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Integrating Life Cycle Assessment and Machine Learning to Enhance Black Soldier Fly Larvae-Based Composting of Kitchen Waste

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Abstract: Around 40% to 60% of municipal solid waste originates from kitchens, offering a valuable resource for compost production. Traditional composting methods such as windrow, vermi-, and bin composting are space-intensive and time-consuming. Black soldier fly larvae (BSFL) present a promising alternative, requiring less space and offering ease of handling. This research encompasses experimental data collection, life cycle assessment, and machine learning, and employs the Levenberg–Marquardt algorithm in an Artificial Neural Network, to optimize kitchen waste treatment using BSFL. Factors such as time, larval population, aeration frequency, waste composition, and container surface area were considered. Results showed that BSFL achieved significant waste reduction, ranging from 70% to 93% by weight and 65% to 85% by volume under optimal conditions. Key findings included a 15-day treatment duration, four times per day aeration frequency, 600 larvae per kilogram of waste, layering during feeding, and kitchen waste as the preferred feed. The larvae exhibited a weight gain of 2.2% to 6.5% during composting. Comparing the quality of BSFL compost to that obtained with conventional methods revealed its superiority in terms of waste reduction (50% to 73% more) and compost quality. Life cycle assessment confirmed the sustainability advantages of BSFL. Machine learning achieved high accuracy of prediction reaching 99.5%.

Keywords: black soldier fly larvae; kitchen waste; life cycle assessment; machine learning

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Citation: Arshad, M.Y.; Saeed, S.; Raza, A.; Ahmad, A.S.; Urbanowska, A.; Jackowski, M.; Niedzwiecki, L. Integrating Life Cycle Assessment and Machine Learning to Enhance Black Soldier Fly Larvae-Based Composting of Kitchen Waste. *Sustainability* **2023**, *15*, 12475. https://doi.org/10.3390/su151612475

Academic Editor: Diego Augusto De Jesus Pacheco

Received: 30 June 2023
Revised: 6 August 2023
Accepted: 7 August 2023
Published: 16 August 2023

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1. Introduction

The generation rate and composition of municipal solid waste varies from region to region depending upon the living standards, cultural norms, geographical location, and economic development [1]. Globally, solid waste handling and management have been declared a vital issue for the environment [2]. Some have identified this problem and devised an efficient method to combat this problem, hence saving time and space, which is beneficial from both environmental and economic perspectives. The poor waste management practices in developing countries are the root of many social as well as environmental issues. They are the main reason behind the contamination of oceans, clogging of drains, flooding of water bodies, and contamination of underground water resources. From respiratory air-borne diseases due to the open burning of the waste to disease transmission due to the breeding of vectors, it has become an itchy point for the environment. Vectors, such as mosquitoes or flies, play a crucial role in transmitting air-borne diseases by carrying pathogens from infected individuals to healthy individuals [3,4]. Many have adopted and developed such efficient systems to change trash into cash but still, the larger part of the globe is struggling with this problem [5,6].

Municipal solid waste (MSW) consists of organic and inorganic fractions. Handling of both fractions is difficult, so turning one into a useful byproduct is desirable [7,8]. The ascribable organic fraction includes residues of fruits and vegetables, food waste, and yard trimmings which can be treated and changed into a useful product [9,10]. One of the best ways to recycle the organic fraction is to convert it into compost [11]. There are several processes of composting such as windrow composting, vermicomposting, and bin composting [12]. However, typical methods of composting are space-taking and slow processes [13,14].

Black soldier fly (BSF) larvae have gained significant interest in the past few decades for their use in the reduction of organic waste and as animal feed [15]. This species has spread subsequently in Europe since the decades of the 1950s and 1960s [16]. The BSF treatment method also results in an effective reduction in waste volume and the compost produced can be used for beneficial purposes [5,17]. In this study, the BSF-based waste composting process is optimized under local conditions (the composition of organic waste typical for Pakistan) and compared with a conventional composting method with respect to waste reduction and compost quality. The waste composting efficiency is influenced by factors such as time, number of larvae, aeration frequency, waste composition, and container surface area. These factors are optimized using suitable ranges derived from literature and advanced statistical tools. The study utilizes life cycle assessment (LCA) and machine learning (ML) to validate the composting process and facilitate future scale-up studies. The incorporation of LCA enables assessment of environmental impact, while ML allows for data-driven analysis and optimization, ensuring sustainable practices and informed decision-making in composting operations.

2. Methodology

2.1. Waste Sample Collection, Preparation, and Waste Container

Kitchen waste used in this study was sourced from households using a dedicated bin placed in the kitchen area, as depicted in Figure 1. The collected samples underwent careful analysis to determine their composition, which was subsequently maintained throughout the experiment. The conventional literature describes the composition of kitchen waste, emphasizing major constituents such as tea, fruits, vegetables, tissues, bread, and pollutants. Additionally, Figure 1a showcases a generalized composting flow sheet, depicting the sequential steps of waste collection, pre-treatment, composting, specialized waste treatment, and the ultimate recovery of valuable end-products.

To facilitate the sampling and experimentation process, a household plastic container was employed for collection of different kind of waste for Conventional Bin Composting and BSF larvae waste container composting, as depicted in Figure 1b. The container's dimensions were carefully selected to ensure proper handling and containment of the waste samples, thereby guaranteeing reliable and controlled experimentation conditions.

2.2. Waste Treatment and Process Optimization

BSFL-aided composting was optimized for different parameters including time, aeration frequency, number of larvae, the surface area of the container, and waste composition at ambient conditions. The variables and the range of tested values are presented in Table 1. During the experimentation, four types of waste composition were used: Kitchen Waste (W1), Fruit Waste (W2), Vegetable Waste (W3), and Municipal Waste (W4) and their detailed composition is shown in Figure 2a–d.

