Modeling the aerobic conversion process of organic waste into organic fertilizers using Aspen HYSYS

Mabelle Wehbe[1], *Jason* Kazzi[1], *Ralph* Dgheim[1], and *Makram* EL Bachawati[1,*]

[1]Department of Chemical Engineering, University of Balamand, 100 Tripoli, Lebanon

Abstract. Waste stemming from various sources and manifested in diverse physical states is growing at a threatening pace globally. Uncontrolled disposals and ineffective waste management practices are escalating issues for societies, ecosystems, and economies. Advances and designs are projected toward transforming waste into a resource. This study treats organic waste by designing and optimizing an aerobic composting system. Effective aerobic composting systems depend on physical, chemical, and biological factors. The feedstock should be carefully selected for efficient composting, and the end-product must be thoroughly tested. Temperature, aeration rate, and moisture levels are the dominating factors regulating the process. We depicted the diverse advantages and drawbacks of the process through the triple-bottom-line assessment to project the current system toward circular economy and sustainability. Using the literature suggestions, we modeled the process using ASPEN HYSYS, but the conversion rate obtained is only 23.04%. After modifying different variables like temperature, pressure, flow rates, and addition of units, the conversion rate reached 100%. We added wind turbines, eco-friendly reactors, recycled streams, and biochar filters to make the process eco-friendly, economically efficient, and socially adaptable. The obtained process is cheap, affordable, and suitable for use in rural areas.

1 Introduction

The rapid increase in organic waste generation due to urbanization and agricultural activities poses a significant environmental challenge. Transforming this waste into valuable organic fertilizers presents a sustainable solution addressing waste management issues while promoting agricultural productivity.

By definition, “waste” refers to something valuable like material, energy, or time lost because an excess quantity is being used or not handled appropriately and effectively during its life cycle. “waste” could be distinguished based on its source, physical characteristics, or chemical nature. According to the Environmental Protection Agency, waste can be generated by various sources, including municipal, agricultural, industrial, medical, petroleum, and construction [1,2]. Municipal waste is considered the most common and significant contributor to waste, comprising any waste generated while people and households go about their daily lives [3]. Based on its physical characteristics and according to the Journal of Environmental Chemical Engineering by the Indian Institute of Technology Kharagpur, waste is classified based on its physical state into solid, liquid, and gaseous waste since different types of waste may require different handling and treatment techniques [4]. Any undesired solid item that is no longer usable is referred to as “solid waste,” which comprises dry materials, including glass, paper, cloth, wood, yard trimmings, metal, plastic, leather, and other miscellaneous items produced by humans, commercial, agricultural, and industrial operations. Concern about this kind of waste is rising due to its lead, mercury, and cadmium content. Such solid wastes are labeled as hazardous as they cause direct danger to exposed ecosystems [5]. Lastly, “waste” could be split into organic, inorganic, and inert waste based on its chemical nature. Organic waste originates from living organisms such as sewage sludge, animal manure, green municipal wastes, and agro-industrial residues. Inorganic wastes are wastes that do not have carbon-to-carbon or carbon-to-hydrogen bonds, such as toxic metals metalloids. Inert waste is defined as waste that cannot spontaneously decompose chemically or biologically, such as glass, plaster, drywall, siding, shingles, insulation, metal, wood, bricks, asphalt or cement concrete, and other building materials.

To mitigate the impact of waste on the environment, economy, health, society, and sustainable development with the global population growth, hasty urbanization, and economic development, this research aims to design and optimize an effective and responsible waste management practice: Aerobic composting.

1.1 Aerobic composting

Aerobic composting is the decomposition process of organic materials with the aid of microorganisms in the presence of air [6]. The primary feedstocks for this process are municipal and agricultural waste that are predominantly solid and organic. They require an adequate balance between “green” and “brown” organic materials: “green,” which includes grass, clippings, manure, and food

---

[*] Corresponding author: Makram.Bachawati@balamand.edu.lb

scraps, characterized by large amounts of nitrogen, and "brown," which provides for branches, dry leaves, and wood chips are depicted with a large amount of carbon [7]. The conversion of these materials preserves the valuable nutrients and carbon in food and green waste to serve as soil quality improvers [8]. The output of this aerobic decomposition is compost and three main byproducts: water, heat, and CO_2 [9]. The compost obtained differs from the initial feedstock because it has a dark brown color, crumbly structure, and pleasant odor [9]. Different physical properties, such as particle size, moisture content, oxygen flow, and temperature, are controlled and maintained during the process [8]. According to the Environmental Protection Agency, four main composting techniques are adopted: on-site composting, vermicomposting, aerated static pile composting, and aerated windrow composting [8]. Compost technology is a necessary step towards a circular economy as it helps to reduce waste, preserve resources, and support sustainable agriculture [10].

