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Assessment of Energy-Efficient Spouted Bed Aerobic Composting Performance for Municipal Solid Waste: Experimental Study

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Abstract: Municipal solid waste contains a high percentage of organic waste, and when it is not disposed of, it becomes a threat to the environment by contaminating the air, water, and soil. Composting is one of the recovery techniques in which the end product of waste eventually contributes to the agriculture industry, reducing the harmful effects on the environment. Composting municipal solid waste is a clean and effective technique for waste disposal. The mechanized composting process is carried out by several methods, like the windrow method or the rotary drum method. However, large-scale composting processes involve energy consumption and labor costs for waste preparation and handling. This increases the market cost of compost. Hence, an energy-efficient composting technique with minimum environmental impact is needed. This research work aims to analyze the performance of an energy-efficient spouted bed technique for aerobic composting of municipal solid waste for the first time using spouted bed technology with sand as the bed material. Spouted bed composting handles the waste using a pneumatic method with minimum power consumption in comparison to conventional mechanical methods with windrow processes or rotary composting machines. The experimental procedure involves a test run of waste along with bed material and the collection of temperature variations, pH variations, moisture variations, and volatile matter content during the progression of the composting process. The results of this experimental study on a single batch of waste are then used to analyze the quality of the compost generated and compare it with existing results. Specific energy consumption for the process was less than 800 kJ/ton of raw waste input, which is much less than the energy used for conventional composting techniques. pH, volatile content, moisture, and temperature measurements indicated agreement with the established parameters of the composting process.

Keywords: spouted bed; municipal solid waste; waste composting; waste disposal; energy efficient composting

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1. Introduction

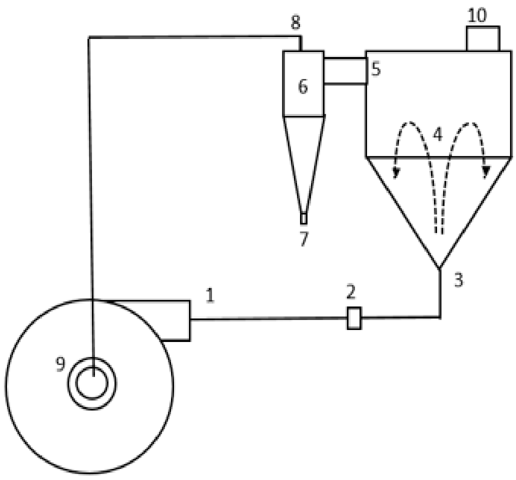
The world generates almost 2.01 billion tons of municipal solid waste (MSW) every year, which is expected to surge twofold by 2050 [1]. Municipal solid waste (MSW) generated from middle- and low-income countries contains a high percentage of organic waste compared to developing countries [2]. Sao Paulo, a city in Brazil, produces approximately 20 million tons of MSW annually [3]. Mumbai, India, reported 28 million tons of waste, of which 73% is food waste and roughly 27% is dry waste [4]. New York City produces 14 million tons of MSW, with ongoing attempts for effective waste management techniques [5]. The urban areas in 23 wards of Tokyo generate around 3 million tons/year of MSW, with a 70% accumulation from households [6]. The Kingdom of Saudi Arabia generates 15.3 million years of MSW every year without any tipping fees [7]. Organic waste, when disposed of untreated, such as by dumping, burning, burying, and disposing into water bodies, is observed to pose a widespread threat to the environment through leachate production, emission of methane, global greenhouse gases (GHG), producing foul/offensive odors, contamination of water and soil, etc. [7]. Organic and inorganic pollutants damage the environment by polluting water bodies, causing deterioration of human life and ecological imbalance when dumped in open landfills. The indiscriminate dumping of waste into landfills not only causes environmental hazards but also leads to the abandonment of the area earlier than the anticipated time of 30 years [8]. An extensive dataset of 827 published articles and other documents was analyzed, revealing the substantial global growth in MSW research, particularly in the last two decades. The research concludes the evidence of the thematic evolution of an MSW disposal transition towards plant nutrition, biochar, soil properties, heavy metals, and microplastics, providing direction for future research [9]. Waste to energy by combustion can produce energy for electricity generation, cooling, and other applications, but produces polychlorinated dibenzodioxins and dibenzofurans, which have adverse effects on humans and the environment [10,11]. Of the MSW treatment in China, 52% is accounted for by landfills, followed by 45% incineration and 3% composting, lower than in developed countries [12]. Life cycle assessments of MSW management have exposed landfilling, anaerobic digestion, composting, incineration, and transportation as major contributors to greenhouse gas emissions. The acknowledgment of the 5Rs inculcation principle, the segregation of waste at its source, and composting as manure, in addition to effective regulations and policies, would serve to mitigate the MSW management problem [13]. Composting is one of the MSW management techniques used to decompose organic waste and involves biological treatment to convert waste into nutrient-rich soil amendments under controlled conditions [14]. MSW compost, when used for soil amendment, recycles nutrients and enhances the water retention capacity and soil structure [15]. The agricultural application of MSW organic waste as a nutrient source for plants and soil is considered the most effective disposal technique over the traditional methods of landfilling and incineration [16]. Composting is a biological process for treating and decomposing the refuse organic waste of MSW under controlled conditions, during which microbes metabolize the material and also reduce the volume of decomposition by 50% [14]. In the MSW composting process, the organic, biodegradable matter is degraded and broken down into carbon dioxide and water under controlled conditions using microorganisms. The controlled quantity of oxygen and temperature achieve a high-quality, stable end product called compost with a large decrease in volume [17]. Sand blend compost contains an appropriate proportion of sand to compost and is used as a ready-to-plant mix for planting and agriculture applications [18]. The experimental results of 20% compost and 6% biochar showed effective plant growth [19]. Depending upon the duration of decomposition and potency of maturity and stability, different types of composting methods are classified as windrow composting, pit composting, vermicomposting, rotary drum composting, and combined windrow cum vermicomposting [20]. Based on the nature of the microorganisms used for degrading the organic matter of MSW, composting methods are broadly classified into aerobic and anaerobic. The composting technique involving the decomposition of organic matter using microorganisms that necessitate oxygen is called aerobic composting. The heat produced during this technique eliminates catastrophic pathogens and bacteria and enhances the quality of compost. The presence of oxygen speeds up the composting process in aerobic composting when compared to the anaerobic method [21]. Proper aeration increases the decomposition of organic matter in MSW; compared to anaerobic composting, which requires almost 6 to 12 months for complete decomposition, aerobic composting requires only 30–120 days [22]. A temperature of 60–70 °C and moisture of 35% are the optimum conditions to produce the required microorganisms, which eliminate the pathogens and weed seeds present in the compost pile [23]. Microbes play a pivotal role in composting; the presence of microorganisms in the aerobic composting method increases the temperature of the compost pile to up to 70 °C supporting the thermophilic phase, unlike in anaerobic composting, where the temperature never reaches 65 °C [24].

