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Development and Performance Evaluation of an Eco-Friendly Rotary Drum Roasting Machine for Maggot Processing Using Biomass Energy

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ABSTRACT

The burgeoning interest in maggot-based feed necessitates cost-effective production methods. Traditional roasting techniques for converting fresh maggots into fish feed pellets, predominantly reliant on liquefied petroleum gas (LPG) burners, impose substantial operational costs. Addressing this challenge, the current study introduces a biomass-fueled roasting machine, engineered to reduce energy expenditure and enhance environmental sustainability. Fabricated in a Yogyakarta-based workshop, the eco-friendly roaster features a stainless steel rotary drum (500 mm diameter, 1000 mm length, 3 mm thickness) actuated by a 2 HP electric motor at 28 rotations per minute. The machine's performance was evaluated through temperature profiling, roasting rate, useful heat generation, specific energy consumption (SEC), and overall effectiveness. These parameters were assessed during the roasting of 10 kg and 30 kg batches of fresh maggots over a two-hour period, utilizing teak firewood as the biomass energy source. The empirical findings indicated an optimized performance at the 30 kg capacity, with a roasting rate of 2.86 g/s, useful heat delivery of 62168.30 kJ, an effectiveness of 0.69, and an SEC of 12798.78 kJ/kg water evaporated. The introduction of this roasting machine not only simplifies the maggot pellet production process but also diminishes investment costs. More critically, it encourages the utilization of biomass waste, slashes operational expenses for maggot farmers, and aligns with the principles of sustainable agriculture. This study underscores the potential of integrating biomass-based technologies within the aquaculture feed industry, promoting both economic and environmental benefits.

1. INTRODUCTION

The larval stage of the Black Soldier Fly (BSF), *Hermetia illucens*, is increasingly acknowledged for its utility in organic waste management and as a sustainable protein source for aquaculture. The BSF larva, commonly termed 'maggot,' represents the initial phase in the species' metamorphosis, Figure 1 shows BSF life cycle, the entire life cycle of the BSF is approximately 38 days [1]. Renowned for their rapid processing of diverse organic substrates, absence of disease transmission, and benign nature toward humans, BSF larvae are considered a safe and valuable resource for cultivation.

Recent advancements have leveraged BSF larvae in the waste management sector, where they enhance the conversion of the solid residual fraction of restaurant waste into biodiesel, demonstrating substantial potential as a feedstock for biodiesel production [2]. Additionally, BSF larvae have been successfully incorporated into fish meal, offering a sustainable alternative to traditional feeds. Studies assert that BSF larvae can replace fish meal in Atlantic salmon diets without compromising the fish's growth performance, with complete substitution yielding improved body weights [3, 4]. In the Indonesian context, the integration of BSF larvae into waste management strategies is identified as a promising technology within the nation's Waste to Energy regulations [5]. Beyond aiding in waste decomposition, the larvae present an economic opportunity, commanding higher market values in dried form compared to fresh, thus enhancing profitability for farmers.

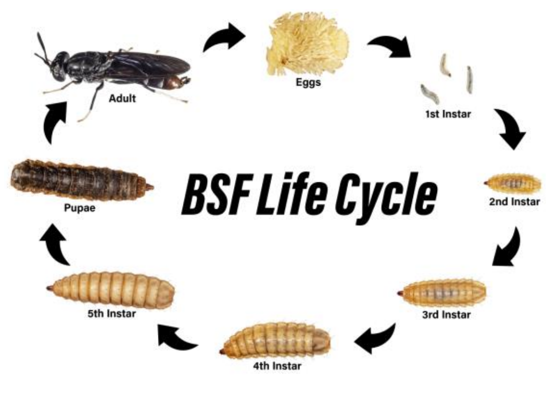


Figure 1. Black soldier fly life cycle [1]

To extend market reach, farmers have adopted drying methods for BSF larvae, typically employing a rotary type dryer. This apparatus, consisting of a continuously rotating cylinder or drum, receives heat from an energy source such as biomass and is particularly appropriate for granular food products like grains [6]. The widespread adoption of rotary dryers across various applications, including heating, cooling, mixing, and drying processes, can be attributed to their ability to provide uniform drying, ease of operation, and cost-effectiveness [7-9]. The design of these dryers is tailored to utilize waste energy sources that are readily available and economically viable, making them well-suited for rural farming communities. The superior performance of indirect biomass drying with rotary dryers has been documented, especially when designed with smaller diameters and more slender proportions [10, 11].

