Sludge composting

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1. Introduction

Sludge composting aims at biologically stabilizing sludges while controlling pollution risks in order to develop agriculture or other end use outlets exploiting the nutrient or organic value of sludges. It can be applied either to non-digested sludge (e.g. Italy, France) or to digested sludge (e.g. the Netherlands). Composting involves aerobic degradation of organic matter, as well as a potential decrease of the sludge water content, the efficiency of which depends on the composting process. Since organic substances and nutrients, such as phosphorus and nitrogen, are in demand by farmers, compost, rich in organic nutrients, is considered a valuable soil improver. Sludges composted for agricultural end use are therefore of value to secondary markets. In the case of sludges treated by incineration, waste sludges can be composted as a pre-treatment to decrease the water content, thus increasing the efficiency of the incineration process. Nevertheless, it may be too expensive to first compost and then incinerate the sludge. Besides, some of the organic matter will decompose, thus limiting the increase of the calorific value linked to sludge drying. 6.1. The Influence of Variable Conditions in Defining the Composting Process Sludges can be composted if they have sufficient organic matter as well as a relevant water content. In order to effectively compost materials, certain nutrients are required, including nitrogen and phosphorus, as well as proper moisture and aeration levels that facilitate and enable, after mixing with a co-product, the sustainability of microorganisms. Since liquid sludges have a high water content, they alone are not sustainable mediums for micro-organism growth. However, they can be composted when used in relevant quantities in a mixture with other highly fermentable organic wastes possessing a lower or a deficient water content. Sludges with a water content greater than 15% are easily co-compostable, particularly when mixed with bark or other structuring materials making the compostable mixture porous. As a general reference, the water content of a compostable mixture of organic wastes should be around 55% while the organic matter content should be greater than 70%, facilitating effective bio-degradation. A high moisture content above 60%, reduces the temperature, porosity and thus the oxygen concentration while a low moisture content, below 50%, could limit the rate of composting. At values of 10-15% the bacterial metabolism generally ceases to function. Bacterial activity is also influenced by pH, with the optimal values being between 5.5 and 8. A balance of the nitrogen and carbon content is necessary for the proper growth of micro-organisms. The carbon to nitrogen ratio (C/N) of the mixture is therefore commonly used to define the optimum functional conditions. Although values ranging between 25 and 30 are recommended, the types of molecules concerned must be evaluated when establishing the ideal ratio. Structuring composting conditions and mixture ratios naturally depend on the types of wastes to be treated as well as the quality specifications set for the resulting compost. For example, the processing of organic materials would be different if the goal was to incinerate the end product, thus demanding that the water content of sludges should be reduced, than if the goal of the composting process was to produce a soil improver, as defined by a particular agricultural outlet, which would therefore require that specific nutritional and structural properties should be present in the end product. Different ratios of wastes and different processing policies would have to be implemented under the constraints of each programme. Therefore the types of sludges to be treated, the quantitative/qualitative constraints for incorporating them into a composting process, and the efficiency of the composting biodegradation process itself, depend on the end product specifications as defined in any given project.