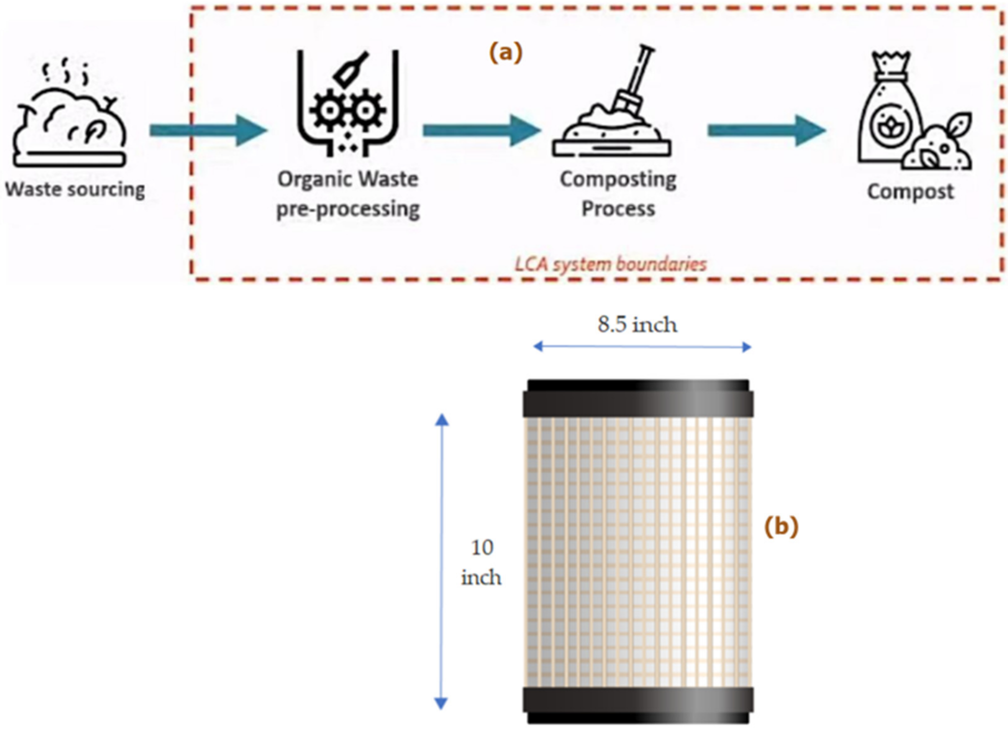

Figure 1. (**a**) Conventional Composting Process (**b**) Waste Collection Plastic Container for waste composting.

W1, which represents kitchen waste, consisted of a combination of Strawberry and Mulberries (0.535 kg) along with Potato Peels (0.136 kg), accounting for 36% and 10% of the total weight, respectively. Additionally, it included Tea (0.15 kg) and 1 green chili, contributing 2% and 10% to the weight, respectively. A bread piece (0.03 kg) made up 2% of the waste composition, and Tissue Papers accounted for a negligible percentage. W2, representing fruit waste, comprised Strawberry and Mulberries (0.05 kg), Orange (0.1 kg), Banana (0.05 kg), Peach (0.05 kg), Apple (0.25 kg), and melon peels, contributing to the respective percentages of 13%, 26%, 13%, 13%, 17%, and 2% of the total weight.

W3, representing vegetable waste, included Green Leaves (0.05 kg), Brinjal (0.1 kg), Pumpkin (0.05 kg), Potato (0.05 kg), Tomato (0.05 kg), Onion (0.08 kg), and small Onion (0.025 kg). These vegetable components accounted for 13%, 26%, 13%, 13%, 13%, 21%, and 2% of the total weight, respectively. W4, representing municipal waste, consisted of Green Chili (0.1 kg), Bread Piece (0.05 kg), Tissue Papers (0.05 kg), Onion (0.05 kg), and Poultry waste (0.016 kg). The respective percentages for these components were 26%, 13%, 13%, 13%, and 4% of the total weight.

In total, the waste compositions used in the experimentation had a weight of 1.5 kg, with each composition contributing to a specific percentage of the overall weight.

Table 1. Treatment Optimization Factors.

Parameter	Tested Range
Time	1 to 20 days
Aeration frequency	1, 2, 3 and 4 per day (referred as At1, At2, At3, and At4)
Number of larvae	300, 600, 900, and 1200 per kg of waste (referred as L1, L2, L3 and L4)
Surface area	56.7″, 78.5″, 113″, and 176.6″ (inch square) (referred as S1, S2, S3, and S4)
Waste composition	Kitchen Waste, Fruit Waste, Vegetable Waste, and Municipal Waste (referred to as W1, W2, W3, W4)