1.2 Factors Affecting the Composting Process

Since composting is a biological process, some microorganisms are essential, so it is crucial to consider the variables that affect their development and reproduction. Some variables include aeration or oxygen, temperature, pH, substrate moisture, etc. [9]

1.2.1 Aeration

Being an aerobic process, composting requires suitable ventilation for the respiration of microorganisms and reducing water filling in the compost pile. The process necessitates varying amounts of oxygen, which peak during the thermophilic phase. Low aeration causes excessive moisture, generating an anaerobic environment with odors and acidity. Contrarily, excessive aeration causes evaporation, leading to moisture loss and the dehydration of microorganisms' cells [8].

1.2.2 Moisture

Moisture level in the compost pile can be directly related to microbial activity since those microorganisms use the water present to transport nutrients and energy. Several factors, including particle size and physical conditions, influence the moisture level of the composting system [9].

1.2.3 Temperature

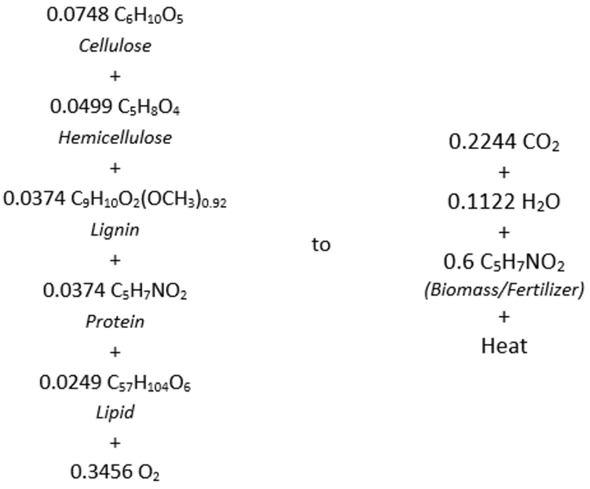
The phase of the composting process vastly influences temperature, which rises from ambient to values as high as 65°C without any external heating and then drops back to ambient temperature. The higher temperature and its prolonged period lead to a higher decomposition rate and hybridization, so the temperature increase and its rate should be controlled to prevent a fast drop [9].

2 Methodology

Aspen HYSYS program is used to design an aerobic composting process for organic waste as well as improve and test conceptual frameworks by investigating several situations and adjusting key parameters in order to create a composting process that is effective, efficient, and sustainable.

The simulation started by identifying all the components involved in an aerobic composting process and adding them on ASPEN HYSIS to a peng-robinson fluid package. These components are cellulose, biomass, oxygen, carbon dioxide, water, lipid, protein, lignin, hemicellulose, and nitrogen.

The stoichiometric equation for the aerobic degradation of organic matter was established with the general reaction represented as:



$$\underbrace{0.0748\, C_6H_{10}O_5}_{\textit{Cellulose}} + \underbrace{0.0499\, C_5H_8O_4}_{\textit{Hemicellulose}} + \underbrace{0.0374\, C_9H_{10}O_2(OCH_3)_{0.92}}_{\textit{Lignin}} + \underbrace{0.0374\, C_5H_7NO_2}_{\textit{Protein}} + \underbrace{0.0249\, C_{57}H_{104}O_6}_{\textit{Lipid}} + 0.3456\, O_2 \text{ to } 0.2244\, CO_2 + 0.1122\, H_2O + \underbrace{0.6\, C_5H_7NO_2}_{\textit{(Biomass/Fertilizer)}} + \text{Heat}$$

The protein component was based on a typical amino acid residue, and the lipid was based on a typical triglyceride. This reaction was added to ASPEN HYSIS with a conversion factor of 0.6 for the organic matter to biomass/fertilizer and complete oxidation of the organic matter.

The aerobic composting process (Figure 1) includes three input material streams: kitchen waste, agricultural waste, and air entering a conversion reactor at flow rates based on the literature. A conversion reactor model in ASPEN HYSYS was configured to simulate the composting process since such a reactor is suitable for processes where the extent of the reaction is the primary focus. The waste streams were first added with all the components typically found in them: cellulose, hemicellulose, water, lipid, and protein, and the compositions were adjusted based on shared values found in the literature. The reactor operates at ambient temperature and atmospheric pressure with two output material streams: the carbon dioxide emitted and the biomass and water produced.

