobic decomposition. The home-made compost obtained from meat and vegetable waste reached maturity more quickly and generated a higher quantity of humus in the organic matter than compost obtained only from vegetable waste. Additionally, phytotoxicity, salinity, viable seed presence, pH or heavy metal content did not increase. Two types of material are needed for appropriate composting: those high in carbon and those high in nitrogen. Microorganisms use carbon as an energy source and nitrogen for protein synthesis. The C:N ratio to ensure efficient decomposition is about 30 parts carbon to 1 part nitrogen by weight. Nitrogen-rich materials are called "greens" because they are mostly fresh, green substances. These can include grass and garden clippings or vegetable scraps. Carbon-rich materials are referred to as "browns" because they are in general dry woody substances such as fallen leaves, straw, and twigs. Additionally, it is preferable when material dimensions are small (5–20 cm) in order to facilitate access by microorganisms to the organic matter [30].

Composting is an aerobic process and adequate ventilation should be maintained to allow respiration of microorganisms that release carbon dioxide into the atmosphere, thus composting material aeration is necessary for efficient decomposition. The oxygen saturation in the medium should not be lower than 5%, 10% being the optimal level. Excessive aeration will cause a temperature drop and a great loss of moisture by evaporation, causing the decomposition process to stop. On the other hand, low aeration prevents enough water evaporation, generating excessive moisture and an anaerobic environment [31]. Most composters are designed to provide adequate aeration of the waste. In the event of insufficient aeration, it is necessary to stir the material.

Microorganisms work fastest when thin liquid films are present on the surface area of composting materials. Optimal decomposition occurs when the moisture content is around 55%. If it is below 40%, microbial activity decreases, the degradation phases cannot be completed and hence, the resulting product is biologically unstable. If moisture content goes above 60%, nutrients are leached and the pile can become compacted. Moreover, water will saturate the pores and interrupt oxygenation through the material. When compaction occurs, decomposition is slowed and anaerobic bacteria may become dominant in the pile, which can create undesirable GHG emissions and odours. Additionally, the pH of composting material should be maintained at 5.8 to 7.2 [30,31].

Furthermore, microorganisms generate heat as they work, thus composting begins at ambient temperature that can increase to 65 °C with no need of human intervention. During the maturation phase the temperature drops to ambient. It is desirable that the temperature does not drop too fast, since the higher the temperature and the longer the time, the higher the decomposition rate and the achievement of a hygienic compost. Too low a temperature (below 35 °C) may be caused by insufficient moisture or a nitrogen deficit in the composting material and too high a temperature (above 70 °C) can be caused also by insufficient moisture or ventilation [31]. Both too low and too high temperatures cause the death of the desired group of microorganisms.

3.1.2. Available solutions

The cheapest way to utilize organic waste is pile composting. This method can be performed when there is an abundant and varied amount of organic waste – at least 1 m^3 [31]. A too small pile may not heat up sufficiently for efficient decomposition or it may lose heat easily, resulting in a slowing down of the process. At the same time the pile volume should not exceed 1.5 m^3. A large pile may hold more water and therefore not allow air ingress. This would create an anaerobic environment. Additionally, multi-bin systems (see Fig. 5.) allow the production of finished compost

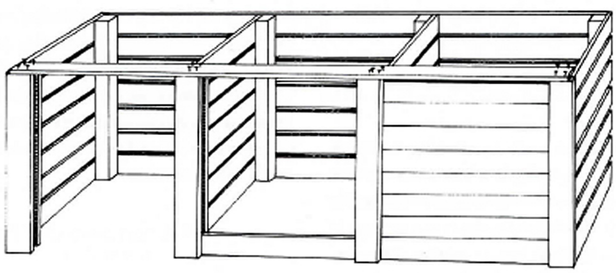


Fig. 5. Multi-bin composting system [32].

faster than one-bin based composting. In this case raw organic material is added only to the newest pile. When enough waste is collected, the material is turned into the next bin to allow faster decomposition and another pile is started in the emptied bin. After the "active batch" becomes mature, it is turned into the final bin where it is stockpiled until needed in the garden [30].

Adhikari [33] studied home composting systems. The types of composter considered are shown in Fig. 6. He found, that the home composter design is important: perforation must be concentrated at the top and bottom to provide an aeration level equivalent to that of a ground pile. Such home composters can reach thermophilic temperatures when fed at least 10 kg/week of organic waste with a dry matter content over 15%. The compost produced generally offers acceptable levels of polycyclic aromatic hydrocarbons (PAHs) and heavy metals, but residents must be careful in applying the right amount of garden herbicides [33,34]. Some commercially available composting units are described in Table 2. Depending on the available space and time, optimal solutions can be found. All of them meet the requirements mentioned below such as good aeration and pest prevention. Even in a very limited space waste can be composted. There are composters available, which are equipped with a leachate collection system. These can be used on a balcony or even indoors. Studies have proven that such a solution is also effective and is not associated with the risk of odour emissions [35].

Fig. 6. Home composting systems: a) rotary drum, b) wood bin, c) plastic bin, d) ground pile, and e) laboratory reactor [33].

A process similar to aerobic composting except that the composting and aeration process are aided by the use of detritivorous worms, is called vermicomposting. Although it is the microorganisms that biodegrade the organic matter, earthworms are the crucial drivers of the process, as they aerate, condition and fragment the substrate, thereby drastically improving the microbial activity [36]. Red wigglers, white worms, and other earthworms are commonly used in vermicomposting. *Lazcano* et al. [36] found that earthworms promoted the retention of nitrogen in compost and the gradual release of phosphorus as well as a reduction in electrical conductivity. The organic fertilizer obtained was of better quality than with conventional aerobic composting. On the other hand, *Chan* et al. [37] found, that the vermicomposting bins produced more CO_2 and CH_4 than conventional composting bins. However, the emission of N_2O was lower. Probably the emission of N_2O from worm gut was offset by the reduction of anaerobic denitrification, due to the burrowing action of the earthworms. In general, vermicomposting produces a solid product named vermicompost and leachate. This liquid is often called 'worm tea' and also can be used a liquid fertilizer [38]. Vermicomposting is considered as an efficient method for utilizing organic waste from agriculture and some industries [39–41]. A commercial vermicomposter is shown in. *Jadia and Fulekar* [42] investigated a hydro-based operating vermicomposter. The reactor consists of five rectangular plastic boxes which were arranged side by side and it was equipped with a water based aeration system and a hydraulic stirrer system. The vermicompost obtained was found to have a comparatively high level of nutrients such as calcium, sodium, magnesium, iron, zinc, manganese and copper and it can be used as a natural fertilizer giving high yields of plants.

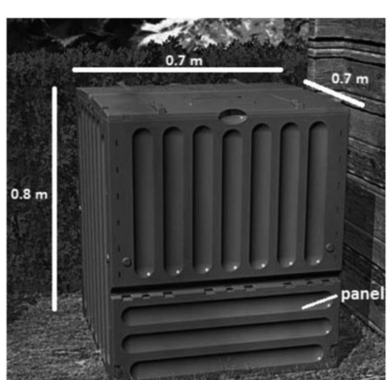
In small flats Bokashi composting can be introduced. This method was investigated in Japan and patented [43]. This method uses a complex of microorganisms mixed with sawdust or bran to cover organic waste in order to decrease the smell and accelerate compost production. An example of a Bokashi bin is also shown in Table 2.

If a composting bin is not equipped with a suitable ventilation system and the lid is closed, there is a deficiency of oxygen inside. Thus anaerobic digestion occurs. However, in this case the aim of the process is still compost production, but the emissions are higher [37]. Anaerobic digestion systems for household waste management connected with biogas production will be discussed in the next section.

Home composting is the simplest way to reduce the amount of waste being sent to landfill. Moreover, carrying out the aerobic digestion in composting bins is easy to operate and cheap. However, the whole process can take months from filling of waste to removing of compost. The simplest system is based on three containers, one of which is filled each year. Completely matured compost is obtained after 3 years! Additionally, the problem with insufficient aeration and temperature may result in an unsatisfactory quality of product or additional emissions. Those problems can be solved by using an automatic composting machine. They provide optimal conditions for the process and good quality fertilizer can be obtained after a few days. These machines are simple in use. Except for filling and removing, they work automatically. On the other hand, they need electricity and a little more space than composter bins, but less than piles. They are more expensive, obviously. Thus the consumers must take into account all the factors and choose the solution tailored to their needs and conditions.

A short explanation of automatic composting was made by Greeneria®. Microorganisms feed on the organic matter and

Table 2
Home composters.

