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A prototype reactor to compost agricultural wastes of Fusagasuga Municipality. Colombia

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Abstract. Crop and animal production generate a high level of organic waste that causes negative effects on the environment and communities. The use of composting processes can improve the quality of these biowastes. Additionally, the application of technologies such as telemetry and remote sensors, allows optimizing the transformation of organic matter in a more controlled and efficient way. The city of Fusagasugá is well known in agriculture. However, it lacks sustainable management of the organic waste system.
In this study, after a three-dimensional electromechanical design, a prototype reactor to compost agricultural wastes of Fusagasuga municipality will provide. The capacity of this prototype reactor is considered to be 20 litres. In order to control temperature and humidity of biowastes in different working conditions, it is used A PI controller with 3 temperature and a humidity sensors. With these sensors the compost materials temperature and humidity will remain at 65 °C and 55–60%. By using a special form of temperature sensor placement, the time to oxygenate the compost materials will be found. Furthermore, this system is integrated by a Human-Machine Interface (HMI), which allows the supervision and manipulation from a remote access user.

Key words: composting, environment, sensors, telemetry.

INTRODUCTION

A compost is an element with plenty of plant nutrients, is very useful as organic fertilizer for soil crops, and is produced by the decomposition of organic matter from plant and animal residues, done by microorganisms in an adequate humidity, pH and oxygen environment.

Around 193 million tons of organic materials are obtained in the photosynthetic process (De Heer et al., 2005). However, most of these materials become a source of environmental pollution, especially what is considered by manufacturers to be ‘waste’ or ‘garbage’. This tragedy is due to the lack of management techniques or to the inappropriate characteristics of these materials for direct human or animals’ consumption. As a consequence, soil, air and water pollution, the reduction of the biology and the waste of the energy of containment in the organic residues take place. Its effect generates high environmental and public health costs (Antil et al., 2014). In this regard, in (Fan et al., 2017) it is mentioned that the commercialization and use of compost in agricultural production have not been used efficiently.

For this reason, the composting method has been introduced as a convenient and easy-to-use alternative in tropical regions (Coelho et al., 2013; Oviedo Ocaña, 2015). This method allows to use of biowastes, reduce environmental pollution and recover the productive conditions of the soil. The common methods for compost production usually are traditional methods and don't involve any technological process (Rodríguez & Córdova, 2006; Gómez Betancourt, 2017; Galeano Barrios, 2018) that improves production times or production quality.

Composting of municipal and residential biowastes has been widely used. However, the optimal application periods have not been established, as well as the maturation time (Ravindran et al., 2019). Research is required not only to establish quality parameters, but also to carry out technological innovations that improve the decomposition process and reduce CO_2 generation (Knoop et al., 2018).

In some cases, organic wastes are used to produce compost in a rudimentary way. The common methods for compost production usually are traditional methods and do not involve any technological process (Corzo-Romero et al., 2016; Calderón Gómez & Calderón Ospina, 2016; Gómez Betancourt, 2017) that improves production times or production quality. According to the above, the objective of this study is to contribute to a technological innovation process, when designing a prototype that allows the optimization of the composting process. Preliminary results of a pilot test will be presented.

METHODOLOGY

To obtain a mixture with high energy content, it is needed an adequate proportion of materials with a rich content of Carbon and Nitrogen (Peña, 2011). After that, those materials are chopped to improve the speed of microorganism biodegradation. As mentioned in literature (Peña, 2011; Galeano et al., 2016), the process that homogeneously mixes the organic matter, the substrate soil and the atmosphere inside the reactor, improves the chemical properties like pH and oxygen concentration and also homogenizing the temperature in its thermophile phase. It is shown that if the rotation process is done every 24 hours, it will increase the maximum peak of the thermophilic phase. In (Bringhenti et al., 2018; Oliveira et al., 2018) it is shown that it is more efficient to keep the compost materials temperature and humidity at 65 °C and 55–60%.

In most cases, bacteria predominate about 100 times more than fungi. In (Golueke, 1977; Castrillón et al., 2006; Calbrix et al., 2007) it is presented that at least 80–90% of the microbial activity in composting is due to the presence of bacteria. The actual population of bacteria depends on the type of basic material, the local conditions and the amendments used. The microbial community in the starting substrates, together with the factors that colonize the compost pile from the surrounding environment constitute the set of biological agents responsible for the biotransformation process. As mentioned in (Morales-Corts et al., 2014), the predominant type of microorganism in each phase depends on its competitive efficacy and its survival capacity against prevailing conditions.