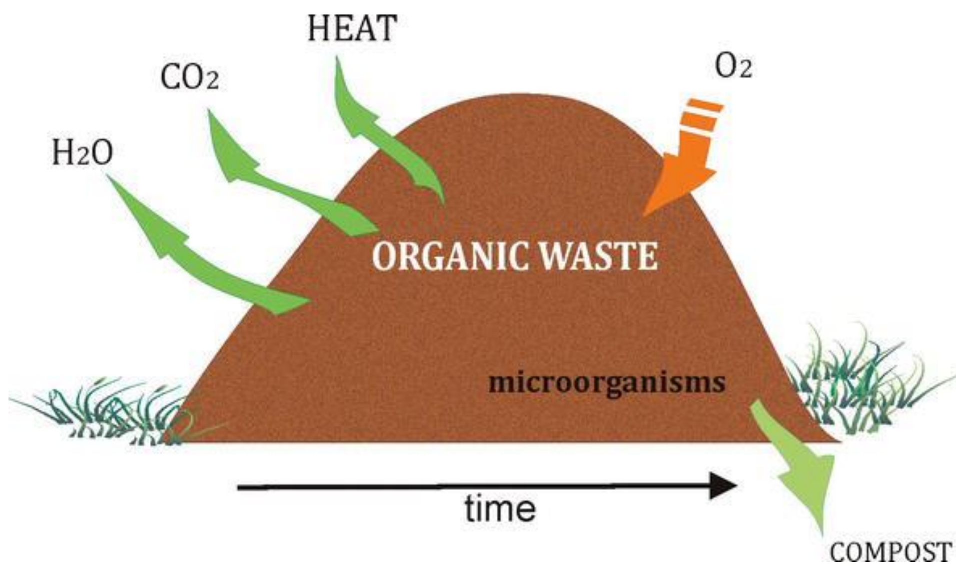

Figure 1. Simple scheme of the composting process where a pile of organic material undergoes the transformation to compost by the action of aerobic microorganisms resulting in the production of heat, carbon dioxide, and water vapor.

If, for instance, a compost end product targeted for an agricultural outlet is considered, many market and regulatory constraints will have an impact on the definition of the composting process itself. For example, although organic pollutants such as the pesticides, PCB, HAP, PCDD, PCDF do not have regulatory limits at European level because the concentration of these contaminants has proven to be low, the contrary is true for the heavy metal content in composts. The heavy metal content of the final compost product is critical. The end product standards must meet the specifications defined by local and national legislation. Obviously, since the materials are composted at a temperature level sufficient to kill pathogens, the risk of pathogenic problems is minimised, an advantage supporting the processing of organic materials by composting over other treatment methods. In addition, microbial competition during composting also favours pathogen reduction. Market conditions also have an impact on the process design of a compost system. In addition to their inclusion in some national regulations, aesthetic contaminants such as plastic, glass, metals or stones are undesirable because they may limit the marketing potential of the final product. In the case of agriculture end use composts, it must not only support local vegetation growth, it must also meet both the qualitative and quantitative demands of the local market; the compost end product must be nutritionally balanced to the local soil demand and produced in quantities which do not exceed the outlet application potential. For example, to utilise the final compost for a soil substrate application, the nutrient and salt content must be low while the water retention capacity must be sufficiently high, thus meeting the necessary water/aeration requirements of specific types of vegetation. The pH of substrate also becomes an important criteria in designating the type of vegetation to be sustained and must be accounted for in compost end quality specifications. Whether designated as a soil improver or a substrate application, decomposition of organic material must be sufficiently high. In addition, the process of producing a quality end-product must ensure germination and sustainability of plant growth and ensure that no germination of foreign seeds occurs as a result of the compost. The example of composting sludges as a pretreatment method for incineration is technically appealing because composting results in both mass reduction and decreased water content, thus providing a more efficient waste stream for incinerators. A financial and market analysis must, however, be completed to validate the viability of this option: is composting in itself viable, and is the level of bio-degradation necessary to justify the incineration of pre-treated, composted sludges over the incineration of raw untreated sludges?