Type of composter	Name	Picture	Details	Region	References
Plastic bin – outside use	Mattiussi Ecologia, model 310		Material: polypropylene, truncated conical body; height: 92 cm, maximum diameter: 80 cm; total volume: 0.31m^3; equipment: a circular opening lid on the upper part (for waste addition), side sliding door on guides (for control, sampling, and final compost withdrawal); channels and slits in the bottom for air supply, an internal vertical cone with non-clogging holes, additional slits on the upper rim and beneath the lid	Italy	[44,45]
Plastic bin – outside use	Compostadores SL; model 400 RRR		Material: HDPE; dimensions: 70 cm × 70 cm x 103 cm; volume: 0,5 m^3; equipment: lateral system of natural ventilation to guarantee aerobic conditions	Spain	[46,47]
Plastic bin – outside use	Humus/Genplast		Material: recycled PE and PP; height: 95 cm diameter: 48 cm (top) and 105 cm (bottom); total volume: 0.32 m^3; equipment: a lid, a fine-masked steel net at the bottom (prevents rodents from entering), a hatch (in order to withdraw the mature compost), a net (to prevent flies from entering); the bottom has plenty of holes through which the surrounding air can enter the composter. Additionally, the unit is equipped with a manually operated propeller.	Denmark	[26,48]
Plastic bin– outside use	Thermo-King, Plastic Omnium Caraibes		Material: recycled HDPE; dimensions: 70 cm × 70 cm x 80 cm; volume: 0,4 m^3; equipment: lateral system of natural ventilation, detachable front panel, aerator tool, small kitchen bins for collection and transport of organic waste to the composter	France	[49,50]

(continued on next page)

Table 2 (*continued*)

Type of composter	Name	Picture	Details	Region	References
Rotary drum – outside use	Envirocycle Composter		Material: recycled plastic and aluminium; dimensions: 64.5 cm × 54.6 cm x 70.36 cm; volume: 132.5 l (drum), 9.5 (base); equipment: easy to turn drum – regular mixing providing good aeration, vents to increase airflow into the drum, 8 drain plugs to collect liquid fertilizer (compost tea) in the base; door for adding feedstock and removing compost	USA	[51]
Vermicomposter – indoor use (balcony, terrace)	Compostadores SL; model Can-*O*-Worms		Material: recycled polypropylene; dimensions: 39 cm × 57 cm and 74 cm of height; volume: 150 l; equipment: three upper trays for composting, bottom tray for liquid collection, effective ventilation system	Spain	[35,52]
Bokashi bin – inside use	Square Bokashi Compost Bin		Material: plastic, dimensions: 30 cm × 30 cm x 42 cm; equipment: easy twist integrated tap, drainage tray, scoop /masher, Bokashi Bran (enriched with effective microbes product accelerating composting)	UK	[53]

convert it into compost. Vegetables, bread, meat, bones, garden waste and other organic biomass can be processed, but big bones, large shells and stones should be removed in order to prevent blade destruction. Decomposition is done by thermophilic microorganisms which thrive in high temperatures and high acid or salty atmospheres Critical parameters like temperature, moisture and oxygen are optimised for the bacteria to thrive and compost the organic waste at a very fast pace. Moisture and temperature are automatically regulated using sensors at the bottom of the tank whenever organic waste is added. Fully aerobic digestion is facilitated by the periodic and intermittent rotation of the mixing blades to maximize microbe activation. A scheme of an automatic composer is shown below in Fig. 7.

The compost goes back as manure for garden and farm needs. It achieves a 90% reduction in weight. It is recommended to mix it with soil in a ratio of 1:10. Compost should be removed once every 10–15 days. Waste to manure duration is only 1–3 days. However, the producer recommends the removal of compost once every 8–10 days in order to obtain better manure [54]. The company offers automatic composters with a capacity from 100 kg/day to 1250 kg/day. The smallest option is shown in Fig. 8. For comparison, Fig. 9 shows another automatic composting machine from Reddonatura™. This is the smallest available option with a capacity of 25 kg/ day. These composting machines are suitable for households, offices and restaurants.

3.1.3. Emissions and other implications

Organic waste composting generates some emissions. *Andersen at al.* [26] studied the GHG emission from home composting. To measure those emissions, a static flux chamber system was fixed to each of the composting units. The gases monitored were CO_2, CH_4, N_2O and CO. A schematic diagram of the composting unit is shown in Fig. 10.

The emissions of CH_4 and N_2O were quantified to 0.4–4.2 kg CH_4/Mg_{ww} and 0.30–0.55 kg N_2O/Mg_{ww} which is equivalent to 100–239 kg $CO_{2\text{-eq.}}/Mg_{ww}$. One interesting finding was that the release of methane was 11 times higher for the composting units that were mixed most frequently compared with the units that

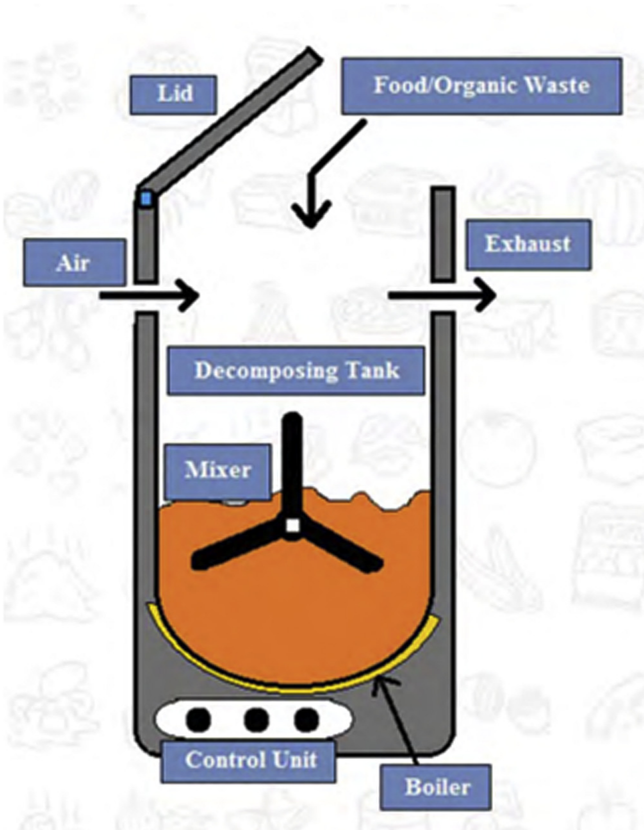


Fig. 7. Elements of automatic organic waste composer [54].

Fig. 8. Automatic waste composting machine from Greeneria® [54].

Fig. 9. Fully automatic composting machine from Reddonatura™ [55].

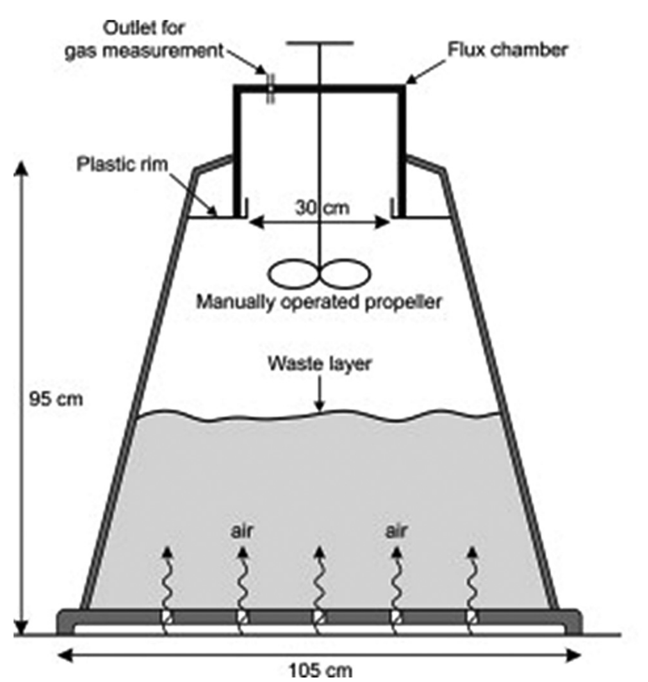


Fig. 10. Schematic diagram of composting unit [26].

were not mixed at all. These results indicate that it might be beneficial to avoid too much mechanical aeration in the composting units. On the other hand, less aeration could lead to slower degradation and maturation of the organic material. Compared with an estimated 80 kg CO_2/Mg_{ww} (with a range of 19–379) released from centralized composting, home composting does not seem to be largely different. Moreover, additional GHG emissions from collection, transportation and mechanical turning have to be included when doing a full GHG account from centralized composting. A comparison of the quality of compost formed in household and industrial conditions was made by *Barrena* et al. [56]. They investigated 52 samples of compost of different origin, and found that there were no significant differences in chemical parameters and the content of nutrients. However, the content of some metals like Cu, Ni and Zn was higher in the industrial compost. Stability, though, is the most important parameter of this organic fertilizer. With reference to compost stability from different processes (home or industrial) it was demonstrated that home compost, if properly managed, can achieved a level of stability similar or even better than that of industrial compost. Additionally, a full Life Cycle Assessment of home composting was made by *Cólon* et al. [47]. They reported, that physicochemical properties of the final compost obtained at domestic level were in the range of high quality and stable compost. Moreover, regarding gas emissions only VOCs were detected. Ammonia, methane and nitrous oxide were always below the detection limit (1 ppmv, 10v ppmv, 10 ppmv, respectively). They suggested also, that using recycled plastic as composter material could decrease energy consumption and emission levels for a Life Cycle Assessment of composting.