Composting is a waste recycling technique that produces a carbon-rich and pathogen-free product. Energy consumption and emissions are the two concerns to be considered during the composting process. A study on windrow composting showed that open dumping of waste on platforms with mechanized handling involves 199 to 250 kg of carbon dioxide emitted and 1500 to 2000 kJ of energy required to produce one ton of compost [25]. The spouted bed composting technique is a branch of the fluidization technique. This technology was initially established in the mid-1950s for drying wheat and other granular cereal materials [26]. The working fluid is introduced vertically upward with suitable velocity through the bottom of the granular material bed, forming a jet region that extends upward with the increase in fluid velocity. With a high enough velocity of fluid, the jet penetrates the bed and produces a spout region of a dilute gas–solid slug that moves upward through the bed center. The particles in the spout region, after reaching a height greater than the bed surface, start falling back to the annulus surface in the pattern of a fountain, forming a fountain region under the effect of gravity with a sudden decrease in the fluid velocity. These returned or falling particles move slowly downwards towards the annulus region in the lower part of the bed and then again go up with the fluid jet, forming a spout region, and the circulation of particles continues [27]. This type of flow phenomenon is termed the spouting bed phenomenon and further has three phases of flow structures: dilute, dense annulus, and fountain phase. As the particles move forcefully, the spouted bed has good mixing of the bed particles, avoiding overheating and ensuring uniformity of moisture distribution along with the temperature of the matter inside [28]. The applications of spouted beds include mixing, drying, pyrolysis, coating, granulation, and gasification [29].