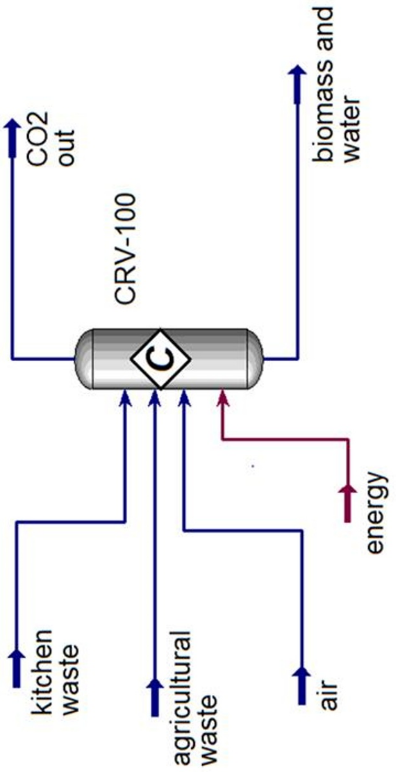


Fig. 1. Block flow diagram of the ASPEN HYSIS aerobic composter model.

3 Results and Discussion

In the simulation of the aerobic composting process using ASPEN HYSYS, the provided data and conditions were applied to model the degradation of organic matter. The simulation yielded a conversion rate of 23.04%, indicating that only a fraction of the organic material was decomposed into carbon dioxide, water, and biomass under the current conditions [11]. This conversion rate is considered low and suggests inefficiencies in the composting process. Therefore, in the next chapter, we will focus on optimizing the process parameters, such as temperature, aeration rate, and others, to enhance the conversion rate. The goal is to identify the optimal conditions that will significantly improve the efficiency of the composting process, resulting in higher conversion rates and better overall performance.

3.1. Optimization

3.1.1 Temperature

The first suggestion is to modify the pile's temperature in the initial condition. For this reason, we increased the temperature from ambient conditions to 60ºC. However, the conversion is independent of the temperature since the conversion rate remains constant while modifying the temperature. The case study conducted on the mass composition of biomass converted with respect to the temperature of the organic waste (Figure 2) and air verified the independence of the process on temperature (Figure 3).

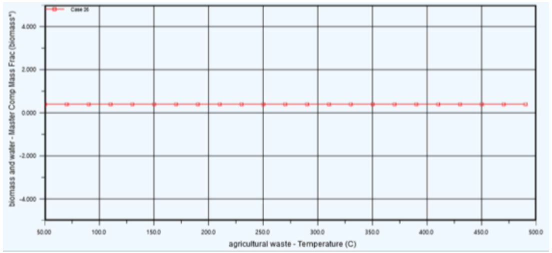


Fig. 2. Biomass mass fraction in biomass and water stream versus the temperature of the agricultural waste.

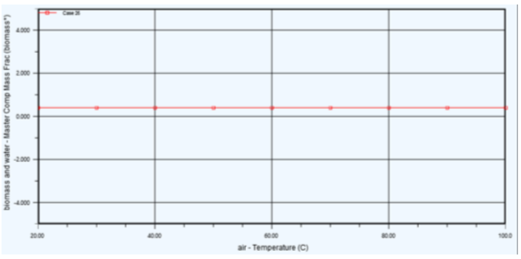


Fig. 3. Biomass mass fraction in biomass and water stream versus the temperature of the air stream.

3.1.2 Cellulose and Hemicellulose Content

Numerous pretreatment methods are adopted to increase and accelerate the conversion by increasing the particle size of the organic waste introduced to the pile (Figures 4 & 5). In this study, physical pretreatment was chosen to reduce the particle size of the feed. An additional optimization is adding a pulverizer responsible for decreasing the size of large particles. The case study showcases that having large quantities of cellulose and hemicellulose will reduce the mass fraction of biomass at the output. These results demonstrate that we should maintain adequate organic waste in the pile. For optimal levels of cellulose and hemicellulose, the conversion of the process reached 100% conversion.