On the other hand, *Joly* [28] demonstrated in her degree project, that a centralized collection system combined with large-scale composting for a city of 50,000 inhabitants in Canada has greater environmental benefits than home-composting. In accordance with her calculation, greenhouse gas emissions were significantly reduced while emissions from home-composting remained at the reference level from landfilling. One important factor influencing this result was the low capture rate for home-composting, it was estimated that only 20% of organic waste was diverted from landfill. When the capture rate was increased to 50%, the reduction in GHG emissions was comparable in both cases home and large scale-composting. However, the actual rate depends on many factors and especially on the geographic situation of the city. Furthermore, home-composting reduces waste management costs by 15% while they represent an increase of 4% with large-scale composting. Another case study was done by *Oliveira* et al. [57]. They analysed the situation of Bauru, Brazil. Each of almost 350,000 of inhabitants generate about 0.85 kg of waste daily, which corresponds to about 100,000 tonnes of waste, including almost 35,000 tonnes of organic matter. This city did not have a composting plant. Seven possible scenarios were analysed: the current situation, in which all organic waste goes to landfill; sending the organic waste to the closest municipality having a composting plant; construction of a composting plant in Bauru; use of home composting for 10%, 25%, 60% and 90% of organic waste. It was concluded, that to achieve 100% of home composting is impossible in practice. But any amount of home composting is important in reducing the amount of organic waste sent to landfill and in reducing other environmental impacts. In addition, it was found that home composting has a greater potential to reduce the CO_2 equivalent emitted per mass of organic waste composted than composting plants. These contradictory results show that the creation of Life Cycle Assessments is still a very difficult process, especially when complex processes are taken into account.

In terms of waste management, it has been identified that personal participation is strongly affected by the type of household, knowledge and the simplicity of the process. *Karkanias* et al. [58] published the results of the Home Composting Programme which was implemented in the municipality of Neapoli-Sykies in Greece. The research interviews took place as part of a door-to-door campaign during 2012 and 2013 concerning home composting monitoring, provision of information and suggestions for solutions to problems. The most frequent problems faced with the implementation of composting were related to the following: the necessary shredding of organic waste such as materials from pruning, the presence of insects close to the composting bin and maintaining the appropriate moisture and aeration levels needed for the optimal production of compost. Results showed, that economic incentives and information represent the main motivation for people to compost, as was reported before [58,59].

3.2. Anaerobic digestion

The second biological method of waste utilization is anaerobic digestion, also called methane fermentation. Anaerobic digestion can be described by the schematic equation:

$$\textit{Organic waste} + \textit{heat} \xrightarrow{\textit{Microorganisms} \left\{ \begin{array}{l} \textit{heat} \\ \textit{biogas} \\ H_2O \end{array} \right.} \textit{Compost}$$

The microorganisms convert biodegradable material into biogas in a series of biological processes without oxygen being present. The most popular feedstock for anaerobic digestion are different types of organic waste like manure [60,61], agricultural residues, crop residues [62,63], wastewater [64] and municipal solid waste [65,66]. The anaerobic digestion is completed after four successive phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis. In hydrolysis, monomers are produced from complex polymers by enzymes, which are further transformed into volatile fatty acids (acetic, propionic and butyric acids) and hydrogen during the second stage of the process - acidogenesis. In acetogensis, acetate, carbon dioxide and H_2 are generated from volatile fatty acids and finally they are converted into methane in the methanogensis process [67].

Biogas is a mix of methane, carbon dioxide and other gases in small quantities (see Table 3), which can be converted to heat or electricity. It contains a high concentration of methane (50–80%), making it suitable for use as a source of energy for combustion engines, turbines or boilers, both alone or mixed with other fuels. For example, in India biogas from a community digester was used as a fuel for a modified Diesel engine to run an electrical generator [68]. In simple applications biogas can power gas cookers. This solution is highly recommended, especially in developing countries. The switch from traditional solid fuels (wood, dung, agricultural residues and coal) to cleaner biogas can significantly reduce air pollution and diseases caused by it [69]. It was reported, that the construction of anaerobic digesters can reduce household energy consumption by more than 40% [70]. A small-scale anaerobic digester also produces digested slurry (digestate) that can be used as a plant fertilizer rich in macro- and micro nutrients. It can be said, that a properly maintained process of anaerobic digestion is one of the best ways of reducing greenhouse gas emissions, promoting the use of waste for energy, and enhancing the value of fertilizer from the process products [71,72].

3.2.1. Anaerobic digestion conditions

Small-scale biogas reactors are typically designed to produce biogas at the household or community level in rural areas. The airtight reactors are typically filled with animal manure from a farm. Toilets can be directly linked to the reactor. Kitchen and garden wastes can also be added [74]. *Bond and Templeton* [69] reported, that the use of multiple substrates often has synergistic effects with higher biogas production. Typical methane yields from different feedstocks are shown in Table 4. *Zhang* et al. [75] characterized food waste as a feedstock for anaerobic digestion even with 74–90% of moisture. Additionally, the ratio of volatile solids to

Table 3
Typical composition of biogas from anaerobic digester [73].

Compound	Unit	Value
Methane	mol. %	50–80
Carbon dioxide	mol. %	15–50
Nitrogen	mol. %	0–5
Oxygen	mol. %	0–1
Hydrogen sulphide	mg/m^3	100–10000
Ammonia	mg/m^3	0–100
Total chlorine	mg/m^3	0–100
Total fluorine	mg/m^3	0–100

Table 4
Methane yields from anaerobic digestion of different feedstocks.

Feedstock	m^3 CH_4/tonne $_{(dry\ mass)}$	Dry matter (%)	% CH_4 in biogas	References
MSW (after autoclaving)	201–297	55.8 (±2.33)	51–62	[76]
MSW (source separated)	221	37	63.2	[77]
MSW (kitchen waste)	271–470	26–33	60–62	[78]
Food waste	340	31	73	[75]

total solids is estimated at 80–97%, and the carbon to nitrogen ratio at 14.7–36.4. Due to its relatively high moisture content, the anaerobic digestion of food waste seems to be more suitable than thermo-chemical conversion technologies, such as combustion or gasification. The food waste used was provided by a waste management company in northern California. The raw waste was screened to remove the unwanted elements and then ground in a hammer mill for size reduction. Digestion tests were performed on food waste samples prepared from the food waste collected weekly. The experiment was carried out for 28 days at 50 ± 2 °C. It was found, that methane production was low during the first five days of digestion and then increased. The product yield from food waste was calculated to be 465.4 m^3 of biogas per ton of dry material with the average methane and CO_2 content of 73% and 27%, respectively. Thus food waste is a highly desirable feedstock for anaerobic digestion. An interesting study was carried out by *Blake* et al. [76]. They investigated the anaerobic digestion of MSW residue after roto-autoclaving. Compared with typical MSW this fibrous material was visually homogenous and free of pathogens. It was found, that methane yields were comparable to those from other materials commonly used for anaerobic digestion and they varied between 201 and 297 m^3 of CH_4 per tonne (dry matter). Moreover, the yields of methane per tonne material as received was high – up to 166 m^3, while usually it is below 120 m^3methane/tonne (as received) for many feedstocks. Thus it is logistically favourable due to low moisture content.

In considering the temperature range required for optimum performance of anaerobic digestion, two types can be distinguished: mesophilic and thermophilic digestion. The first type takes place optimally at around 35 °C with mesophiles as the primary microorganism present, while ambient temperatures are between 20 and 45 °C. Then thermophilic digestion takes place optimally at around 55 °C mainly with the participation of thermophilic microorganisms. Although better performance in the reduction of volatile solids and deactivation of pathogenic organisms can be obtained in this case, additional energy is required to heat the digester [79]. It can be concluded, that in areas where the ambient temperature remains sub-zero, the amount of energy for reactor heating is high, which can make the total energy yield marginal or even negative [80].