Critical to the design of rotary roasters are the parameters of optimum roasting time and temperature, which hinge upon the moisture content and nature of the material being processed [12]. An excessive moisture content necessitates extended roasting durations, while maintaining optimal temperatures is essential for achieving efficient convective heat transfer to the drum. The complexity of determining these parameters can lead to over-roasting and thermal energy wastage, thereby incurring additional costs [13]. Nonetheless, optimization of the roaster's design and operational parameters can lead to significant energy savings and improved thermal efficiency [14-16], particularly when operated under forced convection modes, which have been shown to outperform natural convection modes [17, 18]. A comprehensive evaluation of the thermodynamics of rotary roasters can be furthered through energy and exergy analysis [19-21].

Conventionally, maggot roasters have relied on liquefied petroleum gas (LPG) burners as their primary heat source, contributing to elevated operational costs. The current investigation aims to address this economic and environmental challenge by developing a biomass-fueled, eco-friendly roasting machine. The envisioned machine is designed to lower operational expenses and, consequently, enhance the profitability of maggot farming enterprises. Notably, existing market options for roasting equipment predominantly use LPG or electric energy sources, with none harnessing biomass. The thermal performance of the proposed roaster will be evaluated through the examination of temperature profiles, roasting rates, useful heat generation, specific energy consumption, and effectiveness during the processing of 10 kg and 30 kg fresh maggot batches, utilizing teak firewood as the biomass energy source.

2. METHODOLOGY

The present work is divided into design and fabrication, experimental work, and performance evaluation of a biomass energy-based rotary drum roasting machine. In the present work, rotary drum roaster is selected due to its simple construction and high thermal performance. The capacity of the roaster is determined to be 50 kg of fresh maggot per process with drum rotation speed of 28 rpm.

2.1 Design and fabrication

The main components of the roaster are rotary drum, biomass furnace, prime mover, and transmission system. Based on design capacity, the vtabolume of a drum required is calculated using Eq. (1).

$$V_d = \frac{m_m}{\rho_m} \tag{1}$$

where, V_d is the volume of drum required, m_m and ρ_m are the mass and density of the fresh maggot, respectively. After the volume of the drum is obtained, its diameter and length are calculated by considering the standard diameter of commercial drum available in the market.

For sizing a furnace, heat transfer rate is needed to be obtained first prior to determination of furnace's dimension. Total heat input required for particular roasting time (t) is obtained using Eq. (2).

$$Q = h(2\pi DL)\left(T_f - T_d\right)t \tag{2}$$

where, Q is the total heat required for roasting (J), h is the coefficient of convective heat transfers (W/m^2.°C), D and L are the diameter and length of the drum (m), Tf is the flame temperature (°C), T_d is the temperature of the drum (°C), t is the roasting time (s). Once total heat input is obtained, the amount of feedstock required is determined using Eq. (3) and the volumetric dimension of the furnace can be calculated using Eq. (4).

$$(LxWxH)_f = \frac{Q}{\rho_b HHV_b} \tag{3}$$

where, L, W, and H are the length, width, and height of a furnace (m), Q is the total heat input required (J), ρ_b is the density of biomass (kg/m^3), HHV_b is the higher heating value of a biomass (J/kg).

Meanwhile, the electric motor is used as prime mover of the roaster where power required is calculated using Eq. (4).

$$P = \frac{2\pi NT}{60} \tag{4}$$

where, P is the output power of the electric motor (W), N is the rotation speed of the drum (rpm), and T is the torque required to rotate the drum (Nm) which is calculated using Eq. (5).

$$T = mgr \tag{5}$$

where, m is the total mass of drum and fresh maggot (kg), g is the gravitational acceleration (9.81 m/s^2) and r is the diameter of driven pulley (m). Gearbox with speed reduction ratio of 50:1 is selected to reduce rotational speed of electric motor (1400 rpm) to a drum rotational speed of 28 rpm.