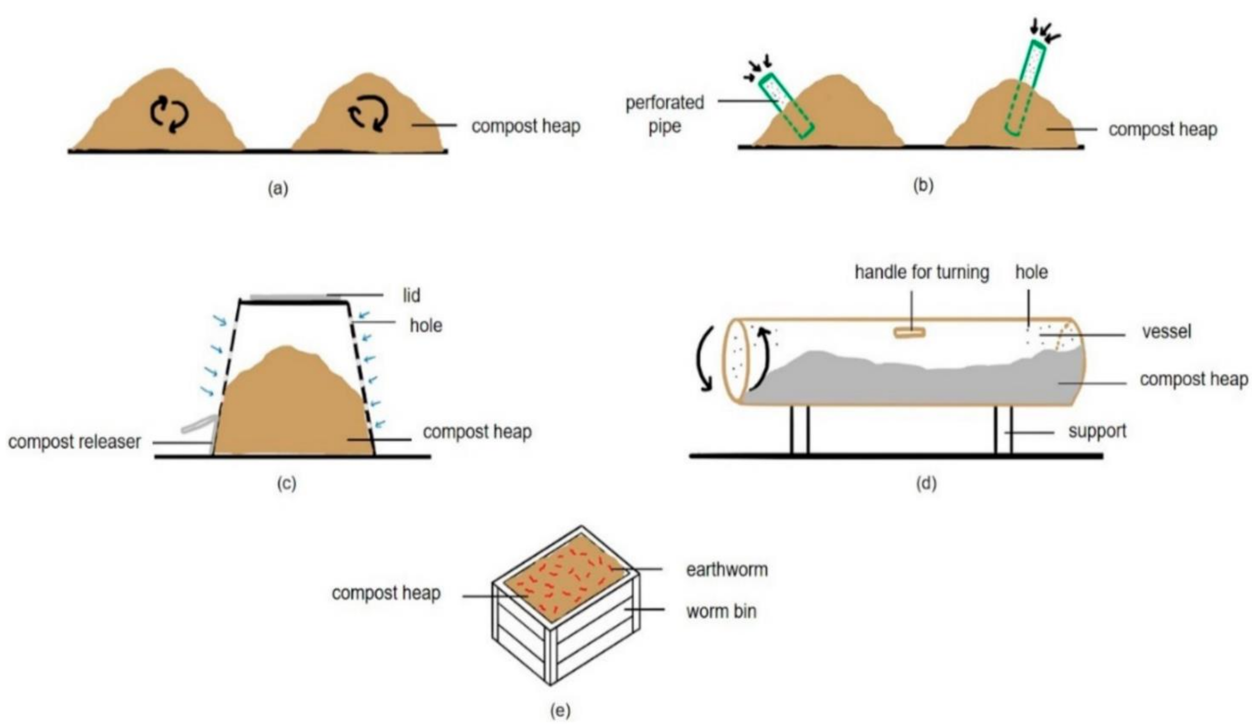

Figure 2. (**a**) Windrow composting; (**b**) passively aerated windrow composting; (**c**) bin composting; (**d**) in-vessel composting; (**e**) vermicomposting.

2. General Description of the Process of Composting and Plant Conception Factors

The process of composting is based on aerobic degradation of organic matter, under variable conditions as described above. In essence, the activity of microorganisms causes both an increase in temperature, hence the pathogen destruction, and a release of energy, CO_2, H_2O, NH_3 and other gases, while consuming oxygen. The rate of the bio-degradation process can thus be controlled by regulating aeration, moisture content and mechanical processing of the material. For instance, the composting process could be controlled and accelerated by:

- Forced aeration, which provides sufficient oxygen to meet demand, while providing an odour control mechanism;
- Mechanical turning of compost, which contributes to the mixing and the increased aeration of the material.

A particular market demand may also be accommodated by mechanical screening to a defined particle size. In developing an actual plant to process organic wastes and sludges into compost, the following system development and costs must be taken into account:

- Waste reception and storage areas;
- Mechanical mixing system to be applied;
- Storage area for the compostable mixture, before aeration: Note, this step is not compulsory but can be interesting for the flexibility of the operation;
- Fermentation/ bio-reactor area. Note: reactors, containers, lockers, tunnels, channels as well as their process retention times, ranging from 10 days to five weeks, are defined in relation to the objectives of the programme;
- Storage area for compost maturation and final stabilization of the product;
- Mechanical screening systems: the size of the screen depends on the local utilization of the compost; the fine fraction can be stored, commercialized or eliminated whereas the raw fraction can be recycled as a structuring material for composting;
- Control of variable local facility demands such as: sewage water, odours, dust control and control of other nuisances such as noise, flies, and the potential of foraging animals. A wide range of composting systems exist world-wide, however they tend to be classified into several general categories:
- Open composting systems
    - static pile : - natural ventilation - forced aeration with suction or blowing in windrows or in silos
    - turned pile : - natural ventilation - forced aeration in corridor silos, in windrows or in tabular piles
- Closed composting systems functioning continuously or periodically with forced aeration rotating horizontal reactors (tube)
    - static vertical reactor (tower)

- ❖ in-vessel systems (boxes)

The choice between the different systems depends on the technical and economic parameters. In general, when composting sludge, process control, reduction of labor, and sensitivity to weather generally necessitate forced aeration technologies.