To produce biogas at home, the feedstock based on organic waste from a household may need water added to create a slurry, because the range of total solids should not exceed 10% [81]. However, a higher solid concentration can slightly increase the tolerance to temperature changes [82]. Additionally, the C:N ratio should be kept between 20:1 and 30:1 to ensure the most valuable biogas composition. An improper amount of carbon in feedstock may lead to carbon dioxide accumulation in biogas [70]. Also orthophosphates are needed for the proper functioning of the bacteria and both N and P should not be limited in the digester [83]. It is also favourable to chop or shred solid material into pieces with dimensions of a few centimetres. A larger surface area available to microbes will promote better digestion of organic material. Furthermore, a neutral pH in the digester is desirable since most of the methanogens grow at the pH range of 6.7–7.5 [84]. Finally, starter culture of methane-producing microorganisms should be added into the digester unless any animal manure is used [81].

3.2.2. Available solutions

Since anaerobic digestion has been used for centuries, many practical solutions have been developed. Simple digesters can be home-made, if all necessary elements are taken into account and the design performed with due diligence. The design of digester suitable for a particular household is chosen based on the geographical location, availability of substrate, and climatic conditions. *Rajendran* et al. [84] studied household anaerobic digesters. Three types are most commonly used: the fixed dome, the floating drum and the plug flow digesters, with many variations.

The fixed dome digesters were investigated and are commonly used in China. This type is filled through the inlet pipe until the level reaches the bottom of the expansion chamber. The emerging biogas accumulates at the upper storage part. The difference in the level between feedstock inside the digester and the expansion chamber creates a gas pressure. The gas produced requires space and presses a part of the substrate into an expansion chamber. The slurry flows back into the digester as soon as gas is released [84]. Fig. 11 shows the scheme of the deenbandhu model fixed dome digester. This model was developed in 1984 in India. It is one of the cheapest among all the available models of digesters. The aim of this design was to reduce the surface area needed for the digester without significantly reducing the efficiency. The design consists of two spheres of different diameters, connected at their bases. The structure performs the function of the fermentation chamber and the gas storage chamber at the same time. The chamber is connected with a feed tank (through the inlet pipe) and a digestate tank [85].

The second type of household biogas plant is shown in Fig. 12. These plants have an underground digester with inlet and outlet connections through pipes. An inverted drum (gas holder), made of steel, is placed in the digester, which leans on the wedge-shaped support and the guide frame at the level of the partition wall. This drum can move up and down along a guide pipe with the

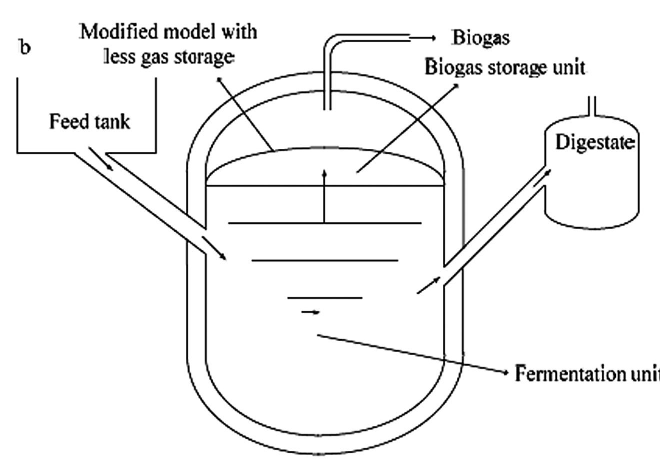


Fig. 11. Scheme of deenbandhu model fixed dome digester unit [84].

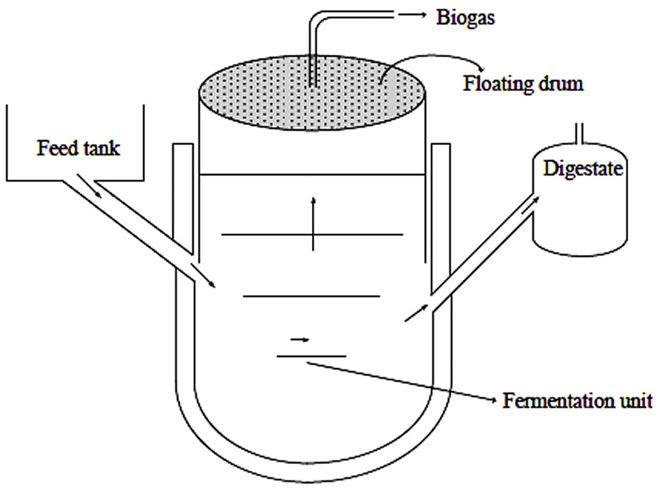


Fig. 12. Scheme of floating drum digester unit [83].

storage and release of gas, respectively. The weight of the drum applies pressure on the gas to make it flow through the pipeline to the place of consumption [85]. The floating drum produces biogas under constant pressure, but the gas volume changes [86]. Additionally, floating drum digesters produce more biogas than fixed dome digesters [87].

The fixed dome digesters and floating drum models are difficult to move after installation, thus portable units were developed such as plug flow digesters (see Fig. 13.). It is a sealed tubular structure usually made of soft plastic that may vary in size and thickness with an average length to width ratio of 5:1. The input and output of the tank are located at opposite sides and the device is inclined to the ground. The inclined position provides separation of acidogenesis and methanogenesis zones. Important advantages of this design are low cost and ease of transportation and maintenance. However, the digesters are relatively easy to damage [88,89]. Plug flow digesters have a constant volume, but produce biogas at a variable (relatively low) pressure. *Yimer* et al. [90] reported, that gas production was higher for a single layered and above ground geomembrane plastic digester than the fixed-dome.

Many different materials may be used for the construction of digesters as follows: plastics (PVC, PE), rubber, bricks and concrete, wood, and steel. For example, plastic is light and easy to transport, but the lifespan is relatively short. On the other hand, a construction made of bricks is almost everlasting, but needs more space and should be built underground [84]. *Jyothilakshmi and Prakashb* [91] presented a very simple small anaerobic digester for domestic organic waste utilization. They successfully carried out the process of decomposition of domestic waste in simply modified PCV cans with a volume of 30 L. From 1 kg of kitchen residues they obtained 0.17 m^3 of biogas at minimal cost. Biogas lab sets available on the market should be widely used to raise the awareness of the younger generation as to the importance of this renewable energy source [92]. Taking advantage of the vast amount of literature sources available, efficient home digesters can be built as long as the household is located in a warm region. Commercially available ready-to-use in home digesters are shown in Table 5.

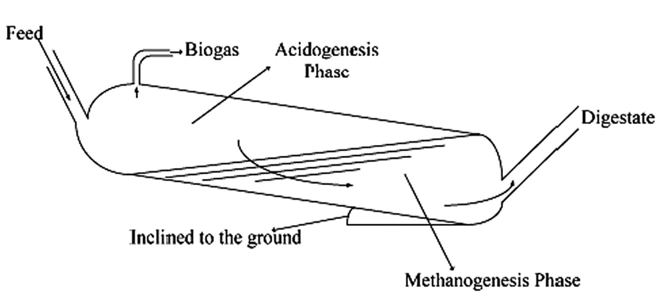


Fig. 13. Scheme of plug flow digester unit [84].

4. Physicochemical methods of waste utilization

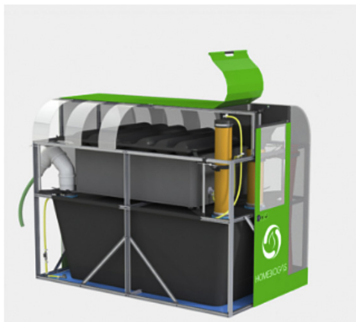
Compared with biological methods, physicochemical methods of waste utilization include waste treatment processes based on changing certain physical parameters such as temperature, pressure or the presence of oxidants or reducers in the environment without the use of living organisms. As a result, physical and chemical changes occur in the waste through which waste becomes less harmful and is even converted into useful products. Most desirable waste transformations include the reduction of mass and volume, the release of energy and its utilization, and the separation of other valuable components from the waste. In centralized waste management systems, thermochemical methods of garbage treatment such as combustion, pyrolysis and gasification are used. Biological or medical wastes sometimes are exposed to high pressure and temperature at the same time to ensure sanitary safety, this process is called sterilization. Obviously, it may be used to treat mixed MSW, too. The potential for using physicochemical methods of waste disposal at the household level will be presented below. The best option should provide the ability of disposing of all waste generated by household members with maximum energy and raw material recovery.