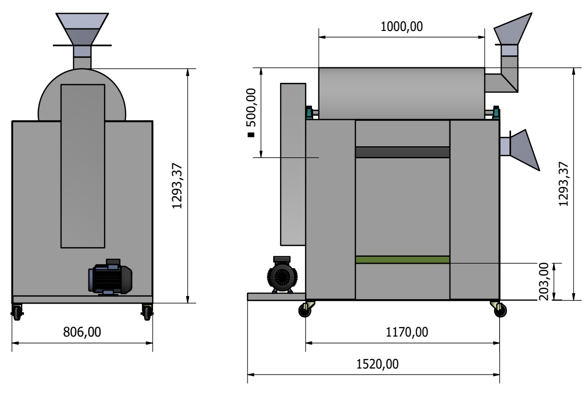


Figure 2. Technical drawing of a biomass energy-based roasting machine (unit: mm)

Figure 2 presents a technical drawing of the roaster. The fabrication work is done in a local mechanical workshop in Yogyakarta. The furnace and the drum are both made from 3 mm thick Stainless-Steel plate. The furnace has a length of 1170 mm, wide of 806 mm, and height of 590,37 mm. The drum has a diameter of 500 mm and length of 1000 mm. Meanwhile, the structure of roaster is fabricated using 400 x 400 × 40 mm L-profile Steel. Meanwhile, Figure 3 shows a photograph of the biomass energy based rotary dryer which has been developed in the present work.

Figure 3. Photograph of a biomass energy-based roasting machine

2.2 Experimental work

Experimental work is conducted to evaluate performance of the roaster in terms of temperature distribution, roasting rate, useful heat, specific energy consumption, and effectiveness of the roaster while roasting 10 kg maggot BSF and 30 kg for 2 hours roasting time. Experimental setup for evaluating performance of the roaster is presented in Figure 4. A fresh maggot is loaded into the drum through hopper, firewood is burnt in the furnace for each test. Every test is conducted for 2 hours. Data taken during the test are temperature of furnace (TF1, TF2, TF3) temperature of outer wall of the drum (TD1, TD2, TD3), temperature inside the drum (TM), and mass of a fresh maggot before and after roasting. Temperatures at those locations are taken every 5-minute using infrared thermometer. In the present work, the feedstock for the furnace is teak fire wood which is obtained from local traditional market di Yogyakarta.

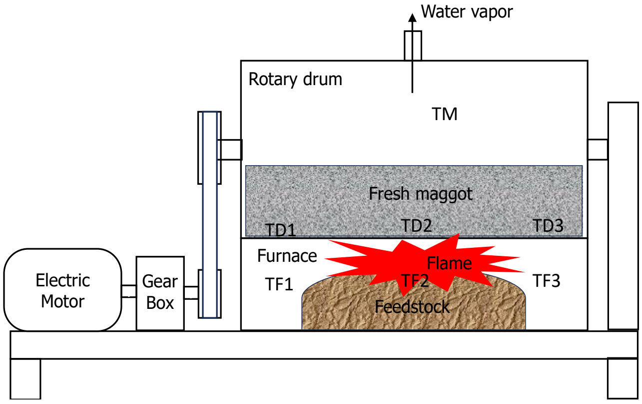


Figure 4. Experimental setup

2.3 Performance evaluation

Once data is collected, temperature distribution, drying rate, and thermal efficiency are analyzed. Roasting rate, useful heat, specific energy consumption (SEC), and thermal efficiency, and roasting effectiveness are calculated using Eq. (6) to Eq. (8), accordingly.