3. Advantages/Disadvantages of Composting Sludges

- **Advantages**

Composting offers several advantages in comparison with other sludge treatment methods.

In comparison with the direct application of non-composted sludges in agriculture for example, composting allows:

- A reduction in the volume of materials to be transported for distribution in agricultural fields;
- A facilitation, with respect to sludge, of storage and use in places and at times far from those of production;
- A facilitation of the spreading process due to the lower water content of the product;
- Control of compost material specifications, which results in a well-defined, stable end product composition with the potential of improving the soil humus layer and nutrient levels;
- Control of nutrient content as defined by application and vegetation standards;
- Product hygiene control before agricultural application;

- **Disadvantages**

- The treatment cost is higher than simple direct raw sludge application;
- Aeration consumes energy;
- There is a need for an outlet market for the compost end product; competitive soil improvers exist;

The need for mixing sludge with other materials in order to obtain an optimal C/N ratio, can be considered either as an advantage when bulking agent is another waste to be treated (complementarity of treatment) or as a disadvantage when this bulking agent has to be bought.

4. Different Composting Technologies

Organic waste management is a major global challenge. It accounts for a significant portion of waste that ends up in landfills, where it gradually decomposes and emits methane, a harmful greenhouse gas. Composting is the most preferred method for managing organic waste, as it applies to the masses, may not require significant areas, and of course, is capable of reducing the rate of the production of waste, while at the same time, producing valuable by-products, in the form of compost with potentially reducing the amount of greenhouse gas emissions, if done properly.

4. Manual Technology

In manual composting, the process is operated by hands and through mechanical means without automation. Five common types of manual composting methods: windrow, passively aerated windrow, bin, in-vessel, and vermicomposting methods, are described.

4.1. Windrow Composting

Windrow is the general term for the use of an elongated pile of stacked raw organic materials for composting, as shown in **Figure 1**a, and represents the most basic composting method. The method is suitable for treating large volumes of organic waste and producing large volumes of compost [1]. However, due to its simplicity, it is one of the most commonly adopted manual composting methods, especially for domestic composting.