4.1. Combustion

Combustion is a process, which occurs between fuel and oxidant to produce heat. The fuel can be gaseous, liquid or solid. When ignited, chemical reactions of fuel and oxidant take place and finally the heat released from the reactions makes the process self-sustaining [100]. In connection with waste the most frequently used term is incineration. Recycling, composting, incineration and landfilling are the basis for waste management in developed countries. Incineration is carried out in controlled incineration facilities. Modern incinerators have tall stacks and specially designed combustion chambers. They must provide high combustion temperatures, long residence times, and efficient waste mixing while introducing air for complete combustion [101]. They are also equipped with efficient flue gas cleaning systems to meet emission limits. In the EU they are specified in the Waste Incineration Directive [102]. Types of waste incinerated include municipal solid waste (MSW), industrial waste, hazardous waste, clinical waste and sewage sludge.

Open burning means the combustion of unwanted combustible material (paper, wood, biomass, plastics, textiles, rubber, waste oils) without control of air flow to maintain adequate temperatures for efficient combustion. Smoke and other emissions are simply released into the atmosphere without passing through a chimney or stack. The emission of combustion products is not controlled, too. Additionally, no device to contain the waste is used to provide sufficient residence time and mixing for complete combustion [103] [101]. Open burning is widely used in many developing countries while in developed countries it may either be strictly regulated, or otherwise occur more frequently in rural areas than in urban areas. The open burning of organic waste usually is carried out on the ground. Air curtain incinerators, pits in the ground, open drums or wire mesh containers may be used, too [104].

Table 5
Different types of home anaerobic digesters.

Brand/ type	Picture	Size	Construction / Equipment	Biogas production	Details	Refe-rences
Home Biogas		127 cm high, 165 cm long, 100 cm wide; gas storage: 0.5 m^3	Device consists of: flexible digester tank; gas storage tank; gas pressure system with active gas filter; feeding sink and fertilizer outlet. All elements are set on a solid aluminium frame. Digester does not need any electricity supply and can be easily installed in the garden.	1 L of waste produces circa 200 l of gas; about 600 l per day	The average temperature should be above 17 °C. Biogas can be used the first time after 2–3 week since initial filling and then it is produced as long as new feedstock is added.	[93]
PUXIN		120 cm high, 120 cm long, 81cm wide fermentation capacity: 0.6 m^3 gas storage: 0.4 m^3	Device consists of a greenhouse made with sunlight sheet and metal supporting frame, stainless steel inlet and outlet part, an inside membrane digester tank and biogas storage system with desulfurizer and dehydrator.	About 500 l per day	Installation time: less than 2 h. Lifespan: over 8 years.	[94]
B-Sustain, floating drum		91 cm × 122 cm	Complete unit consists of: water seal digester, gas holder, inlet pipe (PVC), inlet box with cover, outlet pipe with elbow (PVC), gas outlet pipe with valve. Biogas single burner is included, too. Device is made of high quality material: Fibre Reinforced Plastic.	About 500 l per day	Lifespan: over 10 years. It can be relocated easily any number of times. Cow dung is recommended as the initial start-up. After initial feeding it takes 15 days–30 days before using the biogas for the first time.	[95]
Sistema Biobolsa®, plug flow	 10 m^3 of slurry unit	Reactor size: from 500 cm × 110 cm –1500 cm × 220 cm, From 4 m^3 to 40 m^3 of slurry.	System consists of: reactor with protective liner; input and output pipes with containers; biogas exit with pressure relief valve; and biogas line with humidity trap and filter to reduce H_2S. Reactor is made of linear low density polyethylene geomembrane of 1–1.5 mm thickness. Tubes and assemblies are made of PVC.	Depends on reactor capacity	The geomembrane can provide a total lifespan of the system above 35 years exposed to UV rays. Cooking stove, grill, boiler, motor adaptation, butyl tape to repair leaks and additional gas reservoirs are available, too.	[96]

(continued on next page)

Table 5 (*continued*)

Brand/ type	Picture	Size	Construction / Equipment	Biogas production	Details	Refe-rences
DEDKO Digester		Digester: 68.6 cm diameter and 106.7 cm tall. Storage balloon: 152.4 cm × 106.7 cm wall or ceiling space.	System consists of a tank for feeding waste, a balloon bag for storing gas and a stove to use biogas. The digester is completely sealed and can be installed on an apartment balcony. A 5 amp plug point with earth is required.	About 200 g per day	Installation time: less than 2.5 h. During installation, the digester is charged with starter bacteria. Waste should be crushed and mixed with water before placing into digester.	[97]
Flexi Biogas		Capacity: 4 m^3	Plastic bag made of PVC tarpaulin is the main part of system. Digester is light and portable. Usually it is placed in a greenhouse to increase temperature inside. Extra storage balloons are available.	Up to 1500 l per day	Installation time: about 8 h. Lifespan about 10 years. Daily input: 20–30 kg of organic waste	[98,99]

4.1.1. *Proper open burning*

Organic waste can be utilized by open burning. Examples of organic wastes that might be burned are crop residues, wood, prunings, timber residues or leaves [104]. However, suitable conditions should be met. Furthermore, open burning results in the removal of unwanted organic matter but without any energy or material recovery. It is the least desirable waste utilization method, but in some cases may be justified. Anyway, open burning of MSW including plastics, tyres, painted wood, used oils or paints are forbidden because they pose a serious threat.

If any of the biological waste utilization methods can be used, the organic waste can eventually be burned. Some regions in USA and Canada provide simple indications, how properly to burn organic waste to minimize harmful emissions or the risk of fire [105–108]. First, biomass should be thoroughly dried (at least 10 days) and stacked, covered if necessary to protect the material from moisture. Wet or dirty biomass will smoulder and create more smoke. Big trunks or stumps should be avoided unless they are chipped. Second, fires in the open must be organized during daylight hours with few exceptions. They cannot be left unattended. Appropriate distances from other materials that could ignite have to be maintained. It must be remembered, that fire suppression equipment must be present at all times during any type of open open-air burning. Basic equipment could include: garden hose, buckets of water and sand; shovel and rake.

Moreover, the allowed annual frequency of open burning and the amount of waste utilized in this way may be prescribed. Backyard burning can be also prohibited during certain periods of the year. Before making a decision on burning waste, national and local regulations should be carefully checked to avoid conflicts with the law.

Finally, burning may not be conducted during meteorological conditions such as high winds, temperature inversions and air stagnation. The following meteorological conditions should be considered before and during open burning activities: ventilation, rain, fog or snow, wind, temperature and relative humidity. Poor ventilation conditions are indicated by low wind speed and fog. Moderate winds increase atmospheric mixing, thus contributing to a better dispersion of the smoke and a lower risk of poor air quality. However, high wind speeds increase the risk of fires spreading. Therefore, the optimal wind speed for open burning is approximately 10 km/h. Additionally, predominant wind directions should be taken into account for safety reasons. Burning with snow on the ground or after rain may be safer from a fire safety perspective. On the other hand, biomass may be damp and burn inefficiently with smouldering. High temperatures and relative low humidity accelerate the drying rate on vegetative materials, like grass or leaves and foster the spread of fires.

4.1.2. *Emissions*

A comprehensive study of risks from waste burning, especially in developing countries, was made by *Forbid* et al. [109]. In general, the open burning of waste (especially toxic and hospital waste) causes many problems in relation to human health and the state of the environment. Air pollution from open burning irritates eyes and lungs and may cause coughing, nausea, headaches, and dizziness. Odours, reduced visibility, and pollution of ground and water are noticeable tens of kilometres from sources [110]. Long-term health effects due to exposure to smoke, which contains toxic gases and heavy metals include lung diseases, cancer, mental retardation and genetic disorders. Moreover, contamination of the environment with harmful smoke components affects wildlife and reduces biodiversity.

Lemieux et al. [111] analysed emissions of toxic organic compounds from open burning. Non-optimal combustion processes, which occur during open burning, result in high emissions of major

Table 6
Comparison between open burning of household waste and controlled combustion of MSW [112].

Contaminant	Emission from household open burning, μg/kg waste processed	Emission from MSW controlled combustion, μg/kg waste processed
PCDDs	38.25	0.0016
PCDFs	6.05	0.0019
CBs	424,150	1.16
PAHs	66,035.65	16.58
VOCs	4,277,500	1.17

air pollutants including volatile organic compounds (VOCs); persistent aromatic hydrocarbons (PAHs); chlorinated and polychlorinated biphenyls (CBs and PCBs); dioxins and furans (PCDDs and PCDFs); hydrogen chloride and hydrogen cyanide (HCl and HCN); carbon, nitrogen and sulphur oxides. Additionally, the emission of particulate matter (especially $PM_{2.5}$) and heavy metals is also an enormous problem. It is worth noting, that average pollutant emissions from open burning is very high compared with controlled municipal waste combustion (see Table 6.).

