Vermicomposting Smart Closed Reactor Design and Performance Assessment by Using Sewage Sludge

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Vermicomposting smart closed reactor design and performance assessment by using sewage sludge

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Abstract

This study aims to design a smart closed reactor of vermicomposting to convert sewage sludge and any organic waste to high-quality vermicompost. In this reactor design, all aspects of growth and reproduction of Eisenia Fetida worms, such as aeration, temperature, light, and moisture, were considered. We analyzed the physicochemical, bacterial, and microstructural of produced vermicompost and growth rate of worms in a substrate of 70% sewage sludge, 20% cow manure, and 10% sugarcane bagasse in a container and the smart reactor. The results show that vermicomposting in the smart reactor took 50% less time and 30% more worm growth rate to produce the same quality as in a container. After vermicomposting in the reactor, the parameters of pH, fecal coliform, phosphorus, organic matter, and C/N decreased whereas the parameters of carbon, nitrogen, nitrate, ammonia nitrate, and EC increased, slightly. Although, the EC amount of the reactor production is more than the container one, the amount of moisture, phosphorus, and organic matter of the vermicompost in the container is more than the reactor one.

Based on the odor absorption and leachate elimination of this reactor, we recommend that it be utilized for vermicompost production, including out of smelly organic wastes such as sewage sludge, even in any public zone and personal houses.

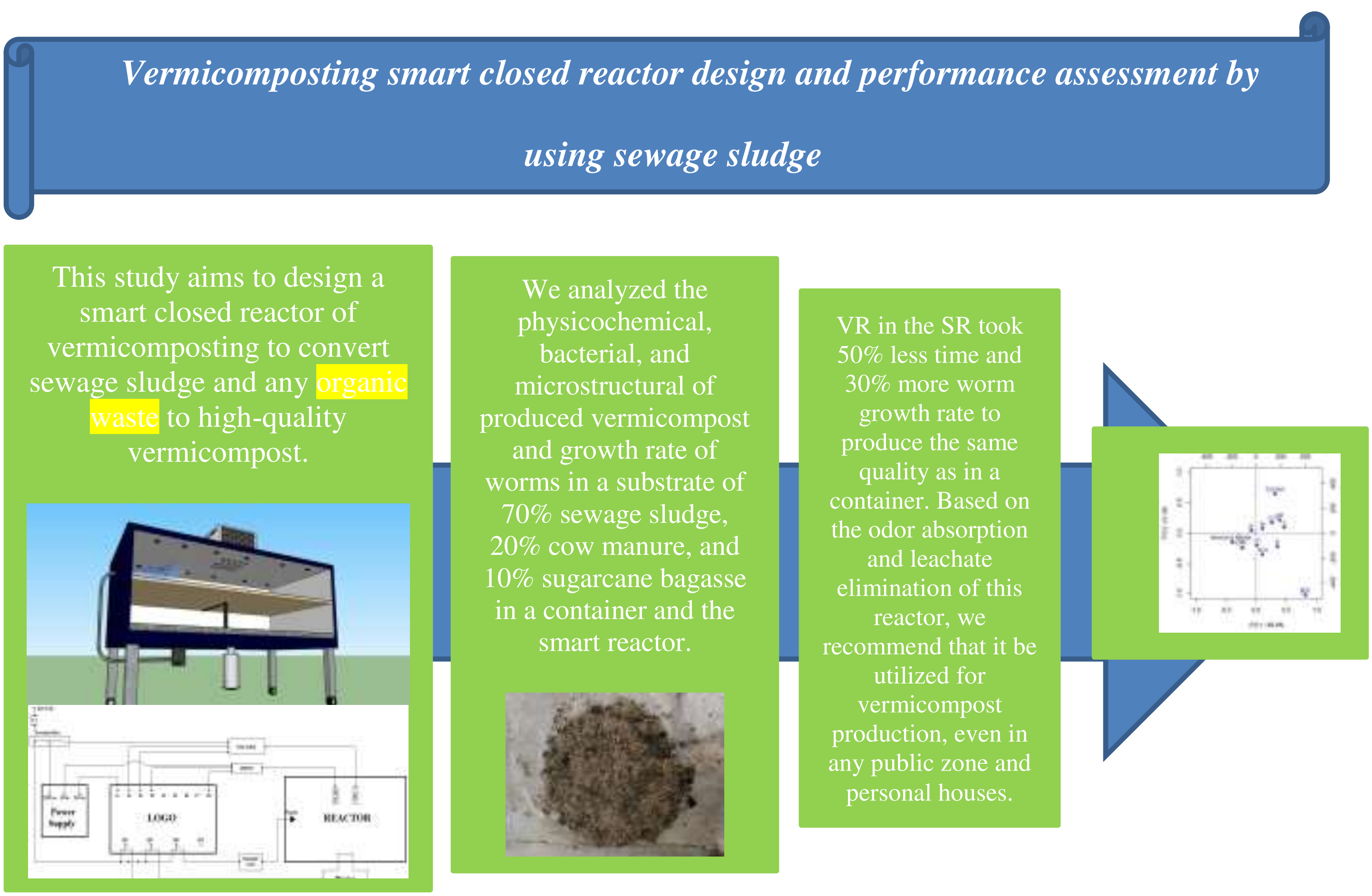
Nomenclature

SR	Smart Reactor
VR	Vermicomposting
PLC	Programmable Logic Controllers
SS	Sewage Sludge
CM	Cow Manure
SB	Sugarcane Bagasse

Keywords

Smart Reactor, LOGO!, Vermicomposting, Eisenia Fetida, Sewage Sludge

Graphical abstract



Novelty statement

This study aims to design a smart closed reactor of vermicomposting (which will be a patent in Canada) to convert cow manure, herbal residues, and any organic wastes to high-quality vermicompost.

In this designed reactor, we used sewage sludge, cow manure, and sugarcane bagasse to produce the same quality vermicompost as in the container with a 50%-time reduction, 30% increase of worm growth rate, and cocoons number, and the hygiene of the production environment. According to the result of this study, it is recommended that this reactor be utilized for vermicompost production, including out of smelly organic wastes such as sewage sludge, even in any public zone and personal houses.

1. Introduction

One of the best methods for various organic solid waste disposal, such as animal manure [1, 2], sewage sludge (SS) [3], crop straw [4, 5], fruit wastes [6], and vegetable debris [7], is vermicomposting (VR) [8–10].

Alidadi H. et al. [11] how various amounts of vermicompost and cow manure affect growth, germination and the yield of tomato plant. The results analysis showed that using 500 g/m2 ratio of vermicompost to cow manure could significantly increase the tomato yield.

Gupta, R. and Garg, V.K [3] used primary sewage sludge amended with cow dung to produce vermicompost. They recorded a reduction in TOC, pH, and the ratio C/N, and growth in EC, TKN, TK, TP, and heavy metal percentage in all mixtures. According to their results, the addition of 30–40% of primary sewage sludge with cow dung had no negative impact on the vermicompost quality and Eisenia foetida growth.

Sharma, K. and Garg, V.K [12] pre-composted rice straw and paper waste to produce vermicompost by employing Eisenia fetida. They prepared cow dung as bulking substrate in nine feedstocks. After 105 days of vermicomposting, NPK and heavy metal of vermicompost were higher than the raw materials. In contrast, the ratio C/N and total organic carbon were lower than raw materials by 19-102% and 17.38-58.04%, respectively. Moreover, SEM images demonstrated the changes in the morphology of vermicompost. It is worth pointing out that the growth and proliferation rate of the earthworms increased significantly in the variety of feedstocks except the one which contains 50% rice straw.

Castillo-González E. et al. [13] chose pineapple waste (rinds, crowns, and cores) at the industrial level as waste materials in producing vermicompost. After pre-composting these waste materials, they put Californian red worms in the substrate of vegetable waste and eggshells with three ratios of pineapple waste. Upon the obtained results, the pre-composting process helps the worm to be reconciled to the substrate readily. The organic carbon was removed between 36.40% and 45.78%, and the total nitrogen content remained between 1.2% and 2.2%. So, the ratio C/N was less than 20, which showed the vermicompost was high-quality.