$$\dot{r} = \frac{m_2 - m_1}{t} \tag{6}$$

$$Q = m_1 c_p (T_2 - T_1) + m_v h_{fg} \tag{7}$$

$$SEC = \frac{m_b HHV_b}{m_v} \tag{8}$$

$$\varepsilon = \frac{m_2 - m_1}{m_1} \tag{9}$$

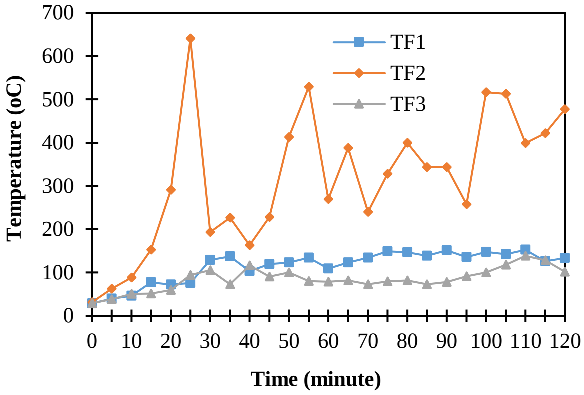
where, $\dot{r}$ is the roasting rate (g/s), m_1 and m_2 are the mass of maggot before and after roasting, Q_1 is the useful heat for roasting (kJ), cp is the specific heat of a maggot (3,47 kJ/kg °C) [22], T_2 is the maximum temperature inside the drum (°C), T_1 is the initial temperature of the drum (°C), m_v is the mass loss of the maggot, h_{fg} is the heat of vaporization of water at STP (2260 kJ/kg), SEC is the specific energy consumption (kJ/kg), m_b is the mass of firewood (kg), HHV_b is the higher heating value of the firewood (17.577 kJ/kg) [23], and ε is the effectiveness of the roaster.

3. RESULTS AND DISCUSSION

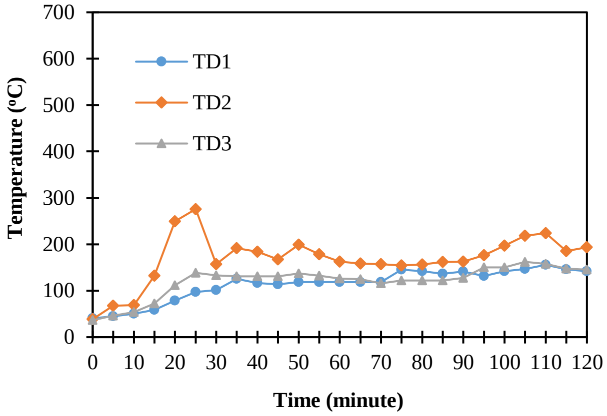
Figure 5 presents temperature profile of a furnace and a drum while 2 hours roasting of 10 kg fresh maggot. Temperature of the furnace fluctuates, especially at the middle, due to uncontrol combustion air into the furnace. This fluctuation indicates unsteady combustion occurs during the roasting process. The highest temperature of the furnace is measured at the middle of the furnace (TF2). This is because the flame is bigger at that point. The heat rate from the flame to the rotary drum is highest at the location of TF2. The flames size at the left side of the furnace (TF1) and the right side of the furnace are lower than at the middle, hence lower temperatures of TF1 and TF2 are observed. Heat from the flame is transferred to the rotary drum wall by means of convection and radiation. The trends of the temperature profiles of rotary drum are nearly like that of the furnace. The temperature at the middle of the drum (TD2) is higher than the temperature of left side (TD1) and right side (TD3). This is because TD2 receives the highest heat from the furnace, as an impact of the highest combustion rate at the middle point of the furnace (TF2). However, the fluctuation of temperature on the drum wall is lower than that of the furnace.

Temperature profile of the furnace dan the drum while roasting 30 kg fresh maggot are presented in Figure 6. The temperature profiles are similar to that while roasting 10 kg fresh maggot, which fluctuate due unsteady combustion of the biomass in the furnace. This unsteady combustion impacts on unsteady heat released by the biomass, and in turns heat transfer from the furnace to the drum also unsteady. Thus, the temperature profiles of the drum follow the trend of furnace's temperature profile.