Additionally, *Akagi* et al. [113] studied emission factors from open burning of different biomass sources. It was estimated, that biomass burning is the biggest source of primary fine carbonaceous particles and the second largest source of trace gases on the global scale. Emission factors were accounted as an amount of substance emitted per kilogram of dry fuel burned using the carbon mass balance method. Emission factors from burning garbage are shown in Table 7 [113–115].

4.2. Sterilization with volume reduction

Sterilization is the process, which aims to destroy pathogens present in the processed material. Various techniques can be used for this purpose such as high temperature and pressure or radiation. The autoclave was invented in 1879 by the French microbiologist Charles Chamberlands. Autoclaving of MSW is a form of mechanical heat treatment - a process that uses thermal treatment connected with mechanical processing. The sorted/unsorted waste is sealed in an autoclave, which is a large, enclosed vessel that rotates to agitate and mix the waste. Steam is injected at pressure - raising the temperature up to 160 °C. The pressure is maintained for between 30 min and 1 h. Thus the waste is sterilized, by destroying microorganisms. Furthermore, the volume of waste is reduced by about 60%, and the moisture content significantly decreases, too [116]. Sterilization by autoclaving is frequently used in medical waste treatment [117–119]. This is the best practice for inactivating biological waste, defined as effectively killing pathogens completely [120].

Table 7
Emission factors from waste burning [113–115].

Component	Emission factor, g/kg
Carbon dioxide	1453
Carbon monoxide	38
Methane	3.66
Acetylene	0.40
Ethylene	1.26
Propylene	1.26
Methanol	0.94
Formaldehyde	0.62
Acetic acid	2.42
Formic acid	0.18
Hydrogen cyanide	0.47
Hydrogen chloride	3.61
Sulphur dioxide	0.5
Hydrogen	0.091
Ammonia	0.94
Nitrogen oxides as NO	3.74
Non-methane hydrocarbons	22.6
$PM_{2.5}$	9.8
Black carbon	0.65
Organic carbon	5.27

Recently autoclaving is also used in municipal waste management systems [76,121,122]. It can be applied to mixtures of MSW in areas where waste sorting is not implemented. It may also be a good solution to treat the rejected fraction from mechanical-biological treatment plants. This rejected waste stream mainly corresponds to the fraction rejected in the first mechanical pretreatment stage with a characterisation similar to the MSW [123]. Autoclaving makes the cellulose in all the organic matter break down into a 'mush' of fibre, also known as floc or fluff. Subsequently this product may be composted or combusted [118]. A system with autoclaving was also introduced as a method for utilization of post-consumer absorbent hygiene products including nappies for children, incontinence pads, and feminine care products. This waste is problematic, because it has complex composition and a significant moisture content. Moreover, it is biologically contaminated material. *Arena* et al. [124] suggested that the proposed utilization scheme, involving the use of the energy content of the cellulosic fraction of the waste to produce the steam for the sterilization stage, allows the loop of the process to be closed, improving its overall environmental sustainability. Organic material after sterilization in autoclaves is directed into a bubbling fluidized bed gasifier in order to produce syngas for energy. In 2016 *Holtman* et al. [121] investigated a pilot-scale steam autoclave system for treating MSW for the recovery of organic matter. An autoclave with 1800 kg per batch capacity reduced municipal solid waste to a debris contaminated pulp product that is efficiently separated into its renewable organic matter and non-renewable organic content fractions using a rotary trommel screen. The renewable organic matter can be recovered at nearly 90% efficiency. Energy requirements averaged 1290 kJ/kg material in vessel, including the amount of free water and steam added during heating. Additionally, steam recovery can recover 43% of the water added and 30% of the energy, supplying on average 40% of steam requirements for the next process. Steam recycling from one vessel to the next can reduce energy requirements to an average of 790 kJ/kg. Autoclaving allows recovery of a good quality, safe fuel even from "waste from waste", but it requires much energy and is quite complicated. Implementing solutions with a closed water cycle and energy recovery from waste would make it possible to obtain a less expensive process.

4.2.1. Available solutions

There is lack of information about source autoclaving of waste in the home. However, Marine Assets Corporation proposed a simple solution to produce Refuse Derived Fuel (RDF) from raw waste in households. MAC Garbage Converter Container can reduce the volume of waste by over 70% with a weight reduction (depending on original moisture content) of around 50%. Further volume reduction (up to 60%) can be achieved by pelletizing the RDF [125]. These pellets can be used as a fuel, because they usually have a high calorific value.

The whole process consists of several stages (see Fig. 14). First, raw waste, either loose or in bags, is placed inside the drum of the converter. The garbage is then macerated and crushed by the rotating blade inside the drum and the resultant friction created causes the temperature inside the process to increase rapidly. Once the temperature reaches 100 °C the moisture content of the garbage is released as steam. This steam is then drawn off from the process using a vacuum pump and is condensed back into water for either disposal into the sewerage system, used for irrigation or filtered for use in other processes. After that, the temperature rises to just over 150 °C and is maintained for 5 min in order to sterilize the contents and destroy any pathogens that maybe present. The latent heat that is generated from the friction of the process now aids the final evaporation stage. The moisture is again drawn off from the contents, condensed and the product cools down naturally. The total process time is around 25 min. The result is a cool dry sawdust type material known as RDF [125].

Even if the production of RDF from household waste can significantly reduce the initial weight of garbage, it is still only a partial solution of the problem. The advantage of the concept is that there is no need to sort waste. In fact, it can be simultaneously disadvantageous, because the composition of RDF is the same as that for raw waste, just without water. Adapting this technology in countries, where combi boilers for solid fuels are popular such as Poland, could have dramatic consequences. Burning RDF in a house would result in a high emission of toxic substances, which are emitted from the combustion of plastics. Unfortunately, it would be expected that people would do this. On the other hand, a garbage truck could receive RDF instead of raw waste and deliver it to the waste incineration plant. Sanitary safe waste can be stored longer in house. Additionally, the decreasing amounts of waste could reduce the frequency of garbage collection by garbage trucks by a half, which is definitely a better solution than the traditional waste collection model. However, the waste to RDF conversion process needs electricity and further research should be done to check the real CO_2 foot print of this solution. Such research on an industrial scale plant was done by *Arena* et al. They suggested, that glass and metal should be removed from the waste directed to RDF production. Additionally, they recommended low emission limits for pollutant concentrations in the flue gas from the combustion of RDF [126]. In general, the production of RDF in a single household does not seem to be the optimal option, because it does not provide a real solution of waste utilization or parts thereof. Volume and mass of garbage is reduced, but it still has to be picked up by a centrally organized system. However, it may be a promising tool in sparsely populated areas, where the transportation of garbage is difficult and thus this could take place less frequently.

4.3. Pyrolysis and gasification

Pyrolysis is a process of the thermochemical decomposition of organic material at high temperature into gas, oil and char. Compared with combustion, pyrolysis occurs in the absence of oxygen. Pyrolysis with a small amount of oxygen present is sometimes called “quasi-pyrolysis” [127]. Gasification in turn is a process that takes place in an atmosphere poor in oxygen and this produces char and synthesis gas, and sometimes it is considered as a type of pyrolysis or sometimes pyrolysis is considered as a type of gasification [128]. Nowadays, this process is getting attention for its flexibility in generating a combination of solid, liquid and gaseous products in different proportions just by varying the operating parameters, e.g. temperature, heating rate, reaction time. It also gives the possibility of transforming materials of low-energy density into high-energy density fuels [129,130]. This process would be favourable for utilizing waste at home, because any material containing organic carbon can be used as a feedstock including food waste [131], biomass [132], plastics [133], tyres [134,135], textiles [136], paper [137] etc. Moreover, even multimaterial packaging can be used [130,138]. This mean that more than 80% of household waste could be successfully treated on-site. Furthermore, even the addition of glass or metal would not be a serious problem [139] because they would just appear in the solid residue from the process.

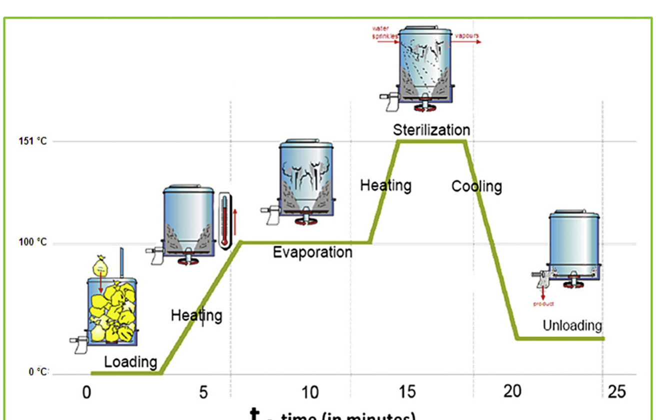


Fig. 14. Waste processing in MAC Garbage Converter Container [125].