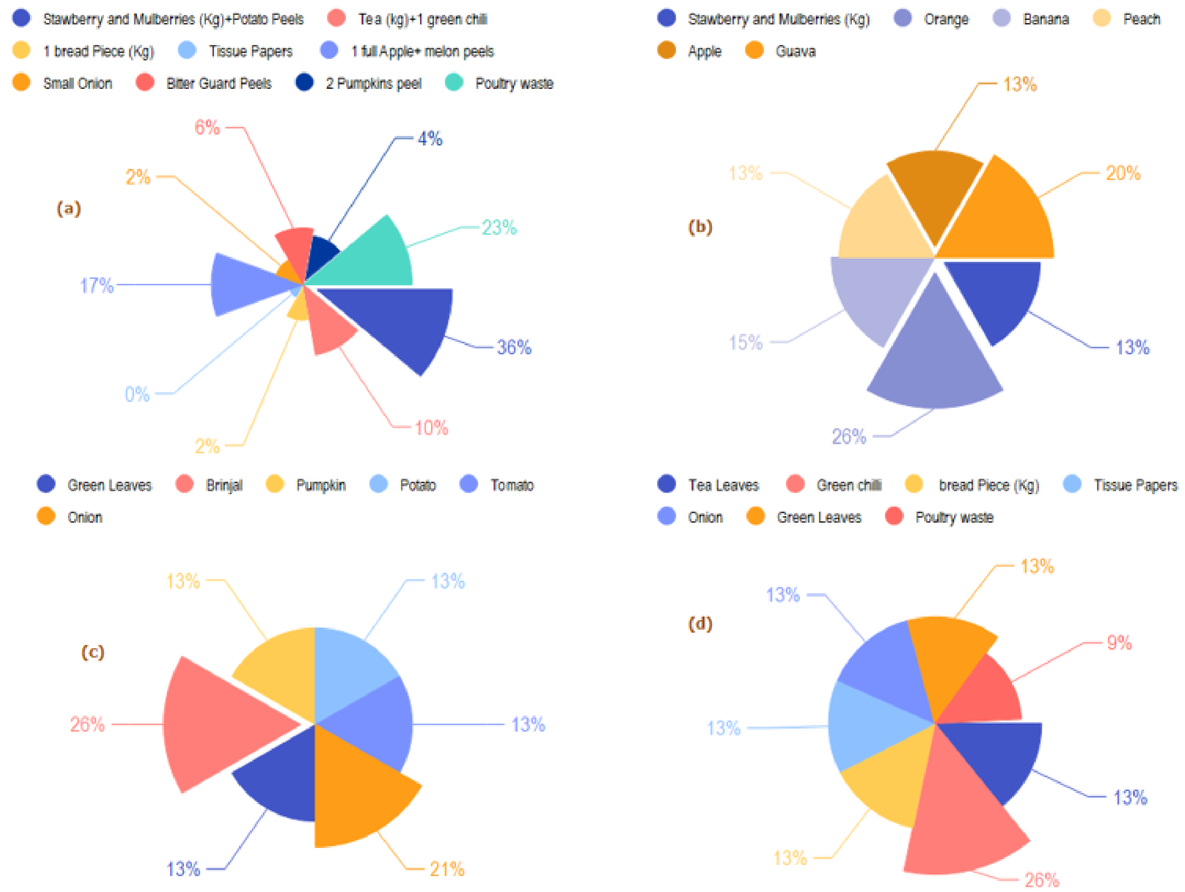

Figure 2. Different Waste Composition (**a**) Kitchen Waste (W1) (**b**) Fruit Waste (W2) (**c**) Vegetable Waste (W3) (**d**) Municipal Solid Waste (W3) used in experimental BSFL composting process.

2.3. Comparative Analysis of Waste Treatment and Compost

In our study, we utilized four different types of waste for treatment using Black Soldier Fly Larvae (BSFL) to explore their composting efficiency. Among these waste types, we sought to identify the one that yielded the highest efficiency when subjected to the optimized parameters for BSFL treatment. This waste was then compared with the conventional bin composting technique to evaluate the effectiveness of the BSFL method in achieving superior efficiency for various parameters.

To assess the treatment efficiency, we compared the compost generated by the BSFL and bin composting methods. Several parameters, including pH, moisture content, total dissolved solids (TDS), conductivity, and nutrient levels such as carbon (C), nitrogen (N), and potassium (K), were evaluated and analyzed. The experiments were conducted following the guidelines outlined in the literature [18] and the values of these parameters were determined using established standard methods. Additionally, the quality of the resulting compost was compared against the characteristics indicative of good compost.

By comparing the performance of BSFL treatment with the traditional bin composting approach, we aimed to ascertain the superiority of the BSFL method in terms of composting efficiency and the quality of the final product. This comprehensive evaluation provided insights into the potential of BSFL as an efficient and sustainable waste treatment option, with implications for waste management and resource recovery efforts.

2.4. Life Cycle Assessment of BSFL Technology and Machine Learning Modeling for Predictive Modeling and Optimization Validation of Waste Treatment and Compost

In order to effectively address the complexities and dependencies involved in composting experimentation, it is crucial to have a comprehensive understanding of the process. To achieve this, various tools and methodologies are employed, including life cycle assessment (LCA) which involves both product stage assessment and detailed process analysis. Additionally, techno-economic assessment is utilized to model the financial implications of composting, taking into account factors such as the importation of larvae, setup conditions, and capital and operating expenditures. Researchers have explored different software tools such as GPX-10, Bio-win 7.8, and MATLAB R-21 for process modeling and simulation in composting studies. However, to date, limited research has been conducted on a three-pronged strategy that combines experimentation, life cycle assessment, and advanced artificial intelligence techniques such as machine learning and deep learning. By integrating these tools, a more comprehensive understanding of the composting process can be obtained, allowing for accurate predictions and analysis of process variables without incurring substantial financial costs.

This multidisciplinary approach, shown below in Figure 3, offers several advantages. At step 1 (experimental analysis), four distinct types of waste are utilized to investigate the effectiveness of BSFL in composting. We evaluated the efficiency of each waste type and compared the most efficient one with the conventional bin composting technique. The goal was to determine the superior performance of the BSFL method across various parameters.