Odor and pests are major problems encountered during open composting. Though aeration is a pivotal factor in resolving this issue, it invites high initial and operational costs, limiting large-scale practices [30]. Moisture content in organic waste is an intrinsic process that affects the growth of microbes; a high moisture content decreases the growth of microbes, decreasing the efficiency of the composting process [31]. Though advanced composting techniques have been reported, such as the utilization of arthropods, their efficiency remains a challenge [32]. After finding the lacunae in the existing techniques, effective methods have to be developed for treating the organic matter that is generated at a tremendous rate with low electrical power and labor requirements. Analyzing the requirements of bed materials for the spouting process and the substantial benefits of sand in making soil blend compost, the present study involves a novel approach, integrating spouting and compost techniques. This required the design and implementation of a composting machine that overcomes the above-mentioned disadvantages of existing composting techniques. The spouted bed composting method uses a pneumatic method for handling the complete mechanism. With the help of the spouted bed technology, air acts as the material transfer agent, mixing as well as aerating. The design of the spouted bed is made as per the existing guidelines [33]. An initial batch of organic kitchen waste is used along with the required quantity of bed material. Waste is tested for its compostability by monitoring the performance parameters continuously. The performance of the newly designed composting machine was compared with existing composting performance in terms of its moisture content, temperature, pH value, and volatile matter content. Also, the energy consumption for producing one ton of compost was determined from the results. The MSW taken in this study is considered after the removal of the recyclable material and is predominantly organics and silt.

2. Materials and Methods

A spouted bed consists of a cylindrical tank with a conical bottom and a central nozzle. A blower is used to force pressurized air into the bed. Spouting action is created by exposing the axial part of the bed, which consists of a mixture of waste and sand as the bed material. The high-pressure air from a blower is used to produce a fountain-like effect on the bed material. The bed material is thrown up into the axial part of the tank and falls back by gravity into the surrounding annular portion of the tank; this forms a mixing action of the particles, which return to the central nozzle by sliding down the conical bottom. Figure 1a gives the process description, and Figure 1b gives a picture of the experimental setup used. Waste to be composted is fed into the bed at the required rate and quantity, along with the bed material in a predetermined ratio.



(a)

(b)

Figure 1. (**a**) Description of the system. (**b**) The experimental setup.

The air is supplied at high pressure from the blower of 1.5 kW capacity (1) with provision for flow control (2), and this air is passed through the apex of the conical bottom (3), forcing the bed particle to be thrown up, forming a spouting action (4). The material falls back and slides back to the center of the cone to be thrown up again. The material to be composted as well as the bed material are fed into the composting tank at the feeding point (10). The lightweight material that rises up moves to the exit (5) and is tangentially taken into the cyclone separator (6), in which the particles are subjected to centrifugal forces, due to which the particles are moved into the periphery of the conical surface, fall down due to gravity and are removed. The clean air from the cyclone separator is taken back (8) into the blower suction side at 9.

The bed material has two advantages:

- Acting as the inoculant by retaining the microorganisms, enabling a continuous composting process;
- Enabling suitable bed density to maintain a stable spout as well as a carrier for the waste.

The very light particles are separated in the cyclone separator, which is connected to the suction side of the blower. This is achieved by the centrifugal action of the dust-laden gas coming out of the tank.

2.1. Design of Spouted Bed Composting Machine

The volume required for the tank is assumed to be two times the volume occupied by the bed material and the MSW, as given in Equation (1). The volume of the waste handled is the weight of the waste (W_W) to be composted divided by its density (ρ_W). Likewise, the volume of the bed material, which is sand, is given by the weight of the sand used (W_S) divided by the density of the sand (ρ_S).

$$Volume\ of\ waste\ used = \frac{W_W}{\rho_W}$$

$$Volume\ of\ bed\ material\ (sand)\ used = \frac{W_S}{\rho_S}$$

$$\mathrm{V} = 2 \times \left(\frac{W_W}{\rho_W} + \frac{W_S}{\rho_S}\right) \quad (1)$$

The volume of the composting chamber consists of the conical lower portion and the cylindrical upper portion. This total volume (V) is equated to the geometrical volume of the cylindrical and conical parts of the composter, as given in Equation (2), to determine the radius of the tank:

$$\mathrm{V} = \pi \times r^2 \times \left(\frac{h_{co}}{3} + h_{cy}\right) \quad (2)$$

The height of the cone is assumed to be twice the height of the cylindrical part of the tank to enable a sufficient inclination angle for the smooth sliding movement of material.