Many researchers have studied the pyrolysis of mixed municipal waste in laboratories and some solutions are available on an industrial scale [140]. A large variety of different types of reactors have been proposed. However, there is very limited information about pyrolysis-based waste management systems at a domestic level. The basic limitation concerns the effectiveness of heat transfer. One of the most important parameters of pyrolysis is temperature. A sufficiently high temperature allows the decomposition of the organic material into other valuable products. Temperatures in the range 300–800 °C are used depending on the products desired. In general, higher temperatures promote the formation of more volatile compounds and lower yields of solid char. Uniform heating of the feedstock is obtained in the laboratory using small samples of particulate material. Another way is the use of fluidizing bed reactors, rotary kilns or stirrers to mix the waste sample. However, in home use the most preferable arrangement would be a fixed bed, because it is simple and easy to use, but the heat transfer is limited und ineffective for large portions of feedstock.

4.3.1. Available solutions

Available small waste management systems using thermochemical processes are designed for treating biomass, and they are still too large to be suitable for simple home use. In the case of the Benev Co continuous pyrolyser, this device heats waste biomass in the absence of oxygen to reduce it to charcoal and combustible gases. It operates at temperatures from 300 to 900 °C. The device is designed so that it can be used in the field, mounted on a trailer (see Fig. 15.) or placed in an open sided shed [141]. The main aim of the process is waste biomass utilization connected with char production in farms. It could be especially useful for crop residues as an alternative to burning them. Syngas can provide the energy which is required for the pyrolysis. The char can be used as a good-quality fertilizer. Biochar increases the retention of nutrients and water in soil and provides habitats for symbiotic microorganisms, thus crop yields increase. Moreover, biochar can also fix carbon for many years due to the strong resistance of its aromatic carbon structure to biological decomposition [142,143].

Biogreen® applied thermochemical processes to utilize waste. Their device can handle biomass, sewage sludge, plastics and tyres [144]. However, this proposition is definitely too big and complicated for a simple domestic application, but it would provide interesting solutions for small communities or as a business idea.

Galloway [145] patented a gasification chamber for converting household waste into energy. The gasifier comprises a waste

Fig. 15. Continuous pyrolyser for biomass utilization [141].

receptor module with a rotary drum, steam reforming for converting domestic waste into synthesis gas and a fuel cell for converting the synthesis gas into electrical energy. The device has a vent, electrical, gas, sewer and water connections. Mixed household waste in bags can be placed in a rotary drum. Glass and metal will not melt, they can be recovered as a sterilized material. The automatic cycle of waste processing lasts about 90 min, and all carbon-contained waste is converted into synthesis gas. The waste inside the drum is rotated slowly and heated. The vapours obtained are directed to the hotter interior, in which their temperature is raised to 900–1050 °C and they react with the steam from the waste and recirculated syngas. The hot syngas is then cooled in two heat exchangers and cleaned. This gas consists mainly of hydrogen (62.7%), carbon monoxide (18.6%), carbon dioxide (10.7%) and methane (7.6%) and can be used in variety of high temperature fuel cells. However, some contaminants such as carbonyl sulphide, hydrogen sulphide, carbon disulphide, hydrogen chloride, and polychlorinated organics were found, and they should be removed before the syngas is used. A suitable cleaning system was proposed, too. Finally, the energy generation module uses a fuel cell to convert syngas into electricity, steam and heat. However, this system operates at high temperatures, which can be potentially dangerous and it requires expensive, high quality materials. Additionally, special equipment (fuel cells) are necessary to utilize the fuel obtained.

In contrast, *Jouhara* et al. [146] designed a low-temperature pyrolysis chamber, which is able to utilize all household waste without any pre-treatment. The unique heat pipe based system ensures uniform heat distribution without moving the waste. This is an important advantage when compared with other systems, which usually need mixing, which increases the demand for energy. The whole integrated process lasts 7 h (5 h - drying, 2 h - pyrolysis and combustion of char). This takes place in the Home Energy Recovery Unit (HERU), which can be easily connected with a boiler either as a stand-alone domestic water heating system or as a pre-heater. Pyrolysis results in the decomposition of any material containing carbon, both organic and inorganic. The waste tested consisted of a variable mix of bread, lemon slices, onions, apples, carrots, mangetout, peppers, cabbage, chicken breasts, potatoes, pancakes, courgettes, rice, cardboards, plastics, papers, metal cans, nappies, latex gloves, plastic bags and plastic bottles. Some of this waste, such as nappies or plastics, are very problematic for most of waste management systems in domestic use. The initial feedstock and char after pyrolysis are shown in Fig. 16.

About 25% of the initial weight of waste was lost during the pyrolysis as a gas and liquid (which were collected). The biochar has a high carbon content and a heating value of about 17 MJ/kg. At the end of the pyrolysis process oxygen was introduced into the chamber, which led to ignition of this char. The heat generated during combustion was recovered through the means of a heat exchanger to warm water, which was stored in a tank. The tests showed that in order to treat 7 kg of MSW 5.5 kWh of electricity was required; approximately 0.78 kWh per kg of waste was consumed. However, the coefficient of performance (COP) could be defined as follows:

$$COP = \frac{Q_{lat} + Q_{comb}}{E_h}$$

where:

Q_{lat} (kWh) is the latent heat that was given to the water flow in the heat exchanger when condensing the moisture that has departed from the waste during the initial stage - drying.
Q_{comb} (kWh) is the heat that was recovered to the water flow in the heat exchanger from the exhaust during the char combustion stage.
E_h (kWh) is the electrical energy that was consumed by the electrical heater during the whole waste treatment cycle.

For average MSW (moisture content ~20%) the COP was estimated at around 4.5. In practice, about 4.5 times more of the heat energy can be recovered than the electrical energy used to heat the unit. The relation between unit COP and the moisture content is

Fig. 16. The feedstock for pyrolysis in HERU and char obtained.

shown in Fig. 17. It can be observed, that even waste with high moisture content (above 50%) still can be treated efficiently.

The consumer can utilize all household waste and at the same time gain energy that can be easily used at home. Moreover, the composition of solid and liquid products was studied and they do not pose a threat to environment or people [146,147]. Fig. 18 shows the prototype unit.

5. Discussion

Available waste management systems, which can be implemented domestically, have been described above. Each of them has advantages and disadvantages, thus a decision to choose a particular solution should be preceded by comparing all of the systems for specific features and parameters. Environmental and techno-economical aspects will be studied.

5.1. Environmental aspects

Environmental aspects must include the effectiveness of solving problems with waste, and potential hazards arising from the application of each system. The more efficient the system is in waste disposal, the more desirable it is. Nowadays, energy sustainability is extremely important, thus the most favorable systems should offer possibility to obtain energy without overexploitation of the environment [148,149]. However, the by-products and emissions should be at least harmless and preferably useful.

The primary purpose of any waste management system is to reduce the amount (mass and volume) of waste generated. It involves mostly the removal of moisture and the treatment of compounds of carbon and other elements. As a result, mainly CO_2 and H_2O are often emitted into the atmosphere. The least weight reduction occurs during anaerobic digestion - only about 10 wt % of the slurry is converted into biogas [97]. In general, biological waste management methods provide partial mass and volume reduction and only in the case of organic waste. Moreover, sometimes even some types of organic waste cannot be processed to avoid damage to the systems. For example, huge amounts of waste meat should not be composted and acidic fruits are undesirable to anaerobic digestion since the optimal pH range is between 6.5 and 7.5. A significantly greater weight reduction has been found in the thermochemical methods of waste disposal, especially as it is reported in the cases of pyrolysis and gasification. It is particularly important that we can process different waste (organic and inorganic) in this way, so that the total waste stream reduction is much clearer. Open burning sometimes is acceptable just because of a quick reduction of the quantity of waste.

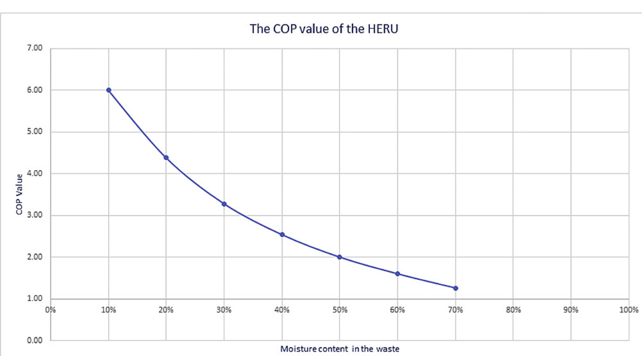


Fig. 17. The COP value of Home Energy Recovery Unit.