Majlessi M. et al. [14] studied the impact of food waste on the chemical properties and germination bioassay of vermicompost. They concluded that adding Eisenia Fetida worms to this substrate produced vermicompost with EC, pH, C/N, and germination index between 7.5-4.9 mS/cm, 5.6-7.53, 30.13-14.32%, and 12.8-58.4%, respectively. According to the Pearson correlation coefficient, the confidence level of EC and GI value was 99%. Also, the amount of C/N shows that the vermicompost is stable, to ensure the quality of the vermicompost, we need check the stability and maturity tests simultaneously.

Disposed organic wastes in disposal sites are an important contributor to global greenhouse gas production [15, 16]. VR can reduce disposal site input and the detrimental effects of greenhouse gases [17]. Mesophilic earthworms play a key role in VR. Vermicompost is the product of accelerated biodegradation of organic matter and its stabilization by earthworms without a thermophilic stage. They use organic wastes to produce vermicast, which is full of nutrients, and they reduce human pathogens [18, 19]. This kind of earthworm grows and reproduces quickly in a proper situation [20, 21] such as 7 pH, 25 °C temperature, and 60-70% moisture. The quantity and quality of the substrates affect the growth rate and the number of earthworms. The most important parameters of vermicompost production substrates are temperature, moisture, aeration, and light.

Due to using wastes with intolerable odor as raw materials, especially in a closed environment, the most important aspect of VR is sanitation and cleanliness level. The second one is the rate of VR, which is an effective issue in industrial production.

In this study, we considered the important parameters, and the two above-mentioned aspects in designing a smart reactor (SR), which the authors had not found in any other research article at a sophisticated level.

Electronic sensors and control systems are widely used for agricultural and environmental purposes. This utilization improves production speed, measurement accuracy, and the resources effective usage as well as reducing reduces costs [22, 23]. Programmable Logic Controllers (PLC) are usually the main part of automatic systems in the industry, research, and monitoring [24]. They also make it possible to measure and control a wide range of variables such as temperature, moisture, pressure, and pH. Indeed, they not only control variables, but also send commands to many types of actuators, pumps, motors, and valves to maintain the required conditions for the process [25, 26].

In the past, the control system was adopted by relay-contactors, with obvious defects such as high failure rate and costly difficult maintenance [27]. PLC was first conceived in the late 1960s and currently is the major player in automation systems [28]. PLC consists of two parts: the hardware and the software. The PLC hardware system is composed of specific building blocks that plug directly into a proprietary bus: a central processing unit (CPU), a power supply unit, input-output modules I/O, and a programming terminal [29, 30]. For software, it uses a programmable memory for the internal storage of user-oriented instructions for implementing specific functions such as arithmetic, counting, logic, sequencing, and timing. The control logic in PLCs using different blocks allows for the design of the simplest to the most advanced control circuits and control loops. The standard IEC61131-3 defines several programming languages for PLCs [31, 32].

PLC has many inputs and outputs, which make it usable in industrial activities. To design this reactor, many functions of PLC are unwanted and too expensive. However, LOGO! has practical features such as low-cost performance and maneuverability [33]. In this study, considering the number of inputs and outputs and the control logic required, we used the Siemens LOGO! 12/24RCE as an intelligent controller. This choice allowed us to reduce costs to a reasonable amount. In this version of LOGO!, eight inputs and four outputs are available, and we can program its control logic by using eight and 39 basic and special functions, respectively: 14 timer functions, three counter functions, 13 analog functions, eight miscellaneous functions, and 1 data log [34]. LOGO! Soft Comfort is a Siemens programming package for PCs (Programming Computers), which runs under many operating systems (we used Windows 10 in this case). The basic features of the software are graphic interfaces implementing programs with ladder diagram or function block diagram, simulation of the programs and online test, comparing programs, and transferring the programs from LOGO! to the PC and vice versa [35]. To create and configure a function block diagram, we used LOGO! Soft Comfort V8.0.1.

The control process in this system was established based on monitoring and intelligent controlling of two main parameters: the vermicompost temperature and moisture. We used a digital temperature controller to measure the heat supplied and regulated by the fan and heater unit.

To characterize the dynamics of vermicompost moisture provided by a fog-diffuser system, we used a resistivity sensor. This hygrometer sensor was powered by a small PCB (Printed Circuit Board) with both digital and analog outputs [36].

Due to the population growth, human life quality improvement, and the advances in industry and agriculture, the production of SS has reached a critical state [37]. Statistics show that each person produces about 26 kg of dry sludge per year [38]. Because of the high percentage of organic matter and the high degree of toxicity of SS, researchers eager to decontaminate this material by using it as a raw material in another industry [39]. One of the most popular cost-effective ways is to compost these materials by microorganisms, which leads to stability, maturation, unpleasant odors removal, and the production of materials with a high percentage of humus [40].

SR is useful to VR and worm production to transform any hazardous organic wastes into high agronomic quality composts. Thus, after designing and building the SR, the objectives of this study are to assess the effect of this SR on worm and cocoon quantity and VR quality for treating SS, cow manure (CM), and sugarcane bagasse (SB).

2. Materials and Methods:

2.1 Reactor Overall Description

Due to the above-mentioned practical factors, in this research, we applied the closed reactor method in a restricted environment to control environmental factors. This situation protects the substrate from wind and direct sunlight. We measured the percentages of different materials and the significant factors for the worm growth process, such as temperature, humidity, and pH alternately.

As shown in Fig. 1, an aeration system is located on the bottom of the reactor under the mesh plate. A blower blows the outside air into the box to prevent leachate sedimentation, and maintain the required oxygen level. Moreover, when the temperature drops, the warm air enters the box. This aeration technique also prevents adhesion among the substrate materials. A layer of tiny stones is poured on the aeration hole to prevent the entry of the substrate. Since the appropriate height of the vermicompost is 20 to 30, we choose a 30-cm height.

At the top of the vermicompost material, there is a 20-centimeter free space. When the moisture content is reduced, the fog diffuser installed on the left side above the box will have the power to disperse water to all surfaces of the material. The fog diffuser source is tap water, which enters the pipe with pressure. The moisture meter and thermometer are placed in the vertical middle axis of the chamber to control optimal conditions. In the upper outer part of the box, we installed a carbon odor filter. Since the worms use even the smallest holes to leave the substrate, we enlightened LED (Light Emitted Diode) lamps placed on the bottom of the odor filter. These lamps prevent the worms from exiting the substrate through the filter. Another obstacle for this purpose is the use of continuous light in the upper part of the odor filter.

To accelerate the vermicompost production, we never turned off the lamps, since the worms did not stop their activity during the nights. The reactor body is made of 2 layers of compact plastic which are filled with styrofoam. This styrofoam is a thermal and moisture insulator to minimize the amount of thermal and humidity waste. We designed the reactor dimensions based on reference [41]. Finally, we designed a box of 50 centimeters height and width and 1-meter length. As seen in the figure, the box is placed on a movable base with a height of 30 cm to facilitate carrying, loading, and unloading (Fig.1).

2.2 Important Parameters of VR and the Chosen Sensor for the SR

2.2.1. Moisture

The moisture content in VR plays an important role in optimizing the bioconversion and mineralization of organic wastes. The previous studies report the moisture content of 45-75% to be optimal for the productivity and growth of the worms [42–45].

We used a resistivity sensor YL-69 to characterize the dynamics of substrate moisture. This hygrometer sensor is powered by a small PCB with both digital and analog outputs. The PCB module comes with an LM393 comparator chip and a potentiometer. The LM393 comparator compares two voltages and returns a digital signal as the output. The YL-69 hygrometer sensor is an electrical resistance sensor that consists of two electrodes. It works by passing a current across the two electrodes through the substrate and returns the measurement of resistance for substrate moisture content determination. The value of resistance was measured by the changes in voltage between horizontal electrode distances within the electrical field created by the current via the electrodes [36]. Electrical resistance is a function of the amount of soil moisture (water). If the substrate is dry, the resistance will be high, and if the substrate is humid, the resistance between the two probes will be very low. The analog output varies from 0 to 1023; 0 indicates the lowest resistance value (the highest moisture), whereas 1023 indicates the highest resistance value (the lowest moisture). The advantages of this moisture sensor are its low cost, ability to provide analog and digital outputs, power saving, and high sensitivity [46]. Soil resistivity for a homogeneous soil is computed by [47]:

$$R_s = 4\pi aR = 12.6aV/I$$

where R_s is the soil resistivity (ohm-cm), R is the soil resistance, I is current, V is the voltage, and a is the space between the electrodes (cm).