In (Ranjard & Richaume, 2001) it is presented that the plants which are decomposed to varying degrees by bacteria, actinobacteria and fungi, remains in the form of simple sugars, hemicelluloses and cellulose. These organisms synthesize their polysaccharides and other carbohydrates, which constitute the majority of the carbohydrates found in the soil. In (Paul, 2014) it is reported that nitrates prefer the activity of bacteria. On the other hand, ammonia and amino acids are best to use by mycobacteria and fungi. The application of nitrates, ammonia, urea and manure increase the speed of decomposition (such as the substrates used in the preparation of the mixtures). In this regard, in (Ryckeboer et al., 2003) it is mentioned that the first microorganisms come with the organic residues. In some cases, they multiply in early stages. As a result, environmental conditions change and become more suitable for the other microbial group.

In (Sundberg et al., 2004), pH varies with temperature, especially in the change from the thermophilic to the mesophilic phase. They showed that the rate of decomposition of municipal biowastes especially of vegetable origin, is very small in the pH ranges between 5 and 8 at temperatures of 36 °C. However, if the temperature rises to 46 °C, the decomposition reduces at low PHs, and increases for PHs above 6.5. This difference can be explained by the sensitivity of microorganism communities to the combined effect of acidity and temperature conditions. Microorganisms can tolerate extreme environmental factors, for example, high temperatures or low PHs, but not both at the same time. Another possibility is the existence of different groups of microorganisms: some mesophilic (which is acid tolerant) and another thermophilic (which does not tolerate acidic conditions).

In (Ferrer et al., 1994; Lazcano et al., 2008) it is reported that the pH is adjusted to a range between 7.5–8.5 at the end of the composting process and can be critical if it exceeds 8.5 levels by the volatilization of ammonia (NH3), which generates nitrogen loss and bad odor. A mature compost has the following characteristics: dark colour, no odor, ambient temperature, average particle size of 10 mm and final $C.N^{-1}$ ratio ranges from 10 to 15. In (Morales-Corts et al., 2014) and (Brito et al., 2010) it is indicated that the ideal $C.N^{-1}$ ratio for a fully mature compost is close to 10, similar to humus. The compost evaluated according to the values and parameters mentioned, generated a mature compost.

In (Benito et al., 2003) it is explained that the Cationic Interchange Capacity (CIC) ascends as a function of humification due to the formation of the carboxyl and phenolic functional groups. The macro-elements, N, P and K elements presented values within the appropriate range in the three treatments. In (Pierre et al., 2009) obtained values of N (4.4–5.9%) and K (2.5–3.6%) higher than those found in this research. In (Diaz-Ravina et al., 1989) it is indicated that some microorganisms are able to establish mutualistic symbiosis with plants, such as the growth-promoting rhizobacteria of the genus azospirillum that fix the atmospheric nitrogen in the endor-rizosfera of grasses, and others like the arbuscular mycorrhizae that colonize the roots of plants.

In this study, the search and analysis of information will be carried out, as well as the quantification and characterization of the biowastes and the elaboration of the basic design. The system will be built and the initial trials will be carried out. Furthermore, the final construction, the three-dimensional of the prototype structure and the elaboration of the respective instructions of use and handling will be presented. Additionally, similar to (Casas et al., 2013), an instrumentation and control phase will be incorporated for the transducers and actuators of temperature and humidity, integrated by a HMI, that allows the supervision and manipulation from a remote access user. Table 1 shows the methodology and the proposed activities to fulfil each objectives of the project.