The average temperature of the furnace and the drum are obtained by averaging TF1, TF2, TF3 for the furnace, and by averaging TD1, TD2, TD3 for the drum. The average temperature of the furnace and the drum while roasting 10 kg and 30 kg fresh maggot are given in Figure 7. The average temperature of the furnace while roasting 10 kg maggot is lower than that while roasting 30 kg maggot. This is due to firewood used during 10 kg roasting is lesser that that during 30 kg roasting. Hence less heat generates during 10 kg roasting. The average furnace's temperatures are 150℃ at roasting capacity of 10 kg and 300℃ at roasting capacity of 30 kg. From Figure 7(a), it can be observed average temperature of the drum is one fourth of the furnace. The average drum's temperatures are 120℃ for roasting capacity of 10 kg and 200℃ for roasting capacity of 30 kg. Figure 7(b) indicates that roasting starts at 15th minutes. The temperature increases significantly up to 15th minute and keeps stable till the end of the test.

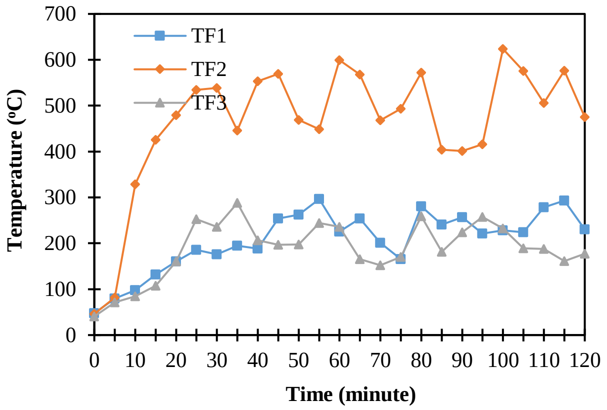


(a) Furnace

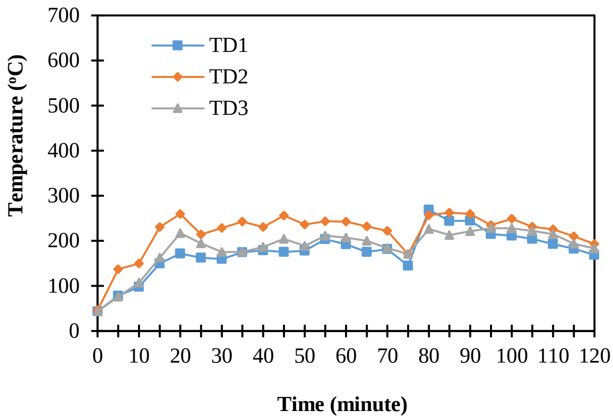


(b) Rotary drum

Figure 5. Temperature profile (10 kg fresh maggot)

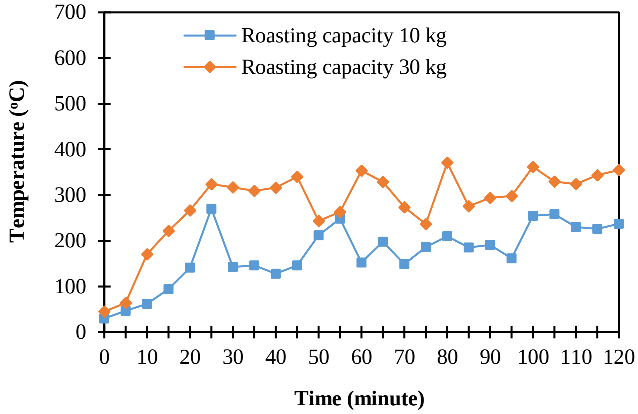


(a) Furnace

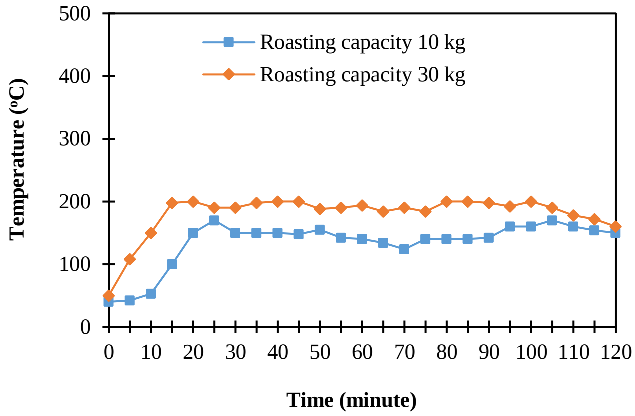


(b) Rotary drum

Figure 6. Temperature profile (30 kg fresh maggot)