The humidity is supplied by a fog diffuser system with a solenoid valve, a plastic nozzle, and connecting hoses. We used a JP fluid control brand solenoid valve, ST-DA type, normally close function, ¼ inch, direct valve operation, with 230V 50HZ coil, which shuts off or allows the fluid flow. When the solenoid valve in a control unit is energized, it generates a magnetic field that pulls a plunger or pivoted armature against the action of a spring. When de-energized, the plunger or pivoted armature is returned to its original position by the spring action. We used a ¼ inch plastic fog nozzle, which is quick and straightforward to install and can be adjusted to closed, misting, or spraying mode. It is made of high-quality plastic material that is lightweight, durable, water-saving, and eco-friendly.

2.2.2. Temperature

The worms do not die at the point of the water freezing. However, they do not continue to function and crawl deep into the soil to survive. They also can reproduce in temperatures up to 31 °C. However, the appropriate temperature, which they can reach maximum reproduction in, is 15-26 ° C [48].

We used an STC-1000 digital temperature controller to measure and control the temperature. This unit is a versatile small electronic temperature controller with heating and cooling functions plus an audible alarm. This advanced temperature controller comes with a 2x relay for heating-cooling, control functions from -50 to 90 °C, NTC (10K) waterproof type thermistors, 0.1°C measuring, 0.1°C control accuracy, 220VAC 50HZ Input power, and a 2x10A relay output. It can also demonstrate temperature measurements on an LED display and easily adjust its parameters using the SET key [49, 50]. F0-F4 codes are customizable parameters that include these items, respectively: temperature set value, difference set value, compressor delay time, and temperature calibration value. The controller activates the error alarm function when the measured temperature exceeds the temperature measuring range or when the sensor opens a circuit or short circuit. All the running functions will pause with the buzzer alarm.

We set a fan and a heater to provide the desired temperature. This simple system operates like a hairdryer with a few differences. The heating section includes a waved heating wire wound around mica, insulated with these specifications; 230V and 450W. The fan section consists of a universal motor with these specifications: 230V AC, 50 Hz, 50W, and 13800 rpm, Johnson brand [51].

2.2.3. pH

Earthworms are very sensitive to the pH of soil or waste. Thus, it can sometimes act as the earthworm distribution limitation factor. The worms can survive and grow in a pH range of 5 to 9 [52, 53]. Also, some research suggests that the optimum pH for most species of earthworms is about 7.0 [54–56]. This parameter can be measured at the first loading, daily, and end of the VR. According to limited variations of pH during the VR, we did not consider any devices to measure it.

2.3. Control Unit

The main objective of the LOGO! PLC is sensor-reading and output generation based on the logic created in the program. For the control system, we adopted the Siemens LOGO! 12/24RCE series.

It is a small-scale programmable controller produced by Siemens, which integrates eight inputs and four outputs. This series has an operator and display panel with background lighting, which makes it possible for the program to be written quickly with very preconfigured standard functions in two ways; using the control panel or PC programming LOGO!. Soft Comfort is the LOGO! programming software that you can use on your PC to quickly and easily create, test, modify, save, and print the circuit programs. We used four relay outputs (10A) and the LOGO! menu provided a setting where you can choose to use two (Inputs I7 and I8 are available as analog inputs by default), or four, or even zero analog inputs. The rest of the inputs are considered digital input [34].

LOGO! must be connected to an external power supply which supplies a voltage of 12 VDC or 24 VDC. We installed a Mean Well RD-35B as a power supply. This 35 W dual-output power supply produces 5 VDC and 24 VDC. The input voltage is 230 VAC 50 HZ and output 24 VDC supply the LOGO! and 5 VDC supply YL-69 moisture sensor PCB board [57].

2.4. System Software Implementation

The controlling parameters in this system are temperature and humidity. While the fan and heater unit supplies the temperature level, the fog diffuser provides humidity. We utilized a standard NTC temperature sensor to measure the temperature level, which we installed in the middle of the reactor for more precise measurement. This sensor is connected to the LOGO! by the STC-1000 digital thermostat controller. This controller is economical, has acceptable measurement accuracy, easy temperature adjustment, and desired temperature modification without changing the LOGO! control logic. We calibrated the sensor using 0 °C water and dissolved ice and applied the corresponding settings to the controller. To prevent the fan and heater from starting and stopping frequently, we set a 2 °C tolerance interval for them. For example, if we set the optimum temperature at 20 °C, by lowering the temperature to 18 °C, the first relay of the controller will be set to heating mode, switches, and the LOGO! DI1 activates. In these conditions, the fan and heater start to reach a temperature of 20 °C. At this time, the relay is switched off, and the DI1 is set on zero. As a result, the heater will be the first to switch off, and then the fan shuts down after 3 seconds. This 3-second delay is intended to transfer the rest of the heat to the reactor and create a uniform airflow. On the second controller relay, which we set on cool mode when the temperature reaches 22 °C, the relay state changes, and the DI2 becomes active. In this case, the fan will only start to decrease the temperature to 20 °C and then turns off.

We used a 2-wire YL-69 sensor to measure vermicompost moisture. This sensor is connected to a module with a comparator chip LM393 with both digital and analog outputs ranging from 0 to 4.2 volts. These outputs are connected to I3 and I8 in LOGO!, respectively. The I8 input in the LOGO! is an analog input that reads the moisture content of the reactor. In this system, we defined the permissible humidity range between 45 and 75 percent. After loading, we used the Lutron PMS-714 moisture meter to calibrate the humidity of the system. The performance of the module is such that the more the humidity level decreases, the more the output voltage increases and vice versa. The potentiometer on the module also adjusts its digital output sensitivity point, so that the output activates if the humidity level drops lower than a specific value.

The control logic implemented in this section is that an analog comparator sends a start command to the fog diffuser by reducing humidity to 45%. We experimented with different templates for the fog diffuser performance time and finally defined its optimal state as a 5-second working period and a 3-minute pause. By increasing the humidity up to 75%, which the user sets by the potentiometer, the fog diffuser shuts down. Also, in any circumstances, if the moisture content increases unintentionally and reaches an 80% threshold, the fan embedded in the reactor activates and reduces moisture to the optimum level.

Fig. 2 shows the logic used in the LOGO! and Fig. 3 shows the schematic electrical diagram.

2.5. Reactor performance assessment

2.5.1. Experiment setup

We used three types of wastes in the VR process: SS was provided by a wastewater treatment plant located in Tehran, Iran, CM was provided by the farm of Amol, Iran, SB was provided by the farm of Ahvaz, Iran. We left SS and CM in the room for two weeks to reduce the intensity of their stinky odor, which causes the worm to escape from the bed.

We sieved the SB herbal residue in 1 cm mesh to find uniform particle size and increase the homogeneity combined with other materials. We should combine these three materials in the best way to feed the worms from all parts of the bed. Otherwise, the worms do not eat parts of the bed with the most SS (Fig. 4).

As CM contains microorganisms that help to destroy the organic matter structures, the Eisenia Fetida worm body is compatible with this substrate, which causes a good growth and reproduction rate [45]. Therefore, we placed the worms prepared by Mehrazin Company, in the manure bed for 30 days to increase the number of adult worms and be ready to live in another bed. We presented the physicochemical properties of raw materials in table 2.

To prepare the samples, we placed a container with dimensions of 40×40×15 cm in an incubator with a temperature of 25 °C and 60-70% moisture, which are the optimum condition according to the previous studies [42–44, 48].

We made 16 holes with 1 cm diameter in the bottom and wall of the containers to increase drainage. Then, we covered the created mesh with banana leaves that had been decomposed for two weeks to prevent materials from passing from these holes. Also, we covered the top of the containers with plastics and made several holes with needles to keep the moisture in the desired range. Finally, we loaded the mixed materials in the containers and the reactor simultaneously. We did all samples in three replicates and compared the results of the experiments to determine the efficiency of the SR.

We calculated the required volume of materials and the number of worms per bed based on the principle that each Eisenia Fetida worm can digest half its weight of food per day [45]. As a result, each container contains 1.5 kg of SS, CM, and SB, with a weight ratio of 70%, 20%, and 10%. According to the bellow calculations, we need 120 mature worms with an average weight of 0.4 grams to digest these substances for 60 days:

Number of worms = 120

The average weight of each worm = 0.4 grams

The nutrition amount of each worm per day = 0.2 grams

The estimated time for vermicompost maturation = 60 days

Consequently, we obtained the weight of required materials in each bed according to the following calculations:

$120 \times 0.2 = 24$ grams of food per day

$24 \times 60 = 1440$ grams of food for 60 days

Which we equivalent it to 1500 grams (1.5 kg). We showed the weight of materials and the number of worms per substrate in table 1. Based on 30 centimeters height of waste in SR, we calculated the loading weight.