$$h_{co} = 2 \times h_{cy} \quad (3)$$

The pressure (ΔP_F) required to lift the material above the nozzle part of the spouting tank is related to the weight of the material in the bed at stationary conditions. The weight of the cylindrical part of the material above the air nozzle depends on its density and volume, as given in Equation (4). The fan power (P) required is given by Equation (5), and the specific energy consumption (SEC) is calculated from Equation (6). The specific energy consumption of the composting machine is the energy consumed during the operating time of the spouting mechanism divided by the composting capacity in kg.

$$\rho_S \times \left(\pi \times \frac{d^2}{4}\right) \times H_B = \Delta P_F \quad (4)$$

$$P = Q \times \Delta P_F \quad (5)$$

$$SEC = P \times T_o / W_W \quad (6)$$

Q is the air flow rate in m^3/s, T_o is the operating time of the blower per day, and W_W is the weight of the waste charged per day. The operating time of the blower was maintained for the composting process at 10 min every 6 h per day. The composting chamber was made of a mild steel sheet of 1 mm thickness. The air piping was made of polyvinyl chloride.

2.2. Substrate

The substrate of municipal solid waste was collected from households in the north-western region of Diriyah, Saudi Arabia. The waste was segregated to remove inorganic matter, such as rubber, plastic, glass, tin and aluminum containers, and other chemicals not considered for composting. The collected MSW was shredded mechanically for a particle size of 2.5 mm. Table 1 shows the physiochemical properties of waste containing organic matter used for the composting process [34].

Table 1. Physiochemical properties of waste.

Food Content	Moisture (M_1)	Carbon Content (C_1)	Nitrogen Content (N_1)	C/N
Spinach	88.43	34.70	4.16	8.34
Orange	75.89	45.78	3.27	14
Banana	90.58	46.26	1.66	27.86
Bread	22.29	46.40	5.34	8.68
Corn husk	7.81	79.11	1.54	51.37
Corn	25	43	0.7	61.42
Rice	61.35	44.12	4.55	9.69
Onion peel	8.02	35.8	1.83	19.56

2.3. Optimum Moisture Content Required

Moisture content in the compost plays an important role in the composting process. A moisture content of less than 35 to 40% hinders the activity of microorganisms and the rate of compost formation [35]. On the other hand, excessive moisture makes the compost and bed material heavier, and the pressure required and power consumed by the blower increase [36]. Figure 2a shows the before-composting and Figure 2b shows the after-composting contrast of the organic matter. Figure 3 gives the relationship between moisture content, fan power consumption, and composting rate. The attainment of the maximum temperature of 50 °C is used as an indicator of composting speed. Particle size is an indicator of composting rate, and it is recommended that a particle size in the range of 1.5 to 3 cm makes an ideal compost [37]. The fan power consumption is measured using the power analyzer.

(a) (b)

Figure 2. (**a**) Before composting, (**b**) After composting.

The initial stage is called the mesophilic stage, during which the organic waste gets broken down. This is followed by the thermophilic phase, during which the temperature reaches about 50 °C. During this stage, the thermophilic bacteria become dominant over the mesophilic bacteria. This normally happens on the third day of the composting process. Temperatures continue to rise to 60 °C up to the eighth day of the composting process, after which the second mesophilic phase begins. After day 12, the temperature starts moving down to the ambient temperature conditions, and the decomposition begins and continues for up to 20 days. The carbon–nitrogen ratio of the waste plays a key role in the microbial action on the waste. The temperature and pH values indicate the settling of the composting process.

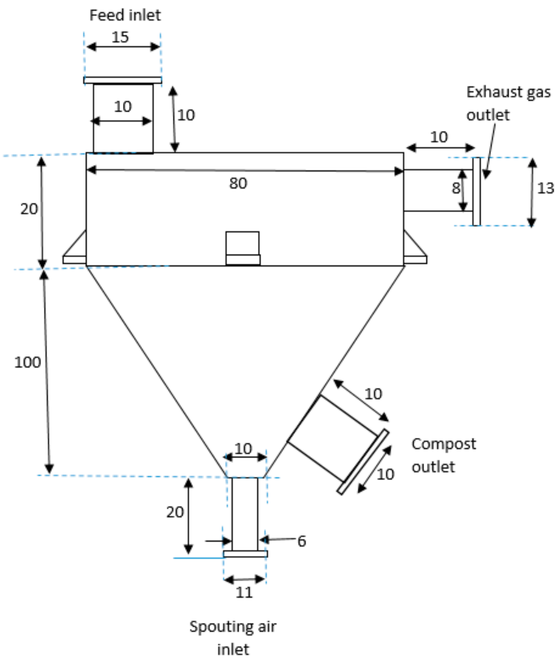


Figure 3. The dimensions used for the spouted bed composting chamber.