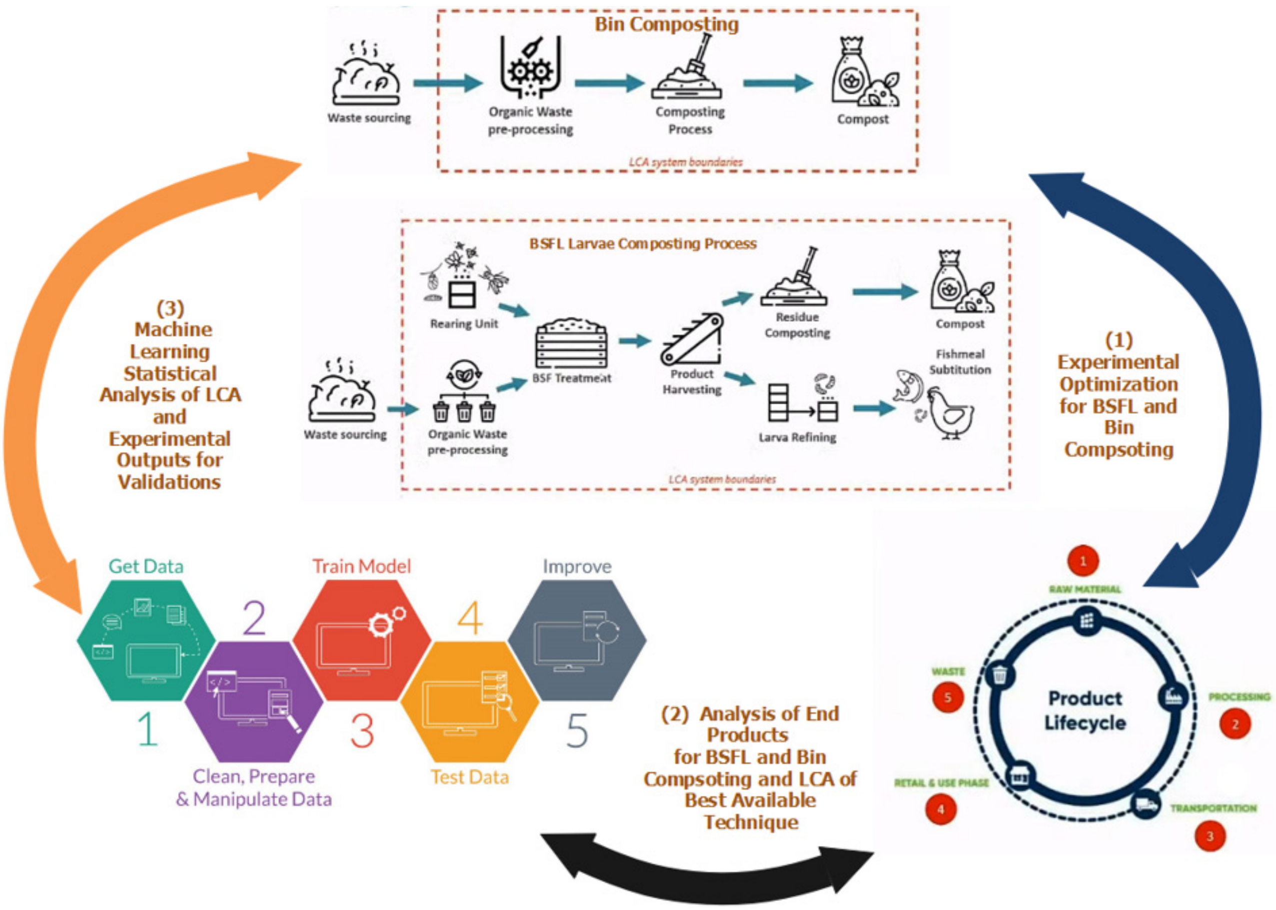

Figure 3. Working cycle methodology for different kind of waste composting and comparison of Bin and BSFL composting.

At step 2 in Figure 3, to ensure the reliability and credibility of our findings, we conducted a Life Cycle Assessment (LCA) of both the BSFL composting and bin composting approaches. We employed Sima-Pro 9.1, a commercially available software, to analyze and compare factors such as global warming equivalents, emissions, and inventory standards associated with each composting technique. A cradle-to-grave approach in LCA is considered when applied to the composting of Black Soldier Fly Larvae BSFL. This approach takes into account the complete life cycle of the larvae, beginning with their introduction into the composting system and continuing through to the final use or disposal of the resulting compost. Through this comprehensive analysis, we sought to gain a deeper understanding of the environmental impact and sustainability aspects of both methods. It provides a deeper understanding of the composting process itself, enabling researchers to identify critical parameters and optimize conditions for enhanced performance. Furthermore, the integration of life cycle assessment provides insights into the environmental impacts associated with different stages of composting, helping to guide sustainable decision-making.

At step 3 in Figure 3, in order to enhance the accuracy and depth of our analysis, we incorporated an advanced deep learning Artificial Neural Network (ANN) model. This model allowed us to further explore the output results from Sima-Pro, enabling us to delve into parameters such as global warming equivalents, emission levels, and inventory standards. This innovative approach provided valuable insights that could not be solely attained through experimental methods. The utilization of advanced artificial intelligence techniques allows for the development of sophisticated black box models that can accurately predict and analyze composting outcomes under variable conditions.

An Artificial Neural Network (ANN) model is a powerful computational tool that mimics the structure and functionality of biological neural networks found in the human brain [19]. It is a subset of machine learning algorithms that excel at recognizing patterns, performing complex tasks, and making accurate predictions based on input data. The ANN model consists of interconnected artificial neurons, also known as nodes, which simulate the behavior of biological neurons. These nodes are organized into layers, including an input layer where data are fed, one or more hidden layers that process and extract features from the input, and an output layer that produces the desired results. The connections between neurons are represented by weighted edges, which determine the importance and strength of information flow between nodes. The ANN model has proven to be highly effective in various domains, including image and speech recognition, natural language processing, predictive analytics, and decision-making systems [20]. Its ability to learn from large amounts of data and generalize patterns makes it a valuable tool for solving complex problems and making accurate predictions [21].

Artificial Neural Networks (ANNs) have found applications in the field of composting, particularly in optimizing and improving the composting process. ANNs can be used to model and predict various aspects of composting, such as degradation rates, nutrient dynamics, temperature profiles, and odor emissions. By analyzing historical data and training the network, ANNs can learn complex relationships between input variables (e.g., waste composition, moisture content, aeration rate) and output variables (e.g., compost quality, process efficiency).

ANNs have been employed in composting research to enhance process understanding and develop prediction models [22,23]. For example, in a study by Chung et al., an ANN model was used to predict the composting process parameters, including temperature, moisture, and oxygen levels, to optimize the composting process [24]. ANN models have been widely used to assess the composting performance and predict the nutrient content of the final compost [25,26].

The use of ANNs in composting offers several advantages. They can handle non-linear relationships and complex interactions among multiple variables, allowing for more accurate predictions and optimization. ANNs also enable real-time monitoring and control of composting systems, facilitating process adjustments, and improving overall efficiency. MATLAB R.21 software has been incorporated for the built-in ANN tools. Nevertheless, ANN has three algorithms, namely, Levenberg–Marquardt (LM) Regression, Bayesian Regularization, and Scaled Conjugate Gradient (SCG). However, due to the compactness of regression activity, only the LM Regression and SCG algorithm have been used, as the dataset is mainly linear and only a single prediction value is required. Machine learning modeling and analysis work have been described in Figure A1 in terms of the timeline for data analysis, prediction, and accuracy.

In assessing the quality of the resulting compost, we compared various indicators. Moreover, our research compared the compost quality against the characteristics of high-quality compost, ensuring that our findings aligned with established composting standards. The study aimed to evaluate the effectiveness of BSFL in waste treatment compared to traditional bin composting methods. Through comprehensive assessments, comparisons, and analyses, we aimed to provide a comprehensive understanding of the performance and sustainability aspects of both composting techniques.

By harnessing the power of machine learning and deep learning, researchers can make data-driven discoveries and advancements in composting. These techniques enable the identification of complex patterns and relationships within large datasets, facilitating the development of more efficient and cost-effective composting strategies. Ultimately, this integrated approach combining experimentation, life cycle assessment, and advanced artificial intelligence techniques offers a promising avenue for research advancement, driving innovation in the field of composting and facilitating the transition towards more sustainable waste management practices.