$1 \times 0.5 \times 0.3 = 0.15\ m^3$ Reactor volume

$0.4 \times 0.4 \times 0.15 = 0.024\ m^3$ Container volume

$0.15 \div 0.024 = 6.25$ Reactor volume / Container volume

After the bed preparation and incubator temperature adjustment, we transferred the adult worms into the new substrate. We checked the humidity of the container substrate once a day to keep it at the chosen level. To prevent unpleasant odors, we revolved the materials manually every three days.

We loaded the SR 9.5 Kg of materials with the mentioned percentages and 760 adult worms (Table 1). In this reactor, we can precisely adjust the humidity and temperature. As the moisture percentage in the containers was 60-70, we set 65% moisture in the reactor, and we programmed it to keep the moisture constant between -5% and +5%.

We determined several analyses to evaluate the quality of the produced fertilizer. We took samples of each substrate from the container on days 0^{th} and 60^{th}, and the reactor on days 0^{th} and 31^{st}. We used these samples to measure the content of organic matter, total organic carbon, total nitrogen, nitrate-nitrogen (NO_3^-), phosphate (PO_4^{3-}), moisture, EC, pH, ammonia nitrate (NH_4^+), ammonium to nitrate ratio, carbon to nitrogen ratio, fecal coliform, and growth rate of worms and cocoons. We air-dried a part of each treatment sample to analyze them by electron microscopy (SEM).

We determined the organic matter and moisture by drying the samples in the oven for six h at 550 °C and 12 h at 105 °C, respectively. To determine the contents of total organic carbon (TOC) and total nitrogen (TN), we used an elemental analyzer (Elemental Vario EL, German). We used the mixture of dried samples and distilled water (1:50, w/v) to measure the EC (Electrical Conductivity) and pH by a conductivity meter and a pHS-3C acidometer. We used the same water mixture to determine the ammonia-nitrogen (NH_4^+), nitrate-nitrogen (NO_3^-), and phosphate (PO_4^{3-}) by the spectrophotometric methods. To analysis fecal coliform, we used the US EPA guide [58].

2.5.2. Statistical assessment

We evaluated differences between treatments by one-way ANOVA (Analysis of Variance) with a significant level at $p < 0.05$ using the SPSS 16.0 software. ANOVA is a collection of statistical models and their associated estimation procedures (such as the "variation" among and between groups) used to analyze the differences among means. We used many parameters such as organic matter, total organic carbon, total nitrogen, nitrate-nitrogen (NO_3^-), phosphate (PO_4^{3-}), moisture, EC, pH, ammonia nitrate (NH_4^+), ammonium to nitrate ratio, carbon to nitrogen ratio, fecal coliform, the number of cocoons, and growth rate of worms to evaluate significant correlated factors affecting vermicompost stabilization in two treatments. We plotted them by using Principal Component Analysis (PCA) implemented in the Statistica 10.0 software (Stat soft Inc. Tulsa, the USA).

2.5.3. Results and discussions

2.5.3.1. Effects of the reactor on worms and the physicochemical and bacterial properties of the vermicompost

We showed all the first and final physicochemical and bacterial parameters of the produced vermicompost of two treatments in table 2. The most important difference between the two treatments is the vermicompost maturation time. The raw materials reach full maturity in 31 days (about 50% less time than in the container) under controlled conditions of the reactor.

According to the average of the physicochemical properties with the ANOVA, the content of moisture, phosphorus, and organic matter in the TC with averages of 68.43, 4.63, and 49.74 are at a higher level than TR with averages of 65.03, 3.89, and 38.93, respectively. EC of the TR with an average of 230.94 is at a higher level than the TC with an average of 210.01. The main point in this table is, the significance of only 4 of the 12 components in the two treatments which means, there is no significant difference in these two treatments in all physicochemical and bacterial properties. As we showed the standard ranges of vermicompost important parameters in Table 3 [59], the produced vermicompost properties, in both treatments, are in class A except for the amount of C/N. Moreover, parameter C of vermicompost in TC is less than the minimum standard range of class A by 0.3, which is negligible.

According to Table 4, which shows the growth rate of worms and the number of cocoons, there is a significant difference at the level of 1% in all parameters related to the growth and reproduction of worms. As the number of cocoons depends on the number of adult worms which in the SR is 6.33 times to the container, we divided the cocoons number of the SR by 6.33. The growth rate of worms and the number of cocoons in the SR with averages of 99.23, and 1245/6.33= 196.6 are at a higher level than the container with averages of 75.36, and 151.00, respectively. The maximum amount of difference between these two substrates is related to the growth rate of the worms.

In general, by increasing worms' activity and growth rate, the organic matter percentage of the substrate in the SR decreases more rapidly.

Based on figure 5, the cumulative variance of the two principal components is 95.8% of the total data changes (first component: 68.4% and second component: 27.2%). In this case, we analyzed the vermicompost physicochemical and worms' growth components together. According to the cumulative variance of the two principal components, this assessment of parameters is reasonable. This figure shows that nitrate had the greatest effect on the first principal component after that, the most effective parameters are carbon, pH, phosphorus, and the maximum number of cocoons, respectively. These effective parameters show the capability for decomposition and remineralization of sludge and worms reproduction in a suitable condition of the substrate.

In addition to pH, carbon to nitrogen ratio, and moisture content have a greater role in the second principal component.

In general, several analyses on worm growth and reproduction have the most role on the second factor than other parameters.

Comparing the physicochemical and bacterial properties of the produced fertilizer in two treatments, the parameters of pH, fecal coliform, phosphorus, organic matter, and C/N in TR decreased and the parameters of carbon, nitrogen, nitrate, ammonia nitrate, and EC increased slightly. However, the growth rate of the worm and the number of cocoons in the reactor is about 30% higher than the container worm. The moisture content parameter was constant as expected and was equal in both treatments. Finally, by using an SR, we can obtain fertilizer with the same quality as the container in 50% less time and a 30% higher worm growth rate.

2.5.3.2. Effects of the reactor on the microstructure of sludge

We investigated the microstructural characteristics of the raw and conditioned sludge samples through scanning electron microscopy (SEM).

Fig. 6 shows the SEM images of SS and its final products in TR and TC treatments. The raw SS surface is compact and platy without any voids or channels.

After 60 days of VR in the container and 31 days in the reactor, the outer surface of the specimens becomes rough with cracks and various sizes of holes. It is probably due to hydrolysis reactions by hydrolase enzymes secreted by bacterial communities and earthworm intestines [60, 61]. The number of heterogeneous pores and irregularities in the surface of samples in each treatment increased significantly. These changes are more in Tr and indicate more sludge degradation in the controlled environment of the reactor. These observations confirm the importance of the number of earthworms and their activity in accelerating the sludge degradation process.

To use the produced vermicompost, we should unload the top layers of the substrate smoothly and let the worms go down. Then, we can separate and use them in another substrate easily. Moreover, it is recommended to let the cocoons stay in a little substrate in order to put them in the new materials without any mortality.

The produced vermicompost in the container was placed in an incubator and controlled temperature, in industry, the substrate is not under a constant temperature. Temperature changes lead to slower production. Besides, due to the controlled environment of the reactor and the elimination of leachate and odor of the substrate, we can use this portable reactor in all situations to produce fertilizer of any hazardous organic raw material. The usage of conventional reactors or containers is not recommended in residential environments due to their low level of hygiene. Moreover, to prevent leachate penetration of hazardous organic waste into the soil and groundwater, conventional methods are not usable in these matters. The reactor was designed and built for $215 and can run on a larger scale with only a little more financial investment. For instance, it can run four times the size of the current system. In this case, this system controller (LOGO!) meets the needs of the system. To measure the temperature and moisture more precisely, we can consider two sensors for each parameter in the control system. The final record is the average value of the measured numbers. Also, to ensure a steady supply of temperature and moisture, we can install two fans and heaters. We recommend placing two nozzles on both sides of the chamber. Considering the price of a larger box, the cost of upgrading the current system to such a volume would be an additional $60.