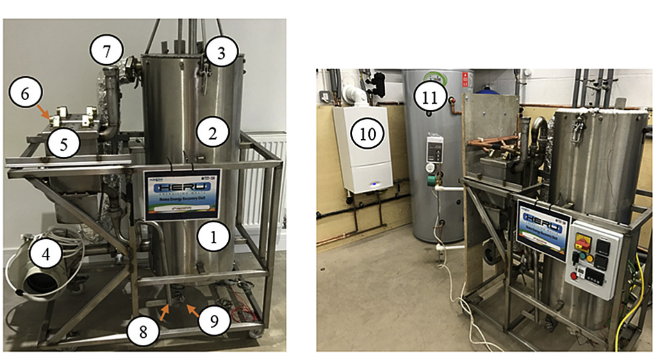


Fig. 18. The HERU system: 1. pyrolysis chamber; 2. Combustion chamber; 3. Compression lid; 4. Air blower; 5. Heat recovery; 6. Hot water feed; 7. Gas vent to atmosphere; 8. Liquid flush to drain; 9. Ash flush to drain; 10. Boiler; 11. Water tank.

The second important factor of effective waste disposal methods is the removal of pathogens for which garbage is an attractive environment. Basically, this condition is fulfilled for all methods analysed. In this context, sterilization deserves special attention, which by, definition, focuses on ensuring the sanitary safety of the waste processed. After this process pathogens cannot be found in the material.

When choosing a waste management system for a household, the way in which the by-products will be used should also be considered. It is true that compost and digestate can be used as fertilizer, but the user must be able to use it easily and quickly, e.g. in the garden. If a householder does not grow any plants, a serious problem with the disposal of the resulting residue may appear. Especially in the case of anaerobic digestion it can be embarrassing, due to the rather unpleasant odour of the digestate. In the case of autoclaving, the resulting RDF should be sent for incineration under suitable conditions. Again, pyrolysis and gasification combined with combustion of the resulting products may be considered as the most desirable method since the amount of residues is minimal and substantially harmless. It was proposed that they could be easily discharged into the sewage system [147]. Considering the issue of by-products from waste processing, it is impossible not to mention air emissions. The large amount of harmful substances emitted by the irresponsible uncontrolled combustion of waste is the reason why it is largely limited. It is worth mentioning that the combustion of low quality solid fuels in developing countries is a source of heavy pollution that causes numerous health problems. Thus, in these areas, biogas (from anaerobic digestion) combustion for the purpose of preparing meals is promoted. This is definitely a cleaner fuel. The use of simple hydrogen sulphide filters and moisture traps can further improve the biogas quality. In highly-developed countries, pyrolysis is a much more interesting solution. This process runs without oxygen, which prevents or significantly reduces the emission of harmful pollutants, even when the feedstock contains plastics, textiles or rubber. Pyrolysis products can be considered as good quality solid, liquid and gaseous fuels, which can be subsequently combusted.

However, most waste is a potential source of valuable raw materials and energy. Thus, the most desirable are those utilization methods, which use this potential. Material recovery is usually very complicated, therefore at a domestic level energy recovery is favorable. It is estimated, that the energy content in typical MSW is about 9–14.5 MJ/kg [1]. If energy from waste produced by every person in the EU could be recovered with 50% efficiency it would give from 600 to 950 kWh of free energy per capita annually. Composting and open burning of waste do not provide any energy recovery. Because it is used by microorganisms or released into the environment, from the consumer's point of view it is lost. Energy recovery is provided by waste management systems based on anaerobic digestion, pyrolysis and gasification combined with combustion of evolved products. Organic waste produced in households after conversion into biogas can cover the energy requirements for cooking. Moreover, waste management systems based on pyrolysis provide an opportunity of producing several times more energy than was consumed by unit. Using this energy to heat water makes the investment very attractive economically.

5.2. Techno-economical aspects

Factors, which must be considered in the process of choosing a suitable waste management system for domestic use are: investment and operating cost, space and time consumption, ease of use and maintenance; any special requirements such as additional infrastructure should be taken into account, too. Moreover, the ability to match the size of the system to the amount of waste generated is an important advantage, thus most of the systems are available in several sizes or can be customized according to need.

Obviously, the cheapest way to treat waste is combustion. This is the reason, why many people burn their waste despite numerous threats associated with it. However, waste incineration on an industrial scale is a complicated and expensive process to ensure compliance with emission limits. Composting using simple bins is also inexpensive, but the purchase of an automatic composter will be a large investment. Additionally, usually this device uses electricity. On the other hand, the price of systems based on anaerobic digestion vary quite widely depending on the materials and construction of digester. Those systems also need special devices, which can utilize the biogas produced, such as stoves, lamps, engines etc. Probably the largest investment is connected with the application of thermochemical waste management systems. However, it should be emphasized, that energy recovery reduces energy costs for the home. Therefore this investment will be returned within a reasonable time and then it will start to generate profits. Moreover, the system proposed by *Jouhara* et al. [146] runs using a standard 13amp heater with no additional infrastructure for home.

Space availability can be a limiting factor for traditional biological waste treatment methods, because the sizes of composters or anaerobic digesters may be large. Usually they are located outside and the user needs a garden for easy disposal of by-products (fertilizers). Therefore, in households that do not have their own garden, the use of these methods can be very difficult or even impossible. On the other hand, systems based on thermochemical methods usually can be implemented indoors even in small houses.

In most systems considered, waste should be sorted and so the time and effort put into preparing the waste for disposal should be taken into account. The amount of time spent on system operation and maintenance is not large and usually limited to waste crushing and its placement in the device. Sometimes it is necessary to periodically mix the contents. In addition, by-products should be regularly removed and utilized. The HERU seems to be the system that requires the least commitment to service, because wastes do not have to be sorted and resulting residues are removed automatically to drain. It must be mentioned, that microorganisms used to process waste in biological methods need a long time to decompose the organic matter. This can be a few days (automatic composters), about two weeks (from the initial loading of the digester to the first biogas) or even several months (traditional composting). Thermochemical methods provide faster waste utilization. Usually processes do not exceed a few hours. For example, the waste processing cycle through gasification proposed by *Galloway* [145] takes only 90 min; the pyrolysis based cycle at 300 °C lasts about 7 h [146].

6. Conclusion

The weakest points of centralized waste management systems are the transportation of waste (often long distances with high frequency) to large processing facilities, and the complex waste separation systems required. Both of them are energy intensive, thus contribute to the deepening of climate change. Additionally, they increase the costs borne by the public.

Garbage treatment in households offers the opportunity to eliminate the inconvenience of extended waste management systems. At a domestic level several waste management systems may be applied depending on available space, time, and the financial resources of the householders. Unfortunately, most of them (composting, anaerobic digestion, open burning) allow the processing of only organic waste.

The most common waste management system in domestic level is composting. Various techniques and equipment are available; from the cheapest home-made boxes to complex but relatively expensive automatic composters. Composting provides the opportunity of returning the nutrients contained in the biomass back to the soil. The consumer can obtain good quality fertilizer. However, it needs time. Furthermore, the energy contained in the waste is consumed by microorganisms. From the perspective of householders it is lost.

Anaerobic digestion offers energy recovery from biogas combustion, but some investment must be made and there is a need for a relatively large space for mounting the digester. It can also be introduced easily only in warm regions, because microorganisms require an appropriate temperature. In moderate and cold climates the digester has to be heated, which generates some complications. As a second product, the householder gets valuable fertilizer; the nutrients from organic waste can be reused.

Open burning of mixed waste is prohibited in modern societies, because it poses a serious threat to the environment and human health. In special cases biomass burning may be justified, when appropriate conditions are ensured.

An interesting alternative to commonly used biological methods is thermochemical waste utilization, especially low-temperature pyrolysis. Obviously, buying a suitable system such as HERU can be an investment, but it provides many advantages in the long run:

- The unit runs with no additional infrastructure for the home.
- The system is easy to operate and maintain
- The unit size may be adjusted to the size of the household
- General waste does not need to be sorted. Separation of waste and metal could be desirable but not necessary.
- Waste can be processed very quickly (in hours) using a small area on site (in house) – no collection and transportation system is needed.
- Pyrolysis transforms waste from a hazardous state to inert and valuable fuel. Moreover, after their combustion the user gains the best possible final product – energy that can be easily utilized for water heating.
- Process residues do not pose a threat for human health or environment.

Considering the advantages and disadvantages of particular waste management systems, low-temperature pyrolysis combined with the combustion of the fuels produced is the most modern solution with numerous advantages for consumer, community and environment.

In the age of demographic explosion centralized waste management systems become insufficient. The demonstration of available solutions and the realization of the benefits of waste processing at domestic level will cause many people to take responsibility for their own garbage.

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