(a) Furnace



(b) Rotary drum

Figure 7. Average temperature profile

Meanwhile, Figure 8 presents performance of the roaster, i.e., roasting rate, load useful heat, specific energy consumption (SEC), and effectiveness. From the graphs in Figure 8, it can be stated that performance of the roaster is better while roasting 30 kg fresh maggot than while roasting 10 kg fresh maggot. The values of roasting rate, useful heat, and effectiveness of 30 kg roasting capacity are higher than that of 10 kg roasting capacity. On the other hand, the value of SEC for 30 kg roasting capacity is lower than SEC for 30 kg roasting capacity. These results are as expected since the roasting capacity design is 50 kg. The roasting rate for roasting capacity of 10 kg and 30 kg are 1.79 g/s and 2.86 g/s. Useful heat for roasting capacity of 10 kg and 30 kg are 17392.22 kJ and 62168.30 kJ. Useful heat is defined as total heat from the furnace which is absorbed by the drum to dry the maggot inside the drum. The effectiveness of the roaster is found to be 0.57 and 0.69 for capacity of 10 kg and 30 kg. Whereas the SEC are 30838.84 kJ/kg water vapor and 12798.78 kJ/kg water vapor for roasting capacity of 10 kg and 30 kg, respectively. SEC is defined as the amount of energy required for evaporating 1 kg of water vapor. The lower the SEC, the better the performance of the roaster. Lower SEC means that to evaporate same amount of water requires lesser energy, hence more energy efficient.