3. Conclusion

VR reactors are considered a new option to advance and expand the fields of organic waste management and the best fertilizer producer. Thus, evaluating all aspects of new vermicomposting reactors to increase efficiency and production speed, is an inevitable fact. This issue helps us achieve more desired results in the waste management and agriculture industry. In this paper, we introduced a semi-industrial SR. This process is controlled by LOGO!; a Siemens intelligent controller. The control parameters in this system are moisture and temperature of the vermicompost (substrate), which are measured through the sensors, controlled by the control logic in LOGO!, and supplied by a fan and heater unit and a fog diffuser.

In this designed reactor, we used SS, CM, and SB to produce the same quality vermicompost as in the container with a 50%-time reduction, 30% increase of worm growth rate and cocoons number, and the hygiene of the production environment. The parameters such as moisture, phosphorus, and organic matter in the TC with averages of 68.43, 4.63, and 49.74 are at a higher level than TR with averages of 65.03, 3.89, and 38.93, respectively. Moreover, the EC of the TR with an average of 230.94 is at a higher level than the TC with an average of 210.01. Overall, the parameters of pH, fecal coliform, phosphorus, organic matter, and C/N in TR decreased but the parameters of carbon, nitrogen, nitrate, ammonia nitrate, and EC increased slightly.

The estimate cost of the reactor is around $215 and we need a little more cost to build it on a larger scale. Due to the comprehensive observance of cleanliness in this design, it is a very suitable environment for VR from any organic hazardous waste. Due to its odor elimination filter, it can be implemented in any personal house and public zone.

Declarations

Ethical Approval: It has not been published elsewhere and that it has not been submitted simultaneously for publication elsewhere.

Authors Contributions: **Mona Ghorbani**: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization, Project administration. **Mohammad Reza Sabour**: Supervision. **Masoud Bidabadi**: Software.

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Reference

1. Haynes, R.J., Naidu, R.: Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. Nutrient Cycling in Agroecosystems. 51, 123–137 (1998). https://doi.org/10.1023/A:1009738307837
2. Garg, V.K., Yadav, Y.K., Sheoran, A., Chand, S., Kaushik, P.: Livestock excreta management through vermicomposting using an epigeic earthworm Eisenia foetida. Environmentalist. 26, 269–276 (2006). https://doi.org/10.1007/s10669-006-8641-z
3. Gupta, R., Garg, V.K.: Stabilization of primary sewage sludge during vermicomposting. Journal of Hazardous Materials. 153, 1023–1030 (2008). https://doi.org/10.1016/j.jhazmat.2007.09.055
4. De Neve, S., Hofman, G.: Influence of soil compaction on carbon and nitrogen mineralization of soil organic matter and crop residues. Biology and Fertility of Soils. 30, 544–549 (2000). https://doi.org/10.1007/s003740050034
5. Trinsoutrot, I., Nicolardot, B., Justes, E., Recous, S.: Decomposition in the field of residues of oilseed rape grown at two levels of nitrogen fertilisation. Effects on the dynamics of soil mineral nitrogen between successive crops. Nutrient Cycling in Agroecosystems. 56, 125–137 (2000). https://doi.org/10.1023/A:1009838618133
6. Hemalatha, B.: Vermicomposting of fruit waste and industrial sludge. International Journal of Advanced Engineering Technology. III, 60–63 (2012)
7. Huang, K., Li, F., Wei, Y., Chen, X., Technology, X.F.-B., 2013, U.: Changes of bacterial and fungal community compositions during vermicomposting of vegetable wastes by Eisenia foetida. Elsevier. (2013)
8. Fu, X., Huang, K., Chen, X., Li, F., Cui, G.: Feasibility of vermistabilization for fresh pelletized dewatered sludge with earthworms Bimastus parvus. Bioresource Technology. 175, 646–650 (2015). https://doi.org/10.1016/j.biortech.2014.11.007
9. Huang, K., Xia, H., Cui, G., Li, F.: Effects of earthworms on nitrification and ammonia oxidizers in vermicomposting systems for recycling of fruit and vegetable wastes. Science of the Total Environment. 578, 337–345 (2017). https://doi.org/10.1016/j.scitotenv.2016.10.172
10. Lazcano, C., Gómez-Brandón, M., Domínguez, J.: Comparison of the effectiveness of composting and vermicomposting for the biological stabilization of cattle manure. Chemosphere. 72, 1013–1019 (2008). https://doi.org/10.1016/j.chemosphere.2008.04.016

11. Alidadi, H., Saffari, A.R., Ketabi, D., Peiravi, R., Hosseinzadeh, A.: Comparison of Vermicompost and Cow Manure Efficiency on the Growth and Yield of Tomato Plant. Health Scope. 3, (2014). https://doi.org/10.17795/jhealthscope-14661

12. Sharma, K., Garg, V.K.: Comparative analysis of vermicompost quality produced from rice straw and paper waste employing earthworm Eisenia fetida (Sav.). Bioresource Technology. 250, 708–715 (2018). https://doi.org/10.1016/j.biortech.2017.11.101

13. Castillo-González, E., Giraldi-Díaz, M.R., De Medina-Salas, L., Sánchez-Castillo, M.P.: Pre-composting and vermicomposting of pineapple (Ananas comosus) and vegetable waste. Applied Sciences (Switzerland). 9, (2019). https://doi.org/10.3390/app9173564

14. Majlessi, M., Eslami, A., Najafi Saleh, H., Mirshafieean, S., Babaii, S.: Vermicomposting of food waste: Assessing the stability and maturity. Iranian Journal of Environmental Health Science and Engineering. 9, 25 (2012). https://doi.org/10.1186/1735-2746-9-25

15. Ghorbani, M., Sabour, M.R.: Global trends and characteristics of vermicompost research over the past 24 years, https://link.springer.com/article/10.1007/s11356-020-11119-x, (2021)

16. Ghorbani, M., Dahrazma, B., Fazlolah Saghravani, S., Yousofizinsaz, G.: A comparative study on physicochemical properties of environmentally-friendly lightweight bricks having potato peel powder and sour orange leaf. Construction and Building Materials. 276, 121937 (2021). https://doi.org/10.1016/j.conbuildmat.2020.121937

17. Ansari, A.A., Rajpersaud, J.: Physicochemical Changes during Vermicomposting of Water Hyacinth (Eichhornia crassipes) and Grass Clippings. ISRN Soil Science. 2012, 1–6 (2012). https://doi.org/10.5402/2012/984783

18. Fernández-Luqueño, F., Reyes-Varela, V., Martínez-Suárez, C., Salomón-Hernández, G., Yáñez-Meneses, J., Ceballos-Ramírez, J.M., Dendooven, L.: Effect of different nitrogen sources on plant characteristics and yield of common bean (Phaseolus vulgaris L.). Bioresource Technology. 101, 396–403 (2010). https://doi.org/10.1016/j.biortech.2009.07.058

19. Contreras-Ramos, S.M., Escamilla-Silva, E.M., Dendooven, L.: Vermicomposting of biosolids with cow manure and oat straw. Biology and Fertility of Soils. 41, 190–198 (2005). https://doi.org/10.1007/s00374-004-0821-8

20. Ndegwa, P.M., Thompson, S.A.: Integrating composting and vermicomposting in the

treatment and bioconversion of biosolids. Bioresource Technology. 76, 107–112 (2001). https://doi.org/10.1016/S0960-8524(00)00104-8