Equations (1)–(3) were used to determine the dimensions of the spouted bed composting tank by taking the initial weights of 225 kg of sand and 56.25 kg of organic MSW. The density of the sand used is 1600 kg/m^3, and that of the waste is 400 kg/m^3. Figure 3 gives the design dimensions obtained for this requirement. The moisture content was determined in the laboratory, as per the ASTM standards, by heating the waste in a muffle furnace at 110 °C for 12 h, and taking samples at regular intervals of time during the composting process. Moisture (M in kg) required to be added to maintain a moisture content of x_2 (in decimal form) to the initial moisture content required x_1 (in decimal form) was calculated from the following Equation (7). W_1 is the initial weight of the waste added, in kg.

$$M = W_1 - \left[\frac{W_1(1 - x_1)}{(1 - x_2)} \right] \quad (7)$$

3. Results and Discussion

The compost sample of sand blend compost from the spouting bed composting machine was analyzed at regular intervals of time during the composting period of 20 days for different samples of moisture and C/N ratio. Different parameters, such as temperature, pH, and volatile content, were recorded. The test was performed for an initial batch containing 56 kg of sand and 14 kg of organic kitchen waste for a single charge of waste on the first day. The spouting action was repeated intermittently every 2 h for 10 min and the temperature of the compost was measured using the Fluke 62 MAX infrared thermometer with an accuracy of ±1.5%. Temperature was measured at a uniform interval throughout the composting period of 20 days. Four different tests for four different moisture contents, 25%, 30%, 35%, and 40%, were analyzed. Moisture content during specific tests was maintained at the same levels by collecting samples twice each day and adding water as required. The carbon nitrogen (C/N) ratio was maintained at 20 for all the tests.

Figure 4 gives the temperature of the compost for different moisture contents. The temperature attained on day 8 of the composting process was taken as an indicator of the speed of the composting process. The power required for mechanical shredding and to run the blower was measured using the Krycard Power Analyzer (accuracy 1.5%). The results of the eighth-day temperature indicate 40% moisture as the ideal value to attain maximum temperature, which is taken as the condition for maximum composting. The corresponding power consumption of the blower is noted as 245 W, which makes it 800 kJ/ton.

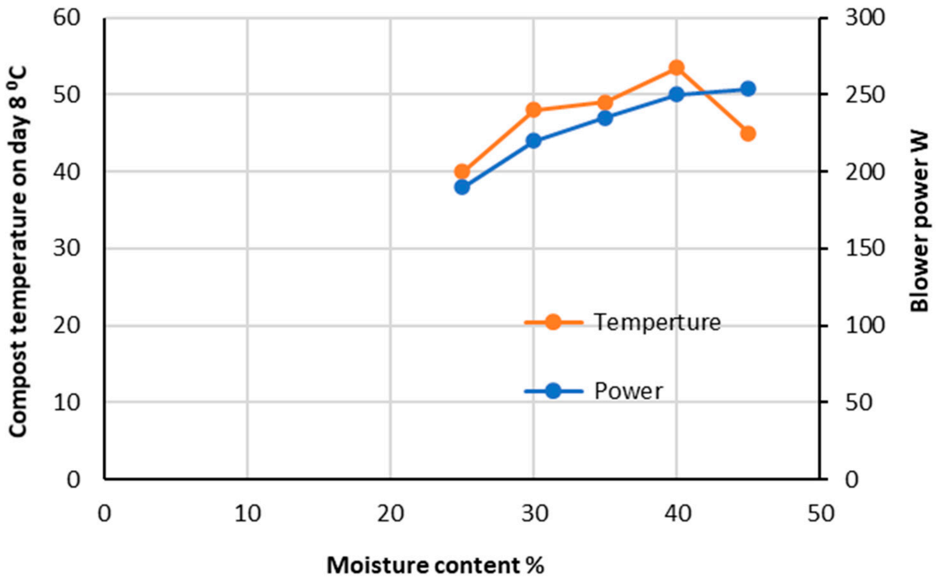


Figure 4. Temperature and blower power consumption.