Table 1. Detailed methodology in phases and activities

PHASES	ACTIVITIES
PHASE 1: information for preliminary design analysis. Actions aimed at the quantification and characterization of Organic Waste, as well as the definition of the most efficient prototype model to be implemented. In addition, we worked on the identification of variables to be quantified, and thus finally the preliminary design was obtained.	• State of the art analysis on organic solid biowastes treatment and HMI systems, as well as communication protocols for information remotely transmitting. • Determine the most appropriate process for the transformation of organic solid biowastes into compost, from the science of electronic engineering, and identify the variables to be analysed. • Quantification and characterization of organic solid agricultural residues. • Determination and measurement of physic-chemical and biological variables involved in the decomposition of organic waste. • Preparation of the preliminary design, a technical outline of the possible prototype from three-dimensional models as well as the electronic system, taking into account the $C.N^{-1}$ ratio calculations and integrating them into the electronic system.
PHASE 2: construction and preliminary system. Trials Actions aimed at the development of the prototype from the input elements obtained in the previous phase, and realization of data collection and initial performance tests.	• Development of data acquisition and measurement systems (DAQ). • Development of the Man-Machine interface as a monitoring and control tool for remote monitoring of variables. • Conditioning of input and output variables, from the sensors selected in the electronic instrumentation stage. • Articulation of the components and construction of the final prototype with the automation system. • Development of tests and monitoring processes, study variables and evaluating results. • Prepare manuals, plans and other technical aspects of the system.
PHASE 3: Preliminary progress of microbiological and chemical variables of composting.	• Quantification of general groups of microorganisms. • Determination of chemical variables present in the compost.

Organic solid waste (OSW) management

The agricultural residues that are identified with greater representativeness in the municipality of Fusagasugá are shells, husks, fruits, vegetables, leafs, seeds and aromatic herbs. At this time, these residues are crushed up to get particles sizes between 1 and 5 cm, (Zhalnina et al., 2015) allowing a better microorganism decomposition and a homogeneous matter at the end of the process with the mature compost.

The reactor is designed with a rotary system (Fig. 1) using a set of rotating opposite blades joined to a rotating shaft in the centre of the reactor. In (Fig. 2), the 3D model of the turning system is shown.

A prototype reactor is built based on the results of computer-assisted simulation and validation. A standard-size barrel with an isolated anti-corrosive coating layer is used as reactor base. Furthermore, the turning blade is made with metallic sheets of calibre 12. The blades and the shaft are covered with an anti-corrosive layer. Fig. 3 shows the reactor built with a temporary manual rotation system.

Figure 1. 3D model of the prototype reactor.

Figure 2. 3D model of the turning system.

Prototype System

In this section, based on the simulated 3D model, a prototype system (Fig. 3) is constructed. This system basically consists of a cylindrical barrel of 20 litres, which common in closed composting systems (Peña, 2011). To facilitate rotation and material homogenization a rotary axis is embedded in the system. As can be seen from Fig. 3, this axis consists of a metal tube and blades. Similar to (Galeano et al., 2016), the whole structure is covered with insulation and anti-corrosive paint In this prototype system, the temperature and humidity are monitored by four sensors distributed inside of the bioreactor. With these sensors the compost materials temperature and humidity will remain at 65 °C and 55–60%.

The main issue is that the microorganism activity will reduced at low temperatures. As shown in Fig. 4, the temperature sensors are located at the two ends (sensor 1 and 3) and centre (sensor 2) of the bioreactor tank. In this study, A PT100 sensor is used due to its lineal behaviour. However to increase sensitivity, a Wheatstone bridge and amplifier 1NA106 are used, which is a good option for measuring small resistance changes (Hoque & Islam, 2018). Using this placement method, when Sensor 2 has a different value than Sensors 1 and 3, it indicates that it is necessary to oxygenate materials by overturning is necessary.

Figure 3. Prototype reactor with a temporary manual rotation system.

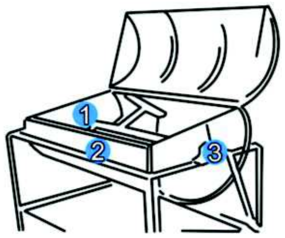

Figure 4. Sensors location inside the prototype system.

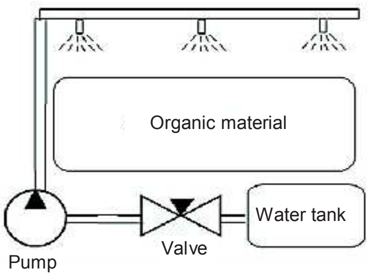

Figure 5. Irrigation system.