21. Aira, M., Monroy, F., Domínguez, J.: Eisenia fetida (Oligochaeta: Lumbricidae) modifies the structure and physiological capabilities of microbial communities improving carbon mineralization during vermicomposting of pig manure. Microbial Ecology. 54, 662–671 (2007). https://doi.org/10.1007/s00248-007-9223-4
22. Vijayan, T., ya, D.: Automatic water and fertilizer sprinkling system based on PLC for Agriculture application. International Journal of MC Square Scientific Research. 9, 126–134 (2017). https://doi.org/10.20894/ijmsr.117.009.002.015
23. Futao, Z., Wei, D., Yiheng, X., Zhiren, H.: Programmable logic controller applied in steam generators water levels. In: Conference Record - IAS Annual Meeting (IEEE Industry Applications Society). pp. 1551–1556 (1996)
24. Bayindir, R., Cetinceviz, Y.: A water pumping control system with a programmable logic controller (PLC) and industrial wireless modules for industrial plants-An experimental setup. ISA Transactions. 50, 321–328 (2011). https://doi.org/10.1016/j.isatra.2010.10.006
25. Ding, J.T., Tu, H.Y., Zang, Z.L., Huang, M., Zhou, S.J.: Precise control and prediction of the greenhouse growth environment of Dendrobium candidum. Computers and Electronics in Agriculture. 151, 453–459 (2018). https://doi.org/10.1016/j.compag.2018.06.037
26. Liu, X., Zhang, T., Li, B., Tian, F., … Y.T.-2018 37th C., 2018, U.: Wireless measurement and control system of environmental parameters in greenhouse based on ZigBee technology. ieeexplore.ieee.org. (2018)
27. Erickson, K.T.: Programmable logic controllers. IEEE Potentials. 15, 14–17 (1996). https://doi.org/10.1109/45.481370
28. Edan, Y., Pliskin, N.: Transfer of software engineering tools from information systems to production systems. Computers and Industrial Engineering. 39, 19–34 (2001). https://doi.org/10.1016/S0360-8352(00)00062-0
29. Ioannides, M.G.: Design and implementation of PLC-based monitoring control system for induction motor. IEEE Transactions on Energy Conversion. 19, 469–476 (2004). https://doi.org/10.1109/TEC.2003.822303
30. Alphonsus, E.R., Abdullah, M.O.: A review on the applications of programmable logic controllers (PLCs),

https://www.sciencedirect.com/science/article/pii/S1364032116000551, (2016)

31. Huuck, R.: Semantics and Analysis of Instruction List Programs. In: Electronic Notes in Theoretical Computer Science. pp. 3–18 (2005)

32. BS EN 61131-1:1994: Programmable controllers. General information. Bsi

33. Liu, J., Lv, Y. jun: The Application of LOGO! in Control System of a Transmission and Sorting Mechanism. In: Communications in Computer and Information Science. pp. 231–236. Springer, Berlin, Heidelberg (2011)

34. A5E00324307-01: Drawing number Edition 1 Product information. (2001)

35. Sita, I.V.: Train comfort, access and security using KNX and LOGO! controllers. In: Electrical Systems for Aircraft, Railway and Ship Propulsion, ESARS (2012)

36. Tan, W.Y., Then, Y.L., Lew, Y.L., Tay, F.S.: Newly calibrated analytical models for soil moisture content and pH value by low-cost YL-69 hygrometer sensor. Measurement: Journal of the International Measurement Confederation. 134, 166–178 (2019). https://doi.org/10.1016/j.measurement.2018.10.071

37. IAEA: Use of irradiation for chemical and microbial decontamination of water, wastewater and sludge - Final report of a co-ordinated research project 1995-1999- IAEA-TECDOC-1225. (2001)

38. Borrely, S.I., Cruz, A.C., Del Mastro, N.L., Sampa, M.H.O., Somessari, E.S.: Radiation processing of sewage and sludge. A review. Progress in Nuclear Energy. 33, 3–21 (1998). https://doi.org/10.1016/s0149-1970(97)87287-3

39. Zhang, L., Xu, C. (Charles), Champagne, P.: Energy recovery from secondary pulp/paper-mill sludge and sewage sludge with supercritical water treatment. Bioresource Technology. 101, 2713–2721 (2010). https://doi.org/10.1016/j.biortech.2009.11.106

40. Ouatmane, A., Provenzano, M.R., Hafidi, M., Senesi, N.: Compost maturity assessment using calorimetry, spectroscopy and chemical analysis. Compost Science and Utilization. 8, 124–134 (2000). https://doi.org/10.1080/1065657X.2000.10701758

41. Suthar, S., Singh, S.: Vermicomposting of domestic waste by using two epigeic earthworms (Perionyx excavatus and Perionyx sansibaricus). International Journal of Environmental Science and Technology. 5, 99–106 (2008). https://doi.org/10.1007/BF03326002

42. Palsania, J., Sharma, R., Srivastava, -J K, Sharma, D.: Effect of moisture content variation over kinetic reaction rate during vermicomposting process. Applied Ecology and

Environmental Research. 6, 49–61 (2008). https://doi.org/10.15666/aeer/0602_049061

43. Zularisam, A.W., Zahirah, Z.S., Zakaria, I., Syukri, M.M., Anwar, A., Sakinah, M.: Production of biofertilizer from vermicomposting process of municipal sewage sludge. Journal of Applied Sciences. 10, 580–584 (2010). https://doi.org/10.3923/jas.2010.580.584
44. Manyuchi, M.M.M., Phiri Anthony, Chirinida, N., Muredzi, P., Govhaand, J., Sengudzwa, T.: Vermicompostingof Waste Corn Pulp Blended with Cow Dung Manure using Eisenia Fetida. International Journal of Chemical and Molecular Engineering. 6, 753–756 (2012)
45. Khwairakpam, M., Bhargava, R.: Vermitechnology for sewage sludge recycling. Journal of Hazardous Materials. 161, 948–954 (2009). https://doi.org/10.1016/j.jhazmat.2008.04.088
46. Math, R.K., Dharwadkar, N. V: A wireless sensor network based low cost and energy efficient frame work for precision agriculture. In: 2017 International Conference on Nascent Technologies in Engineering, ICNTE 2017 - Proceedings (2017)
47. Neidle, M.: Electrical Installation Technology. (1982)
48. Garg, V.K., Gupta, R.: Effect of temperature variations on vermicomposting of household solid waste and fecundity of eisenia fetida. Bioremediation Journal. 15, 165–172 (2011). https://doi.org/10.1080/10889868.2011.598487
49. Gim-Krumm, M., Donoso, P., Zuñiga, R.N., Estay, H., Troncoso, E.: A comprehensive study of glucose transfer in the human small intestine using an in vitro intestinal digestion system (i-IDS) based on a dialysis membrane process. Elsevier. (2018). https://doi.org/10.1016/j.memsci.2018.07.080
50. Garcia-Robledo, C., Charlotten-Silva, M., Cruz, C., Kuprewicz, E.K.: Low quality diet and challenging temperatures affect vital rates, but not thermal tolerance in a tropical insect expanding its diet to an exotic plant. Journal of Thermal Biology. 77, 7–13 (2018). https://doi.org/10.1016/j.jtherbio.2018.07.018
51. Johnsonelectric.com: Johnson Electric - Johnson Electric, https://www.johnsonelectric.com/en
52. Sabagh, E.: EL Sabagh et al.: Wheat (Triticum aestivum L.) production under drought and heat stress-adverse effects, mechanisms and mitigation: a review-1-APPLIED ECOLOGY AND ENVIRONMENTAL RESEARCH X(y): pp-pp. WHEAT (TRITICUM AESTIVUM L.) PRODUCTION UNDER DROUGHT AN. Appl Ecol Environ Res. 15, 1625–1651 (2018). https://doi.org/10.15666/aeer

53. Edwards, C.A., Arancon, N.Q.: the Use of Earthworms in Organic Waste Managements

54. Arrhenius, O.: Influence of Soil Reaction on Earthworms. Ecology. 2, 255–257 (1921). https://doi.org/10.2307/1928978

55. Salisbury, E.J.: The Influence of Earthworms on Soil Reaction and the Stratification of Undisturbed Soils. Journal of the Linnean Society of London, Botany. 46, 415–425 (1924). https://doi.org/10.1111/j.1095-8339.1924.tb00496.x

56. Petrov, B.C.: The active reaction of soil (pH) as a factor in the distribution of earthworms. Zoological Journal. 25, 107–110 (1946)

57. Electronics, S.: Mean Well Switching Power Supply - 12VDC, 12.5A, https://www.meanwell.com/productSeries.aspx#, (2016)

58. EPA: Revised Total Coliform Rule And Total Coliform Rule | Drinking Water Requirements for States and Public Water Systems | US EPA. 1–5 (2017)

59. Institute of Standards and Industrial Research of Iran: Vermicompost- Physical and chemical Specifications. 1st. edition. (2011)

60. Das, S., Pandey, P., Mohanty, S., Nayak, S.K.: Evaluation of biodegradability of green polyurethane/nanosilica composite synthesized from transesterified castor oil and palm oil based isocyanate. International Biodeterioration and Biodegradation. 117, 278–288 (2017). https://doi.org/10.1016/j.ibiod.2017.01.015