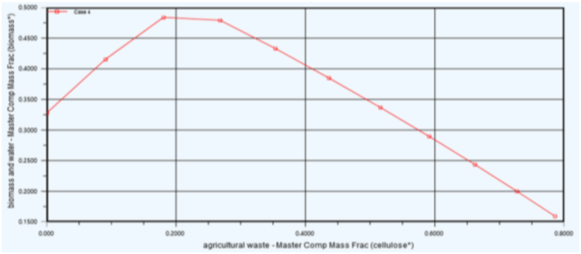


Fig. 4. Biomass content in the biomass and water stream versus the cellulose content of the agricultural waste stream

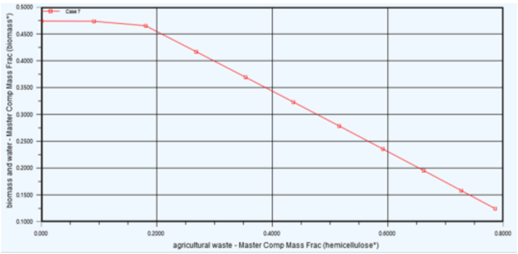


Fig. 5. Biomass content in the biomass and water stream versus the hemicellulose content of the agricultural waste stream

3.1.3 Temperature

When the molar flow rate of air increases, the water content in the output stream decreases but is not set to zero (Figure 6). Hence, it is suggested that a recycling stream for the water at the output be set to ensure the continuous hydration of the feed. This recycling stream will help us in 2 ways. The leachate generated from waste will not pollute the ground, and we will conserve the ecosystem. On the other hand, it will decrease the price of continuous water supply for hydration.

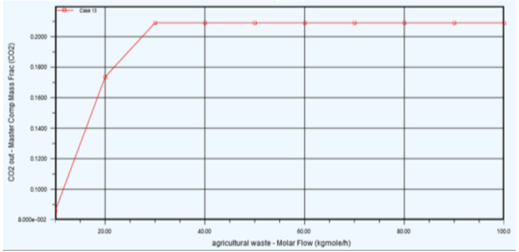


Fig. 6. CO_2 content in the CO_2 stream versus the molar flow of the agricultural waste stream

3.2 Environmental Analysis

High greenhouse gas emissions characterize the aerobic composting process, which is evident in the current process. Adding a bio-filter based on biochar will capture all the emissions, and only clean air will be emitted. The carbon footprint of the process is negligible, primarily since it is based on renewable energy to supply power for the equipment. The wind turbines cover the air blower and pulverizer electric needs—no more contribution to global warming and climate change when adopting this environmentally friendly process.

3.3 Economic Analysis

After modeling the process on ASPEN HYSYS, it is clear that it requires high capital investment and operational costs (Table 1). To make this process more affordable and adaptable, a reactor based on recycled materials like plastic is a cheaper alternative and more corrosion-resistant than a metal-based reactor. Its cost is only 5000$ to 10000$ instead of adopting 177000$ metal reactor. Also, the power supply of the process will be based on wind turbines that don't need backup batteries and require only low capital and maintenance costs. To maintain the pile's optimal moisture content, we will use the leachate produced from the waste as a recycle stream, not to use additional water. The conventional process is displayed in Figure 1, while the optimized process is depicted in Figure 7.

Table 1 Economic Analysis - conventional vs optimized process

Costs	Conventional Process	Optimized Process
Reactor	177,000$	5,000$ - 10,000$
Water/ year	5,000$	1,000$
Energy/year	19,000$	5,000$
Other	5,000$	5,000$
Total	**206,000$**	**16,000$ - 21,000$**