3.1. Effect of C/N Ratio on Composting Performance

The weight of the specific food content waste was measured every time before adding the waste to the composting machine. The individual carbon and nitrogen percentages of waste content were obtained from published data and weighing the different components of the waste. The overall C/N ratio of the waste was determined using Equation (8), where C is carbon content, N = nitrogen content, Q_n = wet weight, C_n = % oF nitrogen, M_n = % moisture content [38].

$$\frac{C}{N} = \frac{Q_1(C_1 \times (100 - M_1)) + Q_2(C_2 \times (100 - M_2)) + \cdots}{Q_1(N_1 \times (100 - M_1)) + Q_2(N_2 \times (100 - M_2)) + \cdots} \tag{8}$$

The initial C/N ratio indicates the maturity of the compost and decreases the effect of pathogens that hinder the composting process. Figure 5 shows the temperature of the compost with different C/N ratios of 11.75, 20, and 30.5 for 40% moisture with each batch of a 4:1 ratio of sand to waste for a total weight of 70 kg. The highest temperature of 58 °C was recorded for the C/N value of 20 on day 8, followed by 51.5 °C and 48 °C for C/N 11.75 and 30.5 for the same day, respectively. This is in agreement with established experimental results, which report optimum composting at a C/N ratio between 15 and 30 [36].

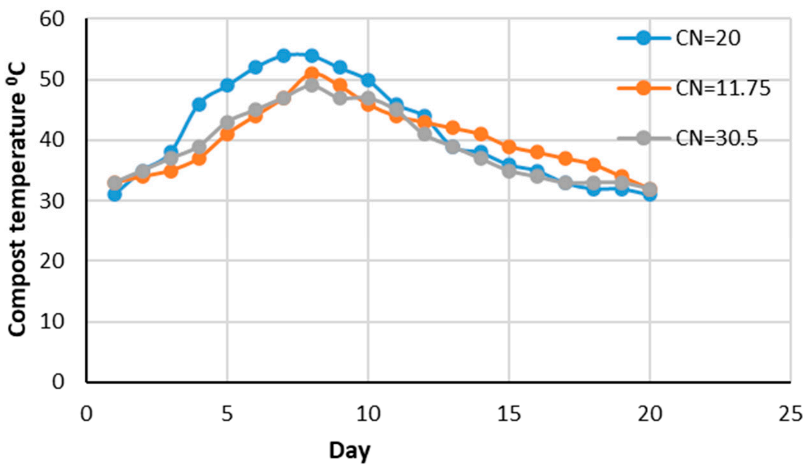


Figure 5. Effect of carbon nitrogen ratio on compost temperature.

3.2. Effect of pH on Composting Performance

The microorganisms that perform composting operate best under neutral to acidic conditions, with a pH in the range of 5.5 to 8. Organic acids are formed during the initial stages of decomposition, and acidic conditions are favorable for the formation of fungi and the breakdown of lignin and cellulose. During the later stages of composting, the organic acids become neutralized, and mature compost generally has a pH between 6 and 8 [37]. Figure 6 shows the pH of the compost for different C/N ratios of 11.75, 20, and 30.5 for 40% moisture. The pH value was recorded using pH measuring strips by taking samples every day. The maximum pH of 6.6 was recorded for the compost with a C/N ratio of 20 for day 8, whereas the minimum of 4.8 was recorded for 11.75, and 30.5 for day 1 of the compost. A pH of 6.2 was recorded for day 8 of the compost, with a C/N of 11.75 and 30.5. Hence, the results are in agreement with established results [39].

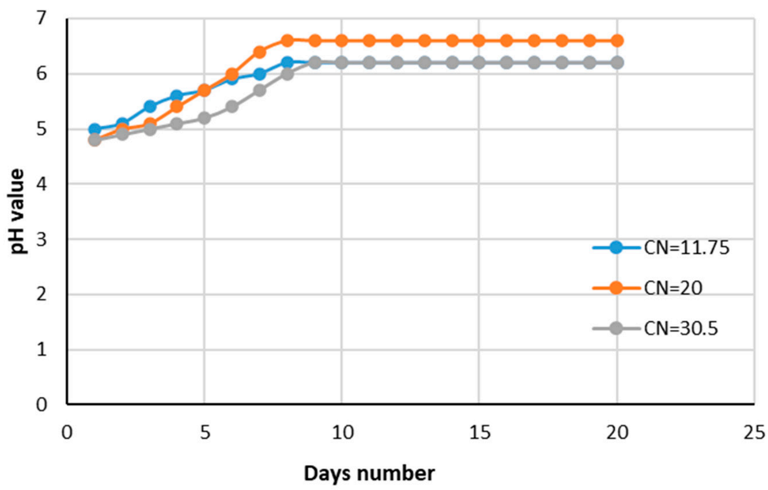


Figure 6. Effect of time on pH value of compost.