Since the organic matter is subjected to microbial action and artificial heating to regulate the optimal temperature, an additional system is needed to control the humidity of the material. It consists of a dryer and a water supply system. Using a linear controller and L-69 sensor, the humidity of the materials is kept at the optimal level. The dryer system includes of a heating system and air extractors in order to extract excess humidity from the reactor. The water supply system consists of a 12-volt electric pump, a water tank, an electrical valve and a nebulizer system (Fig. 5).

The aeration process is essential to accelerate OSW degradation. Therefore, a hot air circulation system is needed to perform the aerobic process. This system controls the oxygen and temperature levels of the organic material in the reactor. The heating system provides a constant air flow with variable temperature based on resistance electrical elements and an air turbine together in a housing (Fig. 6).

With a 10 Ohm resistance and a maximum voltage of 120 VAC, this system can provide a maximum of 1440W of heat power. A TRIAC-based converter with a PWM (pulse width modulator) controller is used to control the heating system.

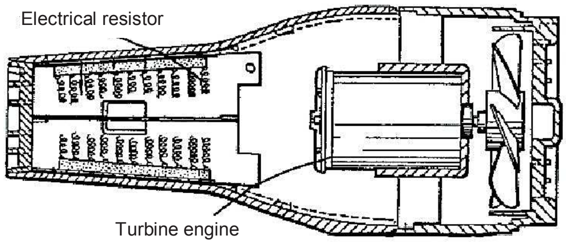

Figure 6. Temperature actuator.

Design and implementation of the controller

The main issue is that the microorganism activity will reduced at low temperatures. As a first design action of the controller, it is needed to do a system characterization test to define its linearity, operation range and the appropriate control technique to implement. For this reason, the Step response for temperature is extracted (Fig. 7).

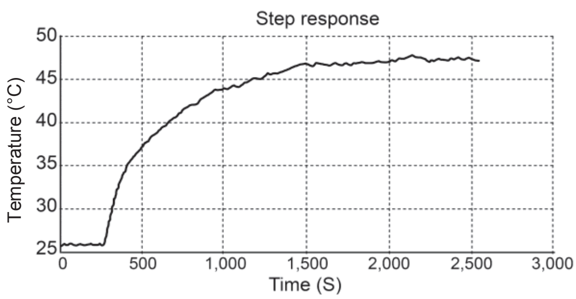

Figure 7. Step response for temperature.

Given that the system is linear, a PI controller is selected to reduce the steady-state error found by the step input test performed on the system. This model is shown in the Fig. 8. These parameters are synchronized with the real model to improve the overall system response.

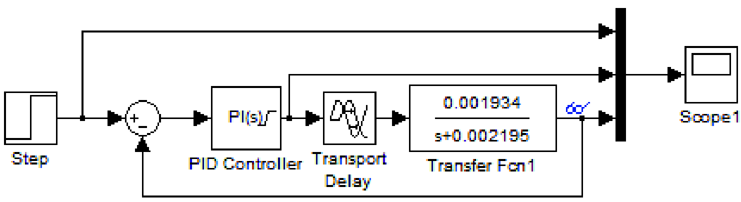

Figure 8. Simulink model controller.

RESULTS AND DISCUSSION

Humidity and temperature behaviour

The physicochemical variables that are evaluated and controlled for the composting process are the temperature and humidity (Hoque & Islam, 2018).

Comparison between a reference pile covered with a single piece of plastic and the compost processed in the prototype reactor with the adequate physical conditions for composting process were performed. Data obtained from the trials shown that the compost in the prototype reactor got a temperature of 60 °C, compared with the temperature of 55 °C reached by the reference pile. This temperature was not maintain for long time, because as soon as the temperature reached 50 °C the rotation process was performed to oxygenate the microorganisms in the compost (Oliveira et al., 2018). As shown in Fig. 9, after 12 days, the temperature tends to stabilize.

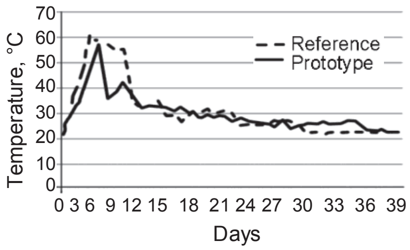

Figure 9. Composting Temperature vs Time.