3. Results and Discussion

3.1. BSFL Experimentation: Composting and Process Conditions Optimization

In BSFL composting, the composting conditions are carefully optimized for experimental purposes using the design of experiment 12.0 methodology [27]. This approach allows for the consideration of multiple independent variables that can influence the composting process. These variables include factors such as time, aeration frequency, the number of larvae, the surface area of the container, and the composition of the waste being composted [28,29]. This ensures accurate and reliable results, as each experimental run in the study maintains a consistent set of parameters while only modifying one specific parameter. This approach helps to isolate the effects of each variable and understand their individual impact on the composting process. By systematically changing one parameter at a time while keeping others constant, researchers can observe and analyze the direct influence of that specific variable on the composting conditions. This detailed examination of variable conditions allows researchers to gain a comprehensive understanding of how each parameter affects the composting process [30,31]. It helps in identifying the optimal conditions for the larvae, waste breakdown, and nutrient transformation. Through these experiments, researchers can assess the effectiveness of different composting strategies and fine-tune the process to maximize efficiency and productivity.

The use of the design of experiment methodology in BSFL composting research enables a systematic and methodical approach to investigate the effects of various independent variables [31,32]. It helps in understanding the intricacies of the composting process and allows for the development of optimized conditions for efficient waste degradation and nutrient conversion by the black soldier fly larvae. Details of each parameter's experimentation is discussed in detail below.

3.2. Effect of Time on Composting with BSFL

The percentage volume and weight reduction were recorded for 20 consecutive days. The results are given in Figure 4a for four different types of wastes. As can be observed from Figure 4, the rate of waste reduction gradually paced up and maximum waste reduction was attained at 15 days. After 15 days, the waste consumption rate was constant. As per study [29], the average larval age of BSFL is 14–21 days and a minimum age of 5-day-old larvae are fed. So, more precisely it has been concluded that after 15 days of composting, the larvae would be starting to change into pre-pupae and the food requirements are at a minimum. Therefore, 15 days was taken as the optimum time of waste reduction with BSFL, with 5-day-old larvae as feed.

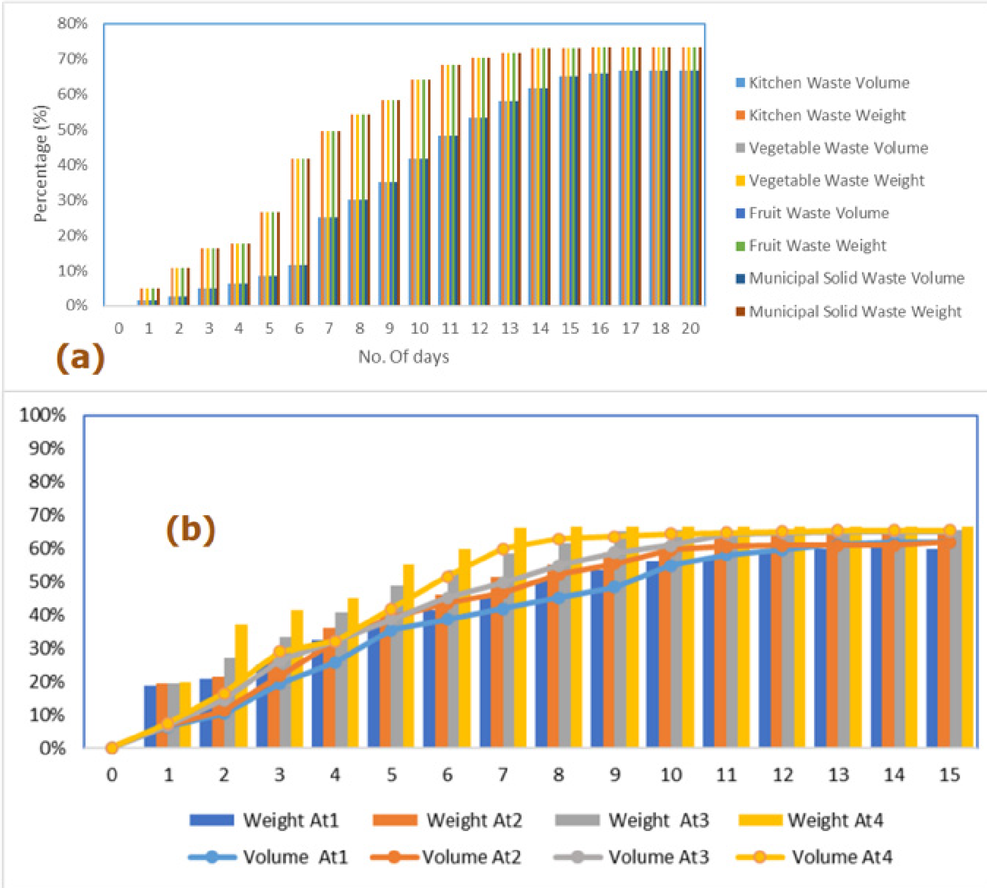

Figure 4. During BSFL composting, the weight percentage and waste volume reduction analyzed for all four different compositions of wastes due to effect of (**a**) variable time (**b**) variable aeration frequency (At1 refers to aeration one time per day, At2 refers to aeration two times per day, At3 refers to aeration three times per day, At4 refers to aeration four times per day).

The study involved monitoring the percentage volume and weight reduction of the waste over 20 consecutive days. The findings are presented in Figure 4a, which clearly illustrates the trend of waste reduction. It can be observed that the rate of waste reduction gradually increased over time, reaching its maximum at around 15 days. Beyond this point, the rate of waste consumption remained relatively constant.

Taking into account previous research on black soldier fly larvae (BSFL), it has been established that the average larval age of BSFL ranges from 14 to 21 days, and waste feeding typically begins when the larvae are at least 5 days old [33,34]. Therefore, it can be concluded with greater precision that after 15 days of composting, the larvae would have started transitioning into the pre-pupae stage, and their food requirements would be minimal. Based on this understanding, it is determined that the optimum duration for waste reduction with BSFL, while using 5-day-old larvae as feed, is approximately 15 days. Kitchen waste outperformed among the four types of waste, and the most significant reduction was observed until day 15; after that, the reduction remained constant. This time frame allows for the most efficient utilization of the larvae's feeding behavior, taking into account their growth and development stages. By adhering to this optimal timeframe, waste composting with BSFL can be effectively managed and optimized, yielding desirable outcomes in terms of waste reduction and resource utilization.