61. Soobhany, N., Gunasee, S., Rago, Y.P., Joyram, H., Raghoo, P., Mohee, R., Garg, V.K.: Spectroscopic, thermogravimetric and structural characterization analyses for comparing Municipal Solid Waste composts and vermicomposts stability and maturity. Bioresource Technology. 236, 11–19 (2017). https://doi.org/10.1016/j.biortech.2017.03.161

Figures

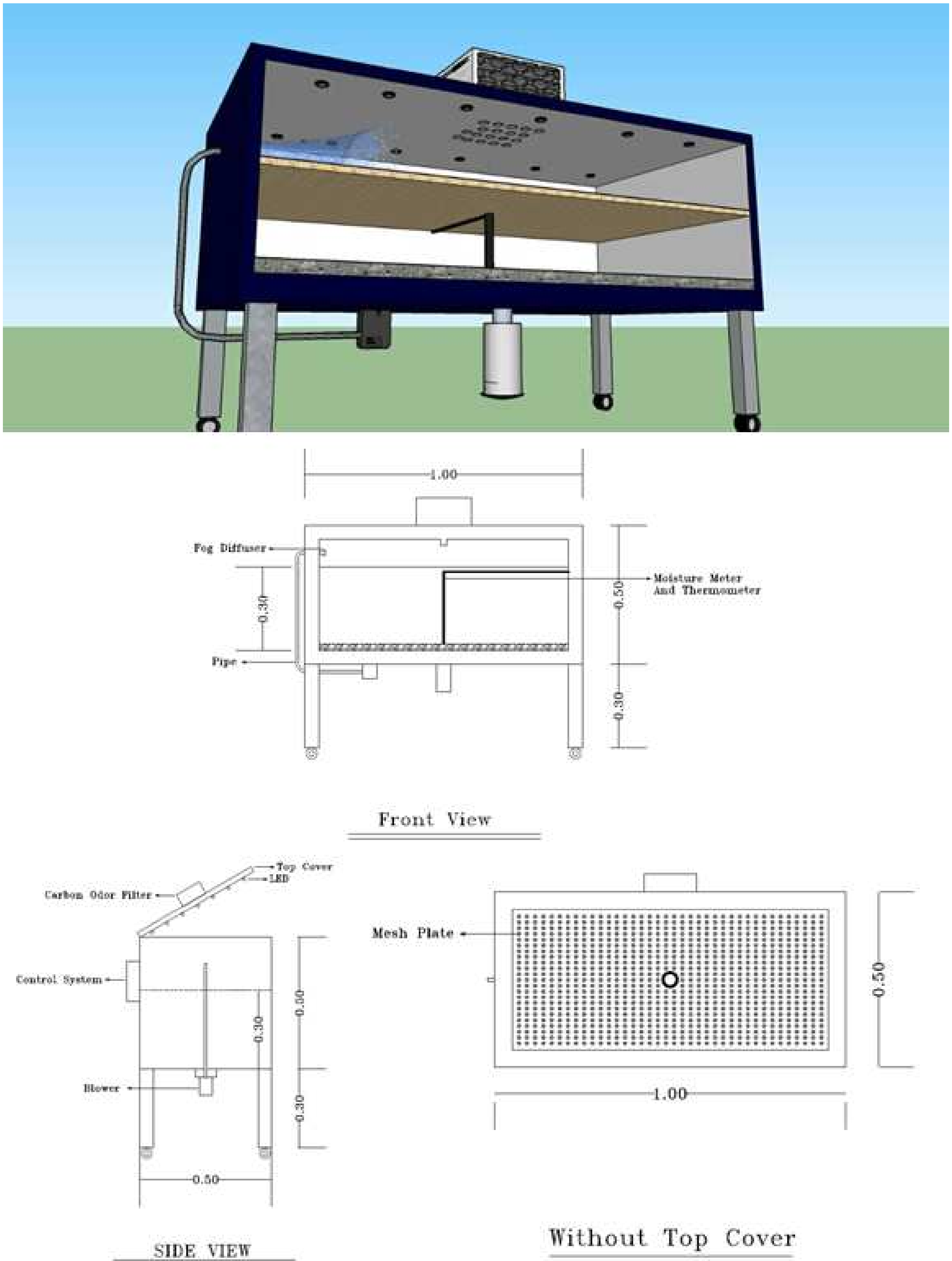

Figure 1

VR smart closed reactor (Structurs are in meter dimentions)