Since the materials used in the experiment have high humidity (such as in the case of organic residues), the humidity level is high as shown in the Fig. 10. However, after 24 days the humidity level is stabilized in the reactor, as opposite to the reference pile that got stabilized after 38 days.

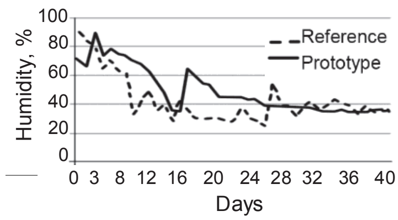

Figure 10. Composting Humidity vs Time.

The HMI for the reactor prototype is intended to monitor and control all its systems (air flow, watering and heating) remotely from the Internet. The lab view is used for the HMI due to its capabilities for data processing and virtual instrumentation.

Figure 11. View of HMI control panel from a web navigator.

The local workstation is geographically near of the prototype reactor, which is necessary to have physical access in case of emergency. This situation allowed to use a local area network (LAN) based on Ethernet to communicate the workstation and the Arduino module. In order to implement the communication between the HMI and the Arduino board through the LAN, a User Datagram Protocol (UDP) based communication is used because

Table 2. Laboratory Analysis results

Results No.	Scientif Name	Population
1	Fungus	< 10 CFU g^{-1}
2	Yeast	11×10E 7 CFU g^{-1}
3	Mesophilic Bacteria	24×10E 7 CFU g^{-1}
4	Pseudomonas	17×10E 5 CFU g^{-1}

a connected oriented communication like Transmission Control Protocol (TCP) is not needed, UDP allowsfast response and als o UDP is simpler to work with.

For the remote communication the tool 'Web Publishing Tool' from Labview is used. This tool runs a web server in the computer running the HMI that serves an HTML page with the same content visualized in the HMI, allowing users to see in real time all the process development. Fig. 11 is shown the panel control viewed from a computer. Composting is characterized by the interaction and succession of several types of microorganisms that present different nutritional and environmental demands. In Table 2, the results of microbiological groups are presented, within which the bacteria predominate in the compost sample.

The results of the experiments show a higher percentage of the bacterial population. In (Rebollido et al., 2008) the bacterial population is specified by 44.6%, followed by actinobacteria 32.3% and fungi 23.1% are found to be predominantly colonized by microbial populations during the composting process of municipal solid organic waste. Table 3 shows the results of the compost chemical parameters for the compost test.

Table 3. Compost Chemical parameters

Parameter	Value	Unit
Dry-Bulk Density	0.200	g cm^{-3}
Ph Satured paste	7.54	%
E.C Saturation Extract	23.80	dS m^{-1}
Moisture	31.89	%
Ashes	25.87	%
Acid Insoluble Residue	16.71	%
Cation-exchange capacity or CEC	31.19	$Meg.100^{-1}$
Total Nitrogen	1.47	%
Total Potassium	2.13	%
Total P2O5	0.68	%
Total MgO	0.44	%
Total K2O	2.56	%
Total CaO	1.98	%
Total Calcium	1.41	%
Total Magnesium	0.27	%
Total phosphorus	0.30	%
Sulfur	0.06	%
Boron	0.005	%
Cupper	0.001	%
Manganese	0.03	%
Iron	0.39	%
Zinc	0.007	%
Sodium	0.18	%
Total Oxidizable Organic Carbon	16.31	%
Carbon-to Nitrogen Ratio $C.N^{-1}$	11.09	
Moisture Retention	147.58	%
volatilization losses	42.24	%

CONCLUSIONS

The closed system implementation used in the prototype, created a controlled environment for the production of compost that reduced the variations produced by climatic conditions specifically temperature and humidity, compared to the traditional system in piles, just as the closed system facilitates the Oxygenation from the voltage and the measurement of the variables and the transmission of the remote way through the telemetry system.

The introduced electronic control system regulated the variations of temperature inside the bioreactor generated by the temperature changes of the area where the prototype of the plant was located, as well as the generation of a historical and real time data record through. The human machine interface allowed to control and monitor the process by industrial control methods.

It stands out in this prototype plant that had desirable physical conditions (humidity of 55% and temperature between 25°–65 °C), the time of compost was reduced considerably obtaining compost in a time of approximately 9 weeks. In addition, it obtained a mature compost according to physical and chemical variables.

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