3.3. Effect of Aeration Frequency

In order to investigate the impact of aeration frequency on waste reduction, a series of experiments were conducted over an optimum period of 15 days. Four samples were set up with varying aeration frequencies, and the results obtained were analyzed. The percentage volume and weight reduction achieved with different aeration frequencies are presented in Figure 4b. Notably, the sample labeled At4, which experienced aeration four times a day, exhibited a significant volume reduction of 65% after just 8 days. In comparison, the sample labeled At3, with aeration three times a day, achieved the same reduction after 11 days. These findings indicate that increasing the frequency of aeration resulted in a faster rate of waste reduction by the larvae.

Further analysis revealed that the At4 sample demonstrated an impressive 88% reduction in weight and nearly 70% reduction in volume within the first 8 days. This highlights the effectiveness of more frequent mixing or aeration in promoting efficient waste consumption by the black soldier fly (BSF) larvae. However, as the experiment reached the 15-day mark, the overall waste reduction showed minimal variation among the different aeration frequencies. This suggests that beyond a certain threshold, the additional benefits of increasing the aeration frequency become negligible in terms of waste reduction.

Based on the experimental results, an optimum aeration frequency of four times per day was determined. This frequency allowed the BSF larvae to consume the waste more effectively while minimizing odor production. The findings underscore the importance of regular mixing and aeration in enhancing waste decomposition efficiency and controlling unwanted odors during the composting process.

3.4. Effect of No. of Larvae

The number of larvae is one of the key factors, as it can vary the degradation speed. Results obtained for waste reduction using a different number of larvae in different samples are presented in Figure 5a. The relation between the number of larvae and waste food consumption is direct, as the more larvae there are, the more rapid will be the consumption of waste, and less time will be taken to convert the waste into compost. The observed weight and volume reduction was more rapid in sample L4 (with 1200 larvae per kg of waste) but for 15 days 600 larvae per kg can provide a similar efficiency. With an increased number of larvae, rapid waste reduction can be obtained and the required number of days to obtain a particular waste reduction efficiency can be achieved.

3.5. Effect of Surface Area

The optimization of kitchen waste treatment using Black Soldier Fly Larvae (BSFL) involved introducing the waste into containers with varying surface areas (diameter), while keeping other factors constant. The outcomes of this experiment are presented in Figure 5b, illustrating the observed trend of percentage weight and volume reduction. The results clearly demonstrated that the degradation efficiency of waste by the larvae increased with an increased surface area of the container. This finding suggests that a larger surface area facilitates enhanced waste reduction by the larvae. One approach to increase the surface area is by distributing the larvae in layers within the container instead of solely feeding them from the top.

Our current research work adopts the layering technique in BSFL composting to achieve efficient waste reduction and high-quality compost production. This method involves creating multiple horizontal layers of kitchen waste and BSFL within the composting container. The process starts with a layer of kitchen waste placed at the container's bottom as the initial substrate. BSFL larvae are then evenly introduced across the surface, where they naturally crawl and burrow into the waste to begin feeding. Successively, additional layers of each waste type are added on top, alternating with the introduction of larvae, until the container is nearly filled. Finally, the process is completed with a final layer of each waste type acting as a cover. As the larvae move through these layers, they effectively consume the waste, converting it into compost and significantly reducing its volume and weight. The layering technique optimizes the surface area available for the larvae, leading to enhanced composting efficiency and the production of high-quality compost.