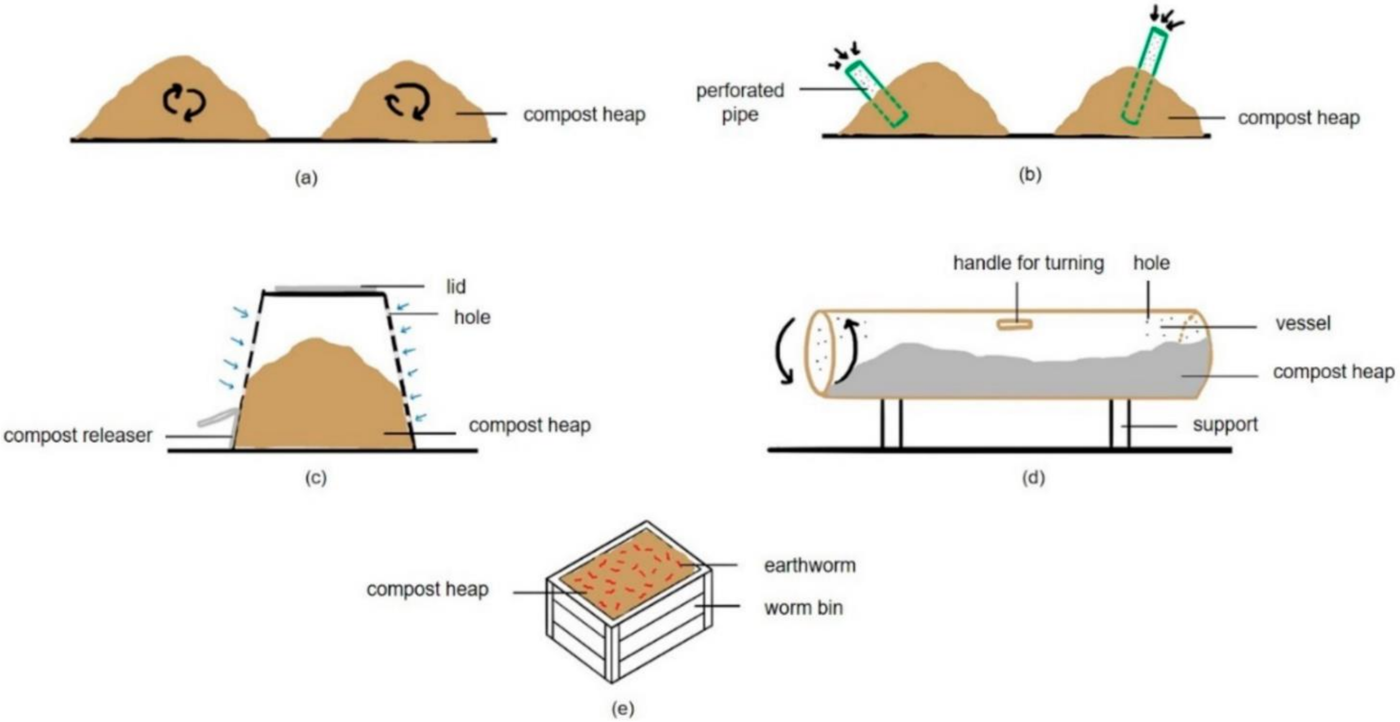

Figure 1. (**a**) Windrow composting; (**b**) passively aerated windrow composting; (**c**) bin composting; (**d**) in-vessel composting; (**e**) vermicomposting.

Due to the sometimes-large windrow compost heaps, air-filled porosity needs to be maintained throughout the compost heaps, and aeration becomes a very important issue [2]. Commonly, the compost heaps are mixed with structure-giving materials, such as twigs, cardboard, or hard vegetables, to allow air to pass throughout the compost heaps effectively and oxygen, which is consumed by the microorganisms, to be replenished [3]. Particles in the compost heaps may also be reduced, either manually or automatically using a grinding machine, to increase surface area and hence, allow faster decomposition. In any case, the compost heaps need to be manually or mechanically turned [4] to re-establish porosity over time and re-introduce air and oxygen back into the compost heap. Additionally, turning also allows the rotation of compost materials, such that the exterior of the heap can be rotated to the interior of the heap and allow the microorganisms to inter-changeably decompose different parts of the heap.

The obvious benefits of windrow composting are that it requires low funding and maintenance [5]. However, it needs an amount of space to accommodate the compost heaps, which need to be spaced out from one another, for an effective composting process. Composting using the windrow method also consumes a relatively longer amount of time to produce good compost and requires manual labor for reducing the particle size to the appropriate size and turning.

4.2. Passively Aerated Windrow Composting

As shown in **Figure 1**b, passively aerated windrow composting is an improvement over simple windrow composting by introducing perforated pipes to allow convection airflow throughout the organic compost heaps, particularly at the center of the heaps [6]. Different pipe configurations can be adopted to bring oxygen to the microorganisms, with the use of the pipe eliminating the need for frequent turning. However, it is important to introduce the right air-filled porosity before putting the organic waste in the compost heap by appropriately reducing the compost particles as well as thorough pre-mixing. Insulation of the compost heap with finished compost may also be done to ensure thermophilic temperatures reach the outer layer of the compost heap.

The main benefit of this technology is that it does not require any turning [7], which subsequently allows the compost heap to retain its heat effectively while still being able to supply the much-needed oxygen to the microorganisms via the passive aeration system. Consequently, the method may result in a slightly shorter composting period than conventional windrow composting. However, the absence of turning during the composting process necessitates more thorough preparations of the organic waste before putting it in the compost heaps.

4.3. Bin Composting

This technology is mainly practiced at a domestic household level with limited space, as depicted in **Figure 1**c. It can treat only a limited amount of waste and only produce compost for self-consumption. Organic wastes are commonly inserted from the top of a specially designed container with a perforated wall to allow convectional air flow to the compost heap. The organic composting material degrades and becomes compacted slowly as it gets down into the container, with the final ready compost collected from the bottom of the container. Some containers may also include a stirring mechanism to allow a convenient method of mixing the compost heap, and as such, improve the air-filled porosity of the heap. The use of the self-contained system with perforated walls allows heat retention while enabling air to be circulated throughout the compost heap. For more extensive composting operations, bin composters can also be used on a large scale by combining the passively aerated method with bin composting [8]. The technology requires medium funding and a minimal amount of maintenance. Additionally, it requires less space than windrow composters as the waste is piled up vertically in the bin. No turning is also required, with the exception of stirring, which may need to be performed occasionally [9]. However, the composting process may take longer than windrow composting as the waste is contained inside a bin, and no turning is performed.