3.3. Volatile Content Variation during the Composting Process

The release of volatile organic matter during composting gives off foul odors, and it is higher during the initial stages of composting. However, it stabilizes after some time. After setting the initial moisture content at 40%, a sample of compost was taken on day 8 to determine the moisture content and volatile content. The procedure adopted to determine the volatile content was as per ASTM D5832 [40]. Figure 7 shows the volatile matter observations recorded. The maximum volatile content of 74% was recorded for a C/N ratio of 11.75, whereas the minimum recorded was 65% for a C/N ratio of 30.5. These values are in agreement with the available data [38].

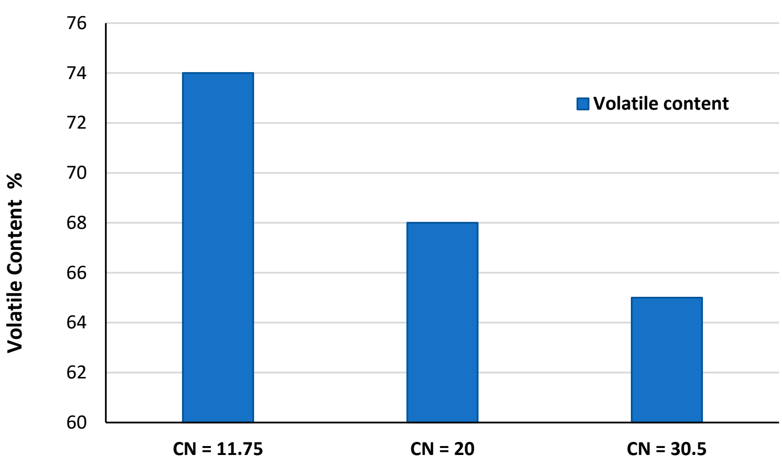


Figure 7. Effect of C/N ratio on volatile content of compost.

4. Conclusions

A new type of composting machine was tested for its performance with organic waste input from municipal waste from urban households. The spouted bed composting machine was designed and installed to match the requirements of organic waste mixed with sand of a particular weight ratio. Sand acted as a bed material as well as a medium to maintain a continuous composting process by carrying the inoculant. A smooth and continuous spouting of the mixture was achieved under specific operating conditions. A series of tests were conducted to determine the optimum moisture content to be maintained in the composting process by optimizing the fan pressure requirement and the waste humidity for maximum composting effect. The air supplied for the mixing process was recirculated using a cyclone separator, and the discharge of emissions into the atmosphere was minimized. The optimum fan pressure and airflow rate required to produce an effective mixing spouting action were determined experimentally. The C/N ratio of the organic waste used varied from levels of 11.75 to 30.5 to find the best composting performance. The temperature variation in the composting process was monitored continuously. The moisture content of the compost, the volatile matter of the compost, and the pH value were monitored intermittently.

The results for a sand-to-organic waste ratio of 4:1 for sand blend composting by weight with four kilograms of sand for every one kilogram of organic waste indicated relatively close results, proving the effectiveness of the system relative to conventional composting technologies. The C/N ratio was maintained at 11.75, 20, and 30.5, and 20 was found to give the best and fastest composting process. The temperature recorded every day at a fixed time was found to be in agreement with the established profile of a temperature of 58 °C on the eighth day of the process. The variations in pH, moisture content, and volatile matter content were in agreement with established results.

The specific energy consumption of the total process was 800 kJ/ton of compost, with no mechanical equipment or manual labor involved for mixing or handling the waste during composting with minimum environmental emissions. This value is equivalent to 50% of the energy consumption of a conventional windrow composting technique. The usual problems of leachates and air-borne emissions were prevented by this composting method. The initial results regarding energy consumption and environment-friendly operation are encouraging, and more tests on the continuous operation of this method will provide more information.

Author Contributions: The concept of spouted bed composting for municipal solid waste was devised by Z.K. The methodology and investigation were carried out by Z.K. and A.S. The investigation and measurements were carried out by Z.K. and A.S. Project administration and funding management were performed by Z.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data are available in the manuscript itself.

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