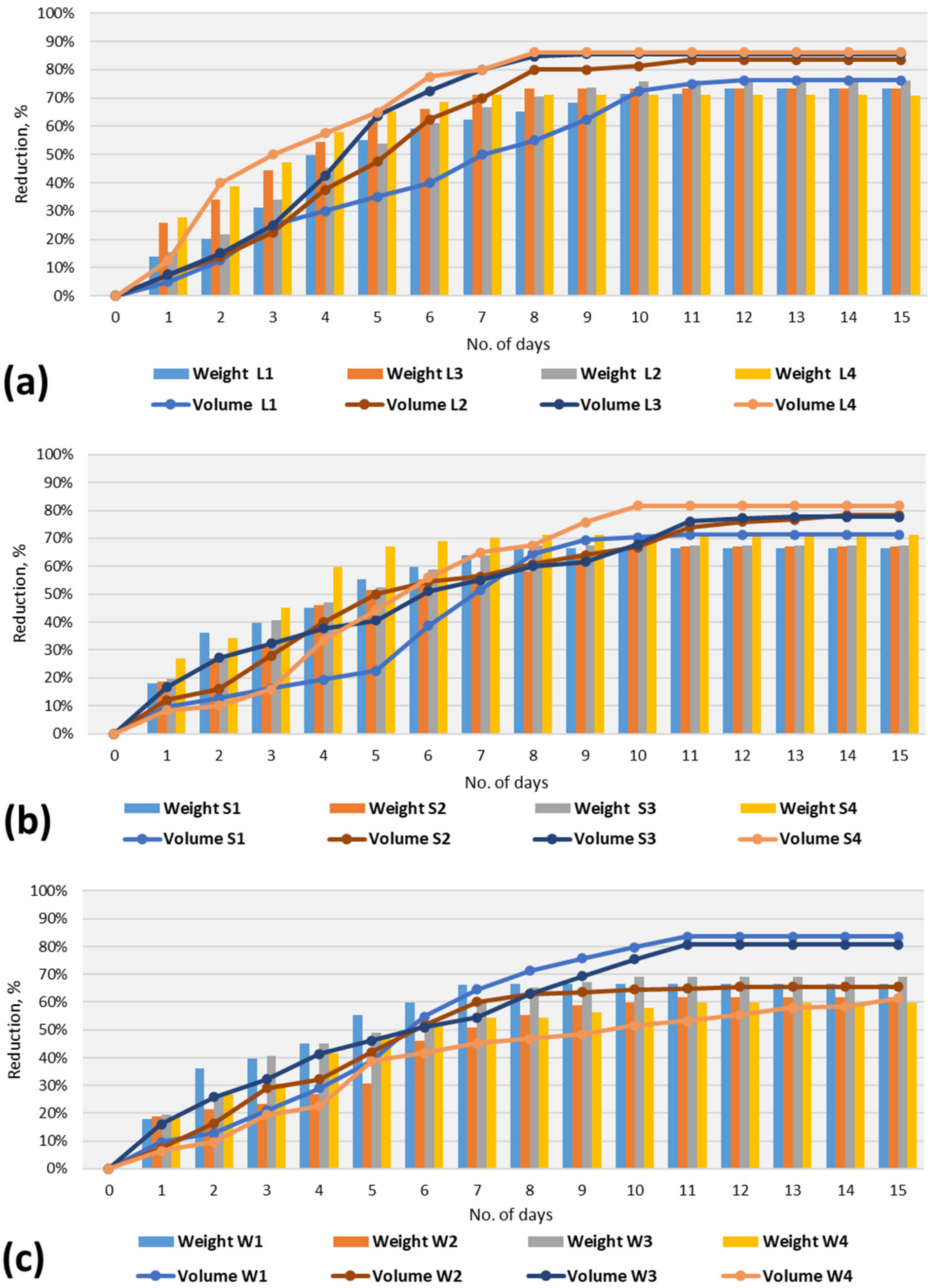

Figure 5. During BSFL composting, percentage weight and waste volume reduction for all four types of waste: effect due to (**a**) Variable Number of Larvae (**b**) Variable Surface Area (**c**) Variable Composition.

The underlying reason behind the improved waste reduction with increased surface area is that a larger surface area and shorter height expose the larvae to a greater availability of food. As a result, the larvae can consume the food more easily and rapidly, leading to a higher level of waste decomposition. This finding highlights the significance of optimizing the container's surface area to maximize the effectiveness of the BSFL treatment process for kitchen waste in line with research validation [35]. By manipulating the surface area of the containers and exploring alternative feeding methods, researchers can enhance the efficiency of waste reduction and promote more efficient resource utilization through the BSFL treatment method. This knowledge can contribute to the development of sustainable waste management strategies, enabling the effective utilization of kitchen waste and minimizing its environmental impact.

3.6. Effect of Waste Composition

Kitchen waste comprises diverse fractions, including fruit peels, vegetables, poultry waste, and more. The digestion time for each type of waste by Black Soldier Fly Larvae (BSFL) varies depending on the nature of the waste [36]. In order to evaluate which waste type is consumed more rapidly by BSF, four different waste types were selected, and their degradation by the larvae was observed. The results, depicted in Figure 5c, indicate the percentage weight and volume reduction for different waste compositions.

It was observed that unsegregated waste, such as municipal waste, exhibited lower degradation efficiency compared to the kitchen waste composed of fruits, vegetables, tea residues, and oily tissues. The kitchen waste demonstrated exponential waste reduction, suggesting that the presence of diverse components enhanced the digestion process. Notably, the degradation of kitchen waste, particularly fruit peels from oranges, guavas, apples, berries, and other fruits, exhibited higher efficiency. This can be attributed to the juice and moisture content present in these peels, which likely facilitated the larvae's consumption and breakdown of the waste [37,38]. Furthermore, the physical structure of fruit waste, particularly the peels, can also influence decomposition. Fruit peels often have a protective outer layer that can be more resistant to degradation compared to other kitchen waste components. This resistance to breakdown may result in slower decomposition rates for fruit waste compared to kitchen waste [38,39]. The study conducted by Lalander et al., which investigated the biodegradation of kitchen waste and municipal solid waste using BSFL, reported similar results. They reported that kitchen waste, rich in organic matter and diverse components, was more efficiently decomposed compared to municipal solid waste. The presence of fruit peels and other organic residues contributed to the enhanced digestion process as observed in our research work [40].

Understanding the varying degradation rates of different waste types by BSFL is crucial for efficient waste management strategies. By identifying the waste fractions that can be more rapidly digested by the larvae, appropriate segregation and treatment methods can be implemented to maximize the reduction of organic waste. This knowledge can contribute to the development of targeted waste management approaches that harness the capabilities of BSFL, leading to improved resource utilization and reduced environmental impact associated with kitchen waste disposal.

3.7. Life Cycle Assessment of BSFL

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts associated with the entire life cycle of a product, process, or service. It provides a comprehensive assessment of various environmental aspects, such as resource consumption, energy use, emissions, and waste generation, from the extraction of raw materials to final disposal or recycling [41]. LCA considers the entire life cycle stages, including raw material acquisition, manufacturing, transportation, product use, and end-of-life treatment. It helps in identifying the environmental hotspots and potential areas for improvement, guiding decision-making towards more sustainable options.

Several tools and software are available to conduct LCA studies, such as SimaPro, GaBi, and OpenLCA, are popular LCA software tools that enable practitioners to assess environmental impacts and make informed decisions. Such a tool offers a vast database of life cycle inventory data and impact assessment methods. It allows users to model life cycle systems, analyze environmental impacts, and compare different scenarios, which assists in performing life cycle assessments.

BSFL composting of kitchen waste is an important area of study from an environmental perspective and conducting a Life Cycle Assessment (LCA) is crucial to understand its sustainability and potential benefits. LCA helps in quantifying the environmental impacts associated with the entire life cycle of BSFL composting, including raw material acquisition, larvae rearing, waste processing, and end-use of the composted material.

Several studies have investigated the Life Cycle Assessment (LCA) of Black Soldier Fly Larvae (BSFL) composting of kitchen waste, shedding light on its environmental impacts and sustainability. An LCA study on the use of BSFL as feed ingredients in aquaculture was conducted to assess various stages of the life cycle, including larvae rearing, waste processing, and the production of fish feed. The study highlighted the potential of BSFL as a sustainable alternative to conventional feed ingredients, demonstrating reduced energy consumption and greenhouse gas emissions [42].

The LCA of food waste management options, including BSFL treatment, was examined. The researchers compared the environmental performance of different waste management methods and found that BSFL composting exhibited favorable outcomes in terms of energy consumption, greenhouse gas emissions, and waste reduction. The study emphasized the environmental benefits of incorporating BSFL into food waste management systems [43]. An LCA to assess integrated biowaste treatment systems based on BSFL in China was conducted to evaluate the environmental impacts of various waste treatment options, including landfilling, composting, and BSFL composting. The findings indicated that BSFL composting had significant advantages in terms of reducing greenhouse gas emissions, energy consumption, and land use. The research suggested that integrating BSFL into waste management systems could contribute to more sustainable and environmentally friendly practices [44].