4.4. In-Vessel Composting

In-vessel composting is a method that encloses the composting materials within a container or a vessel [10], as shown in **Figure 1**d. Installations vary from very high-tech options, with different parameters monitored to very low-tech alternatives. In all configurations, airflow and temperature can be more easily controlled using this technology via the air portals from the holes around and on the sides of the vessel, allowing some air to pass through, which speeds up the composting process. Turning takes place manually, and it needs to be turned more frequently during the first two weeks of the composting process to help with the aeration process as well as to control both temperature and moisture. Large batches of organic waste can be added and composted using this technology, with the main benefit of requiring less space than the previous technologies. The organic waste is reduced in volume, and usually, after three weeks to months, the compost is further treated in an open space for the curing stage. Additionally, less labor is required as the mixing or turning occurs within the vessel. However, it is capital-intensive and requires high maintenance, necessitating regular checks inside the vessel to ensure a favorable composting environment [11] and manual mechanical rotation.

4.5. Vermicomposting

Vermicomposting, as depicted in **Figure 1**e, is a type of composting in which microorganisms and certain macroorganisms, such as earthworm species, are utilized at room temperature to improve the organic waste decomposition process and to provide a better final compost [12]. The method is different from conventional aerobic composting, with specially chosen red worms, commonly *Eisenia Foetida*, added to the compost heap. These worms have high appetites and breeding abilities, can digest the organic waste materials and pass them through their digestive tract to produce vermicompost in the form of granules [13]. Essentially, vermicompost is the worms' feces, also known as castings, which are rich in nutrients. Their castings are packed with microbes, which help continue the decomposition process to produce the final compost. However, they need a comfortable space to live and work. Some bedding materials, either shredded paper or cardboard, have to be prepared inside a worm bin for the worms to live and work. They also need some moisture and organic waste. The timeline for the whole process varies depending on the quantity of worms, the temperature, and how much waste is added to the bin. Furthermore, worm reproduction can occur [14], which eventually floods up the worm bin with worms after some time, and this may require transfers to an additional worm bin to maintain effectiveness. Vermicomposting can decrease the pathogens in the process, albeit not as effectively as traditional composting, as pathogens are generally eliminated quicker in hot conditions. However, the worms cannot survive very hot temperatures, allowing some pathogens and weeds to survive. This method requires relatively low costs, maintenance, and space [15]. The worms used have the ability to consume the organic matter quickly, resulting in a faster composting process with additional help from the microbes in their castings, and the method requires very little labor.

5. Automatic Composting Technology

There are various reasons for the relatively low adoption level of composting, including a lack of awareness, the relatively long time required for composting to complete, and lack of knowledge of the biological composting process. Manual composting methods require some time to produce good compost, in addition to monitoring and effort, which can be a hassle for busy working people. Additionally, some composting methods also require plenty of space [16], and hence, may not be suitable for those who live in urbanized areas. An automatic composter aims to solve some of these problems.

5.1. Forced Aerated Windrow Composting

In a forced aerated windrow setting, blowers are installed at the end of perforated pipes to force airflows to the compost heaps, as shown in **Figure 2**a [17]. The blowers inject air into the compost heaps, especially during the active stage, to supply the much-needed oxygen for the microorganisms, and hence, allow decomposition of organic waste materials. Airflow can be adjusted by changing the frequency and duration of the blower. The compost heaps are also commonly insulated to prevent heat loss and allow thermophilic temperature throughout the compost heaps, including the outer layers. Due to the efficient retention of heat and the ability to supply oxygen without turning, the composting process is commonly shorter. Little labor is required as compost heaps need not be turned [18]. However, the method requires high investment, given the need for blowers and aeration channels for airflow. Maintenance is also high and requires high space requirements.