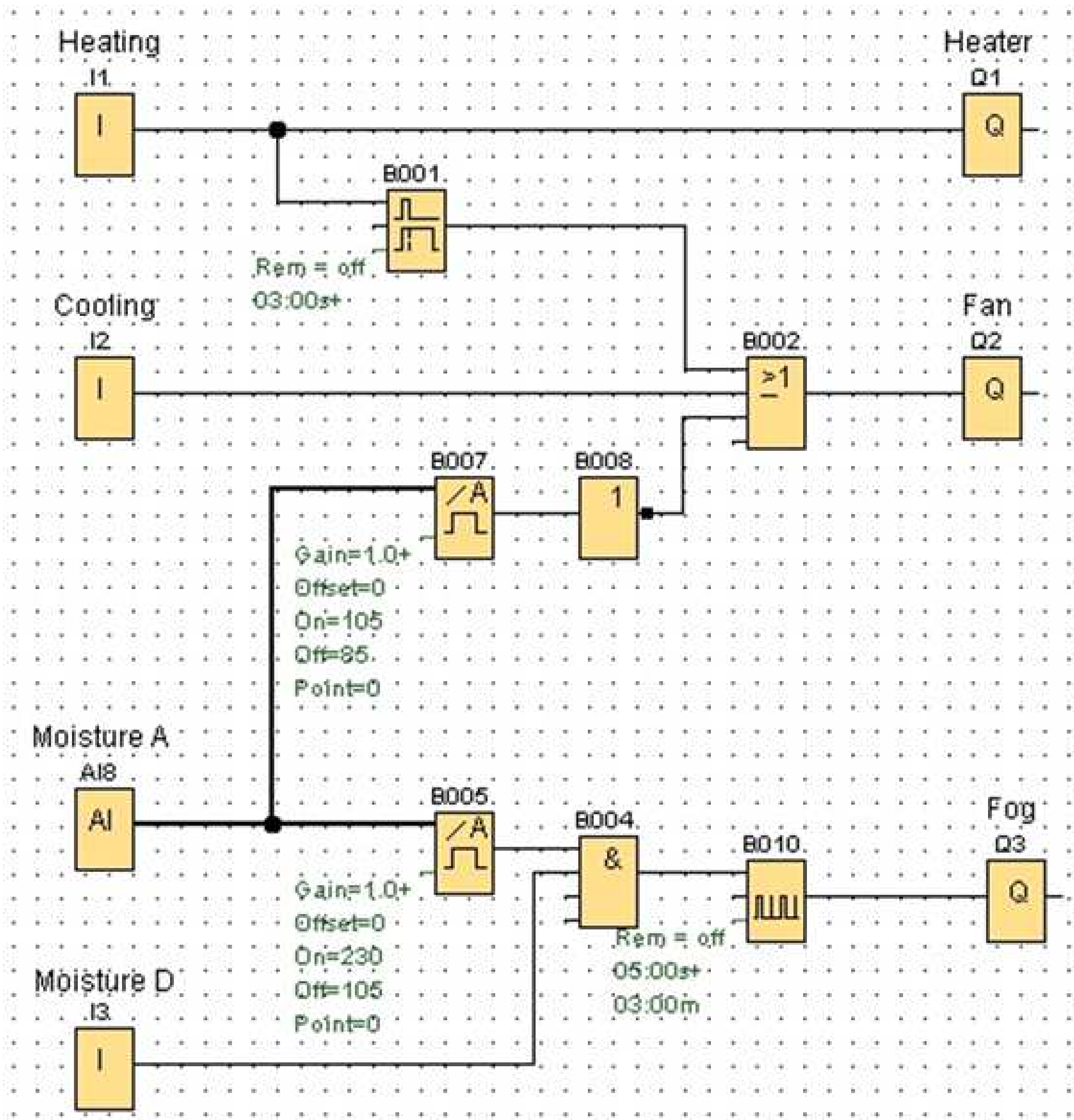

Figure 2

LOGO! logic

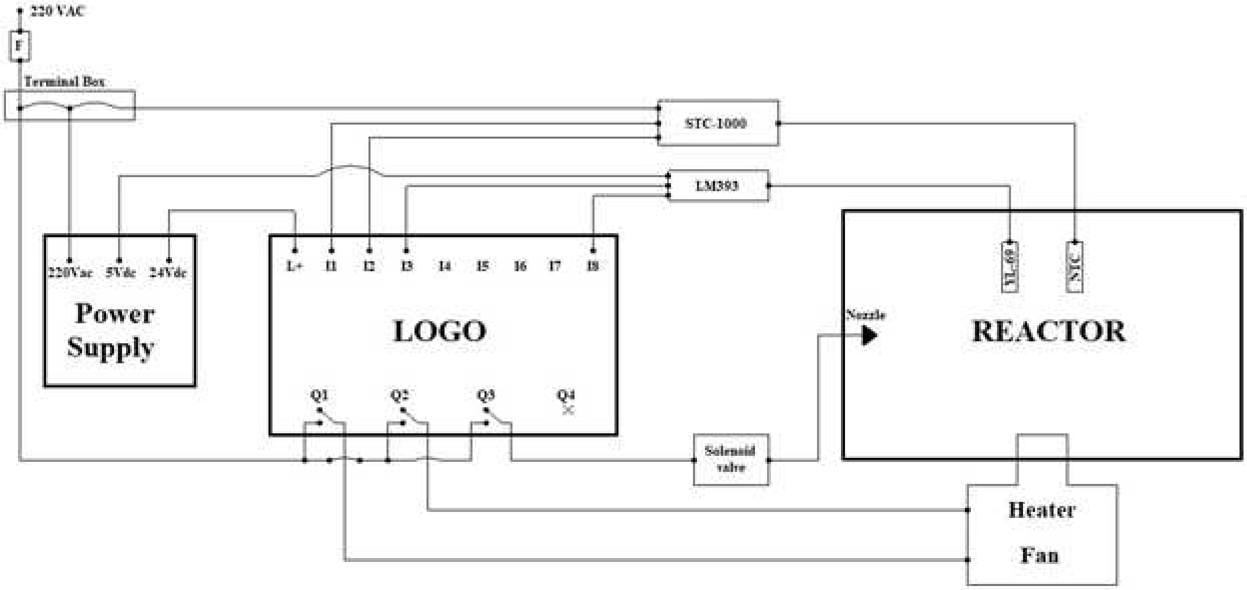

Figure 3

Schematic electrical diagram

Figure 4

The mix of SS, CM, and SB

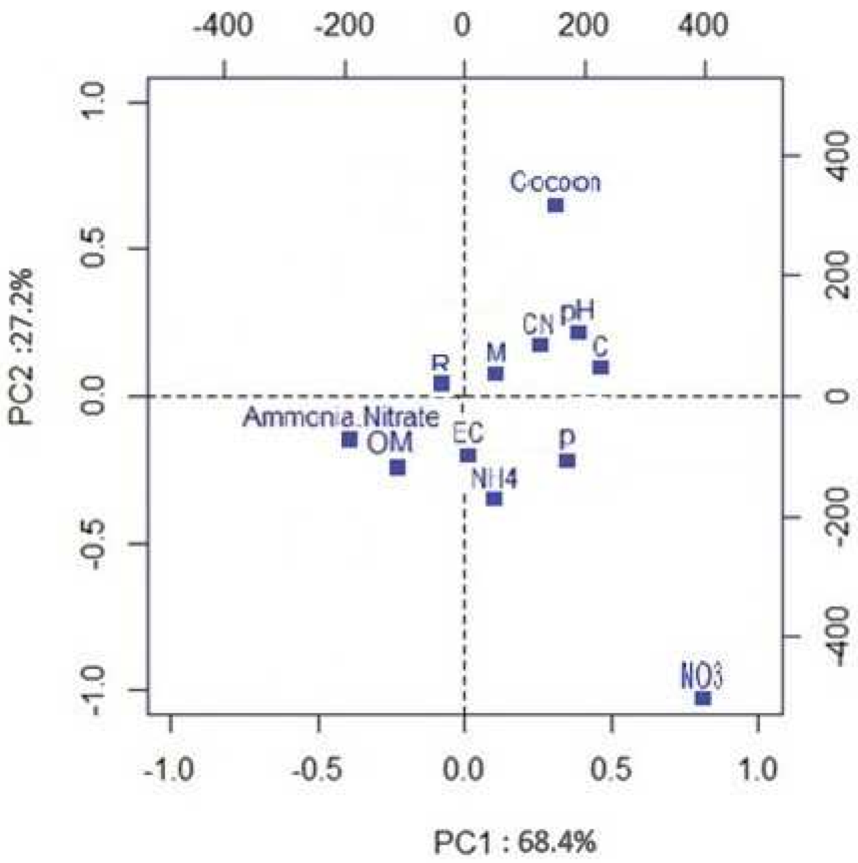

Figure 5

Principal Component Analysis of vermicomposting in the container and the reactor. In this figure, we presented moisture, organic matter, coliform, and worms growth rate by M, OM, Coli, R.

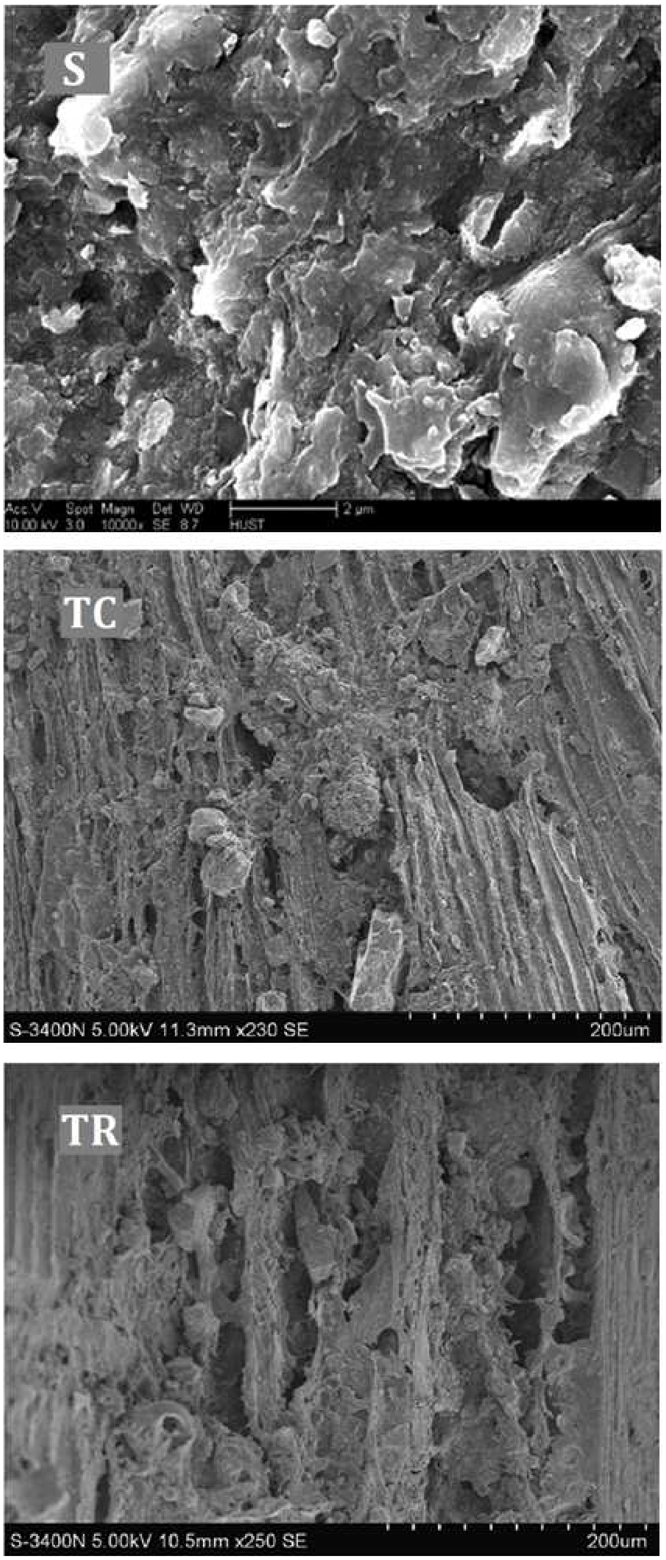

Figure 6

SEM images of the raw sludge and produced vermicompost: (S) SEM image of raw sludge, (TC) SEM image of produced vermicompost in the container, (TR) SEM image of produced vermicompost in the reactor.