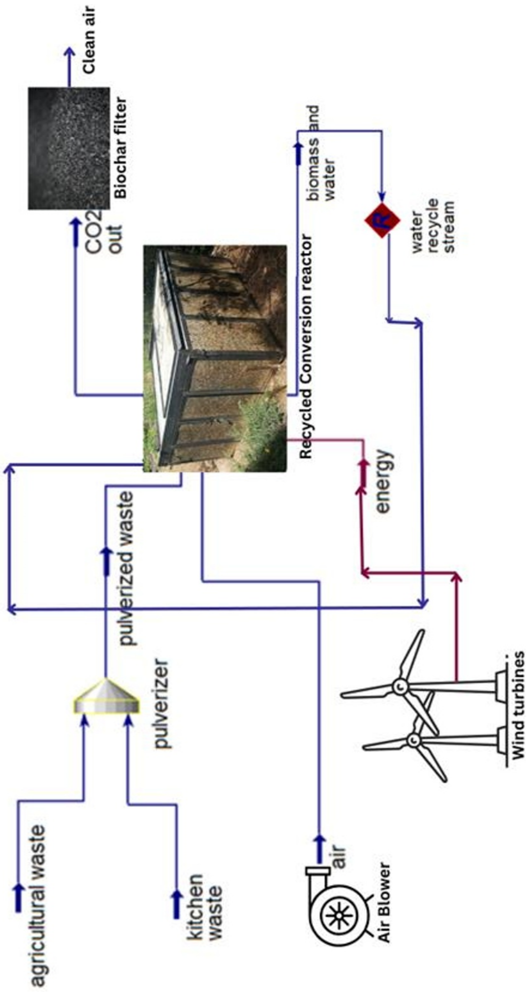


Fig. 7. Flowchart of the optimized process

The literature lacks studies about modeling aerobic conversion processes using Aspen HYSYS; the existing studies are dedicated to anaerobic conversion processes and using Aspen Plus. As an example, the analysis of the biogas production process from food waste using Aspen Plus demonstrated that the best combination was an organic loading rate of 2 l/day and 5 l/day at a fat concentration of 40%, which achieved a methane content of 74.82% and 77.10%, respectively. Likewise, a hydraulic retention time of between 10 and 20 days at a fat concentration of 60% showed the highest methane content, 77.10% [12].

On the other hand, the study about modeling and optimizing domestic and agricultural wastes-based anaerobic digestion using Aspen Plus showed that at optimum temperature (37.26°C), hydraulic retention time (15.20 days), and operating pressure (0.89 bar), the optimum kitchen waste-CH_4 (59.46%), cow dung-CH_4 (55.00%) and poultry droppings-CH_4 (60.21%) were feasible. Moreover, the sensitivity analysis showed that operating pressure is the most important input variable, followed by temperature, while the hydraulic retention time is the least important variable [13].

4 Conclusion

This research depicts the different types of waste split by origin, physical state, and chemical nature and the importance of setting up an efficient waste management process: the aerobic composting process to convert the organic waste into organic fertilizers. ASPEN HYSIS is used to design the aerobic composter using data from the literature. Multiple factors were analyzed in the model to find the optimum values to obtain the maximum conversion and efficiency of the process. The initial operating conditions led to a conversion rate of 23.04% only. The optimized system (Figure 7) led to a 100% conversion.

Furthermore, the economic analysis demonstrated that the optimized system is more affordable as the total cost dropped from 206,000 USD to 16,000-21,000 USD. From another perspective, the optimized system is better from an environmental point of view, as its carbon footprint is negligible because it is based on renewable energy to supply power for the equipment. Therefore, even though the optimized system could be the solution, it can be further enhanced based on the three pillars of sustainability.

The authors would like to acknowledge the financial support provided by the Sustainable Wastewater Treatment for Hospitals/SWaTH project (618540-EPP-1-2020-LB-EPPKA2-GBHE-JP) co-funded by the Erasmus Programme of the European Commission. Without its generous support, this research would not have been possible.

References

1. Environmental Protection Agency. (n.d.). Waste classification - EPA. Waste Classification List of Waste & Determining if Waste is Hazardous or Non-hazardous.
2. Z. Gareiou, C. Chroni, K. Kontoleon, M. El Bachawati, M. Saba, R. Herrero Martin, E. Zervas, Sustainability. **14**, 1912. (2022)
3. E. Drimili, R. Herrero-Martin, J. Suardiaz-Muro, E. Zervas. Waste Management & Research. **38**, 614 (2020)
4. G. Yadav, S. P. Panda, R. Sen, J. of Env. Chem. Eng. **8**, 104518 (2020).
5. J. A. Nathanson, Encyclopedia Britannica, (2023)
6. A. Meena, M. Karwal, K J. Raghavendra, E. Narwal, Food and Scientific Reports, (2021)
7. Environmental Protection Agency. https://www.epa.gov/sustainable-management-food/types-composting-and-understanding-process
8. Environmental Protection Agency. Composting|U.S. ResearchGate (2023b) https://www.epa.gov/sustainable-management-food/composting#scale
9. A. L. Meena, M. Karwal, D. Dutta, R. Mishra, Agri and Food: e-newsletter **3**, 85 (2021)
10. Trends in solid waste management. (n.d.). https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html
11. Y. Jiang, X. Li, J. Yao, X. Wan, J. Zhang, Y. Dai, Renewable Energy, **196**, 547 (2022)
12. W. Anaya Menacho, A. M. Mazid, N. Das, Fuel, **309**, 122058 (2022)
13. O.O. Ajala, O.J. Odejobi, Biomass Conversion and Biorefinery **22**, (2023)