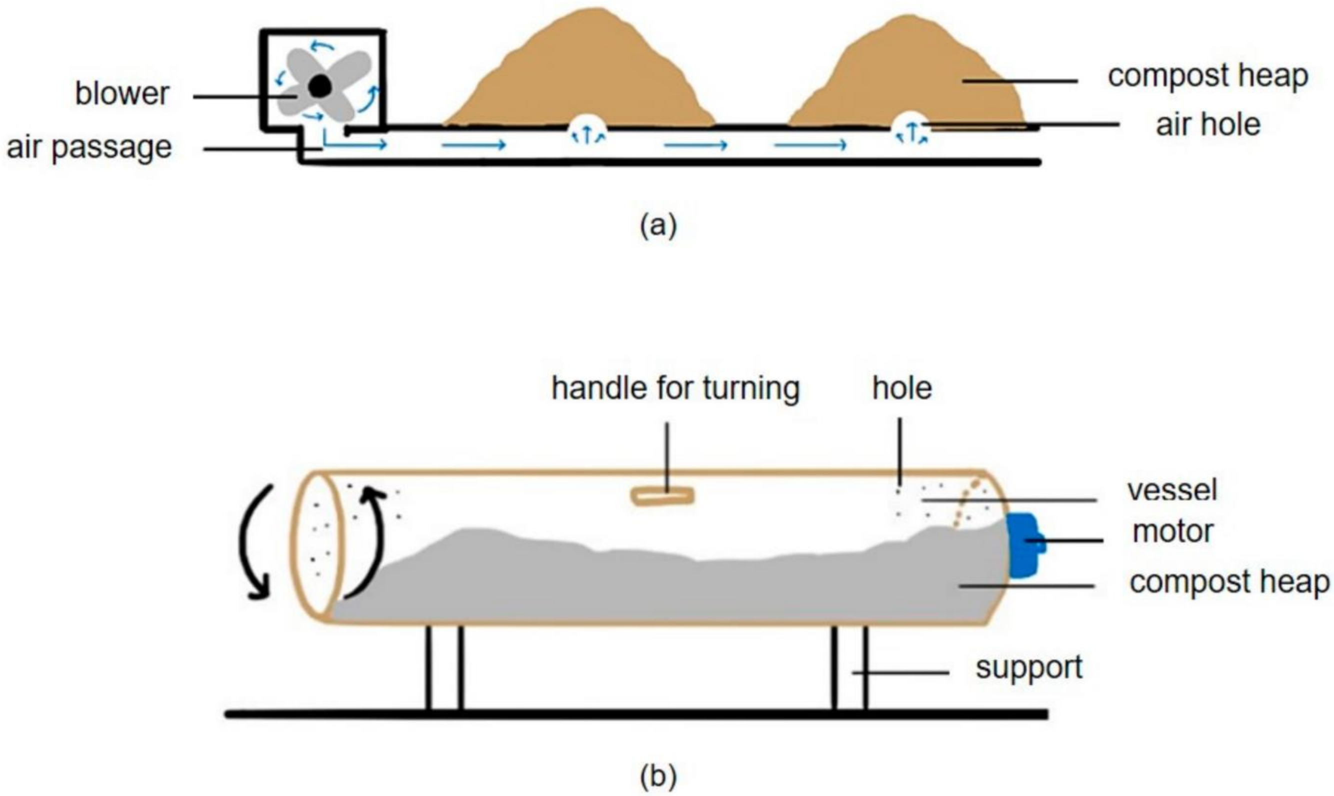

Figure 2. (**a**) Forced aerated windrow composting; (**b**) automatic turning in-vessel composting.

5.2. Automatic Turning In-Vessel Composting

The technology illustrated in **Figure 2**b is similar to the manual in-vessel composting; however, the technology may vary in designs, size, and equipment. One of the automatic in-vessel composting processes is the motorized turning in-vessel composter. The automatic turning in-vessel composting uses a powered motor to rotate the vessels for aerating the compost heaps and can be scheduled to rotate at desired times and frequency [19]. Some in-vessel composting processes also utilize a motor for rotating the vessel, and are equipped with temperature and humidity sensors to automatically monitor important parameters; replacing most of the manpower required in manual in-vessel composting. As a high torque motor is needed to rotate the heavy waste-filled vessels, the method requires very high investment and maintenance to ensure every piece of equipment works well to carry out the work. However, the in-vessel composting method is considered space-efficient and requires a low amount of labor.