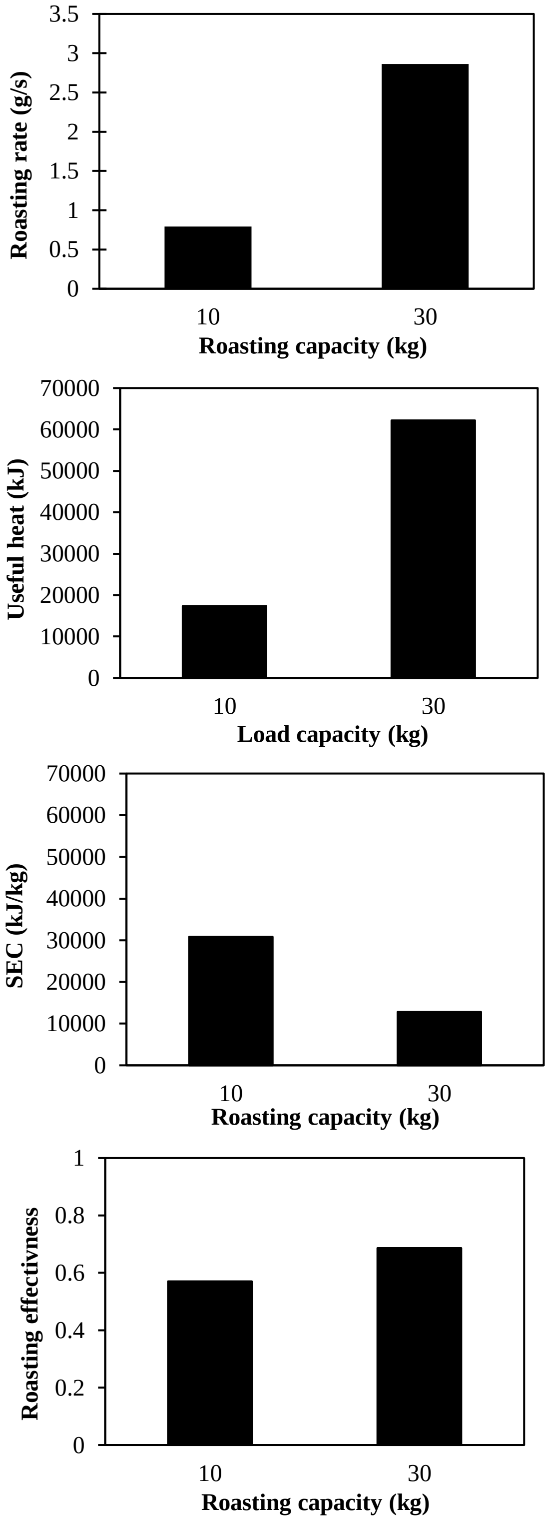


Figure 8. Performence parameter

The photograph of the fresh maggot and roasted maggot are displayed in Figure 9. The color of roasted maggot has fulfilled the standard, hence the roaster fabricated in the present work is suitable for maggot. For future work, a comprehensive evaluation of water vapor required for industrial purposes has to be performed. For example, the water content of the dry maggot has to be fulfilled the requirement of the standard for making maggot pellet.

(a) Fresh maggot

(b) Roasted maggot

Figure 9. Photograph of fresh and roasted maggot

4. CONCLUSION

The eco-friendly rotary drum roasting machine has been designed, fabricated, and tested its performance in terms of roasting rate, useful heat, SEC, and effectiveness while roasting 10 kg and 30 kg fresh maggot. It can be concluded that the roaster is suitable for roasting maggot BSF. The performance of the roaster is better while roasting capacity of 30 kg where roasting rate 2.86 g/s, useful heat of 62168.30 kJ, effectiveness of 0.69, and SEC 12798.78 kJ/kg water are gained. It can be stated that the roasting machine have a good potential to be applied in small enterprise of maggot pellet production. Besides its simple construction and low-cost investment, the roasting machine also promotes utilization of biomass waste, reduce operational costs, and promote sustainable farming practices. However, more comprehensive evaluation of thermal characteristic of the roasting machine has to be performed in the future work. The heat loss from the furnace and heat loss from the drum have to be figure out in order to enhancing performance of the roasting machine.

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REFERENCES

[1] Terrell, C., Andingwell, L. (2022). Black Soldier Fly Composting Guide. Department of Entomology, Purdue Univeristy.

[2] Zheng, L., Li, Q., Zhang, J., Yu, Z. (2012). Double the biodiesel yield: Rearing black soldier fly larvae, Hermetia illucens, on solid residual fraction of restaurant waste after grease extraction for biodiesel production. Renew Energy, 41: 75-79. https://doi.org/10.1016/j.renene.2011.10.004

[3] Belghit, I., Liland, S.N., Gjesdal, P., Biancarosa, I., Menchetti, E., Li, Y., Waagbø, R., Krogdahl, Å., Lock, E. (2019). Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon (*Salmo salar*). Aquaculture, 503: 609-619. https://doi.org/10.1016/j.aquaculture.2018.12.032

[4] Attivi, K., Mlaga, K.G., Agboka, K., Tona, K., Kouame, Y.A.E., Lin, H. (2022). Effect of fish meal replacement by black Soldier Fly (*Hermetia illucens*) larvae meal on serum biochemical indices, thyroid hormone and zootechnical performance of laying chickens. Journal of Applied Poultry Research, 31(3): 100275. https://doi.org/10.1016/j.japr.2022.100275

[5] Farahdiba, A.U., Warmadewanthi, I.D.A.A., Fransiscus, Y., Rosyidah, E., Hermana, J., Yuniarto, A. (2023). The present and proposed sustainable food waste treatment technology in Indonesia: A review. Environmental Technology & Innovation, 32: 103256. https://doi.org/10.1016/j.eti.2023.103256

[6] Susana, I.G.B., Alit, I.B., Okariawan, I.D.K. (2023). Rice husk energy rotary dryer experiment for improved solar drying thermal performance on cherry coffee. Case Studies in Thermal Engineering, 41: 102616. https://doi.org/10.1016/j.csite.2022.102616

[7] Xie, Q., Chen, Z., Mao, Y., Chen, G., Shen, W. (2018). Case studies of heat conduction in rotary drums with L-shaped lifters via DEM. Case Studies in Thermal Engineering, 11: 145-152. https://doi.org/10.1016/j.csite.2018.02.001

[8] Trojosky, M. (2019). Rotary drums for efficient drying and cooling. Drying Technology, 37(5): 632-651. https://doi.org/10.1080/07373937.2018.1552597