These LCA studies collectively highlight the potential of BSFL composting kitchen waste as a sustainable waste management option. The findings demonstrate the environmental benefits of this approach, including reduced energy consumption, greenhouse gas emissions, and waste generation. By utilizing BSFL in the composting process, organic waste can be effectively converted into valuable resources, contributing to a circular economy and mitigating the environmental impacts associated with traditional waste management methods.

By performing LCA on BSFL composting of kitchen waste, we assessed various environmental aspects such as energy consumption, greenhouse gas emissions, water usage, and waste generation. This assessment provides insights into the potential environmental benefits and drawbacks of utilizing BSFL as a composting method compared to conventional alternatives; details are given in Table 2 below. Our LCA study mainly focuses on assessing the environmental impacts of BSFL composting of kitchen waste by considering parameters such as energy consumption, greenhouse gas emissions, and resource utilization to provide insights into the environmental performance and sustainability of this approach.

Figure 6a illustrates the selection of the Sima-Pro 3.8 tool for conducting a Life Cycle Assessment (LCA) of Black Soldier Fly Larvae (BSFL). The LCA process typically consists of eight steps when using the SimaPro software: Goal and Scope Definition, Inventory Analysis, Life Cycle Impact Assessment, Interpretation of Results, Sensitivity Analysis, Improvement Analysis, Reporting, and Communication. The flow chart includes a sensitivity analysis, which predominantly involves Monte Carlo simulation. In our specific case, we have adopted a cradle-to-grave approach. The cradle-to-grave approach in Life Cycle Assessment (LCA) is particularly justified when considering the composting of Black Soldier Fly Larvae (BSFL). Composting BSFL involves the entire life cycle of the larvae, from their introduction into the composting system to the final use or disposal of the compost.

Two distinct scenarios were considered for the LCA studies. The first scenario involved a pilot-scale experimental run, while the second scenario focused on the scale-up study of a three-ton BSFL working facility. The Eco-invent library was utilized, and the method 2016 H-16 midpoint was chosen for the analysis.

Table 2. Impact Category for Input/Output Material LCA results.

Impact Category	Unit	BSFL Compost [45] | Treatment of Kitchen and Garden Biowaste, Home Composting in Heaps and Containers | APOS, S-Inputs	Fish Feed-Output	Fertilizer, N, DK-Outputs
Water consumption	m^3	1.30	1.86	0.00
Fossil resource scarcity	kg $_{oil\ eq}$	3.89	1.56	0.25
Mineral resource scarcity	kg $_{Cu\ eq}$	0.060	0.113	0.003
Land use	m^2/a $_{crop\ eq}$	7.57	0.27	0.00
Human non-carcinogenic toxicity	kg $_{1,4\text{-}DCB}$	14.26	4.67	0.00
Human carcinogenic toxicity	kg $_{1,4\text{-}DCB}$	0.15	0.61	0.00
Marine ecotoxicity	kg $_{1,4\text{-}DCB}$	0.161	0.058	0.000
Freshwater ecotoxicity	kg $_{1,4\text{-}DCB}$	0.317	0.014	0.000
Terrestrial ecotoxicity	kg $_{1,4\text{-}DCB}$	66.85	84.10	0.00
Marine eutrophication	kg $_{N\ eq}$	0.0153	0.0001	0.0000
Freshwater eutrophication	kg $_{P\ eq}$	0.0036	0.0005	0.0000
Terrestrial acidification	kg $_{SO2\ eq}$	0.166	0.027	0.005
Ozone formation, Terrestrial ecosystems	kg $_{NOx\ eq}$	0.060	0.021	0.004
Fine particulate matter Formation	kg $_{PM2.5\ eq}$	0.035	0.013	0.001
Ozone formation, Human health	kg $_{NOx\ eq}$	0.057	0.020	0.004
Ionizing radiation	kBq $_{Co\text{-}60\ eq}$	0.122	0.049	0.000
Stratospheric ozone depletion	kg $_{CFC11\ eq}$	112.8×10^{-6}	3.1×10^{-6}	63.5×10^{-6}
Global warming	kg $_{CO2\ eq}$	17.67	7.41	2.71

The LCA provides an analysis of the environmental impact categories associated with the BSFL composting process, fish feed production, and fertilizer production, as shown in Figure 5b,c, following the steps outlined in Figure 6a. The impact categories identified through the LCA offer valuable insights into the resource consumption, pollution potential, and overall environmental performance of each process. Multiple trends were calculated using LCA tools in addition to material flows as shown in Table 2 and Figure 6. Water consumption is an important aspect to consider and the results indicate that the BSFL composting process requires 1.298 m^3 of water, while fish feed production utilizes 1.861 m^3 mainly due to moisture contents in organic waste as shown in Figure 7a,b. In contrast, fertilizer production does not involve water consumption, indicating a potential advantage in terms of water conservation, so fertilizer production is 1.5-fold higher than fish feed.

Fossil resource scarcity, measured in terms of kilograms of oil equivalent, provides another significant category. The results show that the BSFL composting process has an impact of 3.894 kg oil equivalent, while fish feed production has a lower impact of 1.558 kg oil equivalent. Fertilizer production demonstrates a relatively smaller impact of 0.250 kg oil equivalent, suggesting a more efficient utilization of fossil resources as shown in Figure 8a,b. Land use highlights an important consideration when assessing the environmental footprint of a process. Sima-Pro LCA revealed that the BSFL composting process requires 7.569 m^2, a crop equivalent of land, indicating the space needed for composting activities. In contrast, fish feed production has a significantly lower land use impact of 0.266 m^2, crop equivalent. Fertilizer production does not contribute to land use impacts. LCA also highlighted the ecotoxicity impacts in different environments, including marine, freshwater, and terrestrial ecosystems. The Global Emissions and Impact bar chart at Normalization was measured and is shown in Figure 8c. The BSFL composting process exhibits varying levels of ecotoxicity, with higher values compared to fish feed production. Fertilizer production, however, shows no ecotoxicity impact.