5.3. Electrical Home Composter

An electric composter is an indoor compost bin that uses aeration, heat, and pulverization to minimize the volume, emissions, and odor of food waste. A common home composter may be small enough to fit on a counter, but for other types, large amounts of garbage also do exist and can be used in both indoor or outdoor applications. A home electrical composter, also known as a food recycler, uses three-phase cycles to break down food waste [20], with most composters taking an average of 24 h to a few days to break down waste into simpler compositions.

An electrical home composter attempts to provide the optimum composting environment occurring during selected phases of the natural composting process. Mesophilic and thermophilic phases are shortened in most electrical home composters through the applications of heat, such that excess moisture in the organic materials can be rapidly reduced. Organic materials are commonly automatically ground to increase their surface area to speed up the composting process before the materials are mixed with soils or additives to populate the microorganisms. After going through the accelerated mesophilic and thermophilic phases, the end products are eventually cooled down to room temperature to give entirely dry and sterile products, instead of the common texture of mature compost. This is because the end product from the home composter has only undergone partial phases of the composting process: the mesophilic and thermophilic phases, but has not undergone the maturation phase. These end products may be further cured outside of the system to ensure the resultant compost is adequately matured.

Electrical home composters may differ in terms of the adopted processes, quality of end product, and duration to completion. Nevertheless, the majority of the electrical home composters are based on three-phase cycles, which include drying, grinding, and cooling phases [21]. Some electrical home composters may also produce non-dehydrated and non-dry compost. This is possible due to the implementation of an additional phase, called the curing phase. In this phase, the organic materials that have been broken down into smaller substances are stabilized, applied with some heat, aerated, and turned until the compost is partially-cured (albeit not fully cured and stabilized) and able to be used as a garden compost as a final product. Due to the extra phase, these types of composters may take up to two weeks to complete the whole process.

There are quite a number of electrical home composters available in the market, with some of the products.

Electrical home composters are commonly embedded with different sensors for monitoring and control purposes. Temperature and moisture sensors are the most common sensors integrated onto an electrical composting system [28] to aid in the monitoring of thermal conditions inside the electrical composter and to ensure effective decomposition of the organic matter, preventing too wet or too dry contents, as well as to regulate the temperature from exceeding 70 °C, which can kill the microbes. An air pump is commonly used as an actuator to regulate temperature, such that the temperature within the system does not rise beyond a certain value, which may kill the microorganisms. Grinders are commonly used to shred organic materials to increase the surface area for the microorganisms to act on. These systems can be commonly operated with just a click of a button to activate the process, equipment, and sensors, from start to end product completion.

Most food recyclers use ventilation and heat to quickly break down food waste, much like a pile of regular compost. However, most of the end-product is completely dry, sterile, and immature [29], and hence, it cannot be considered proper compost. A home composter is primarily designed as an alternative for conventional composting; by reducing the hassle of managing compost heap and, as such, is suitable for people who want an odorless composting process with limited space to carry out conventional composting methods. This composter is designed to be used by anyone and may facilitate the reduction of food waste or organic waste from home. Despite its fast process, the initial investment of the machine itself can be high and requires high maintenance. However, its low space requirement and very low labor requirement make it an attractive alternative to conventional composting.

5.4. Comparative Summaries of the Manual and Automatic Composting Methods

Table 2 shows the comparative summary of manual and automatic composting methods. The literature indicates that many benefits may be obtained by adopting an automatic composting process; faster, easier, and more convenient composting, which may encourage composting at the source. Subsequently, this may reduce the need to transport the bulk of the waste to landfills and its associated problems. However, despite a large number of scientific pieces of research on the topic, none have specifically addressed the technological advancements in composting from the patent perspective. This is despite patents representing valuable information on the technology and may indicate directions of the composting technology. As such, there is a clear need to perform a systematic patent review on the technological advancements in the field.

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