[9] Ettahi, K., Chaanaoui, M., Sebastien, V., Abderafi, S., Bounahmidi, T. (2022). Modeling and design of a solar rotary dryer bench test for phosphate sludge. Modelling and Simulation in Engineering, 2022: 5574242. https://doi.org/10.1155/2022/5574242

[10] Del Giudice, A., Acampora, A., Santangelo, E., Pari, L., Bergonzoli, S., Guerriero, E., Petracchini, F., Torre, M., Paolini, V., Gallucci, F. (2019). Wood chip drying through the using of a mobile rotary dryer. Energies, 12(9): 1590. https://doi.org/10.3390/en12091590

[11] Havlík, J., Dlouhý, T. (2020). Indirect dryers for biomass drying-comparison of experimental characteristics for drum and rotary configurations. ChemEngineering, 4(1): 18. https://doi.org/10.3390/chemengineering4010018

[12] Tulashie, S.K., Appiah, G., Akpari, E.E.A., Saabome, S.M. (2020). Design of shea nut rotary roasting machine used for shea butter production in Ghana. International Journal of Thermofluids, 1-2: 100015. https://doi.org/10.1016/j.ijft.2020.100015

[13] Krokida, M., Marinos-Kouris, D., Mujumdar, A.S. (2007). Rotary drying. In: Handbook of Industrial Drying, Taylor & Francis, Philadelphia.

[14] Abbasfard, H., Rafsanjani, H.H., Ghader, S., Ghanbari, M. (2013). Mathematical modeling and simulation of an industrial rotary dryer: A case study of ammonium nitrate plant. Powder Technology, 239: 499-505. https://doi.org/10.1016/j.powtec.2013.02.037

[15] Abbasfard, H., Ghader, S., Rafsanjani, H.H., Ghanbari, M. (2013) Mathematical modeling and simulation of drying using two industrial concurrent and counter current rotary dryers for ammonium nitrate. Drying Technology, 31(11): 1297-1306. https://doi.org/10.1080/07373937.2013.791307

[16] Silvério, B.C., Arruda, E.B., Duarte, C.R., Barrozo, M.A.S. (2015). A novel rotary dryer for drying fertilizer: Comparison of performance with conventional configurations. Powder Technology, 270: 135-140. https://doi.org/10.1016/j.powtec.2014.10.030

[17] Asnaz, M.S.K., Dolcek, A.O. (2021). Comparative performance study of different types of solar dryers towards sustainable agriculture. Energy Reports, 7: 6107-6118. https://doi.org/10.1016/j.egyr.2021.08.193

[18] Rabha, D.K. (2021). Performance investigation of a passive-cum-active dryer with a biomass-fired heater integrated with a plate heat exchanger. Renew Energy, 169: 598-607. https://doi.org/10.1016/j.renene.2020.12.126

[19] Darvishi, H., Zarein, M., Farhudi, Z. (2016). Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices. Journal of Food Science and Technology, 53: 2317-2333. https://doi.org/10.1007/s13197-016-2199-7

[20] El-Mesery, H.S., El-Khawaga, S.E. (2022). Drying process on biomass: Evaluation of the drying performance and energy analysis of different dryers. Case Studies in Thermal Engineering, 33: 101953. https://doi.org/10.1016/j.csite.2022.101953

[21] Silva, J., Cristina, A., Teixeira, S., Martins, L., Ferreira, E. (2021). Sawdust drying process in a large-scale pellets facility: An energy and exergy analysis. Cleaner Environmental Systems, 2: 100037. https://doi.org/10.1016/j.cesys.2021.100037

[22] Shinozaki, J. (1957). The specific heat of insects. Hokkaido University Collection of Scholarly and Academic Papers: HUSCAP, 13(1-4): 470-474.

[23] Susastriawan, A.A.P., Saptoadi, H., Purnomo. (2019). Comparison of the gasification performance in the downdraft fixed-bed gasifier fed by different feedstocks: rice husk, sawdust, and their mixture, Sustainable Energy Technologies and Assessments, 34: 27-34. https://doi.org/10.1016/j.seta.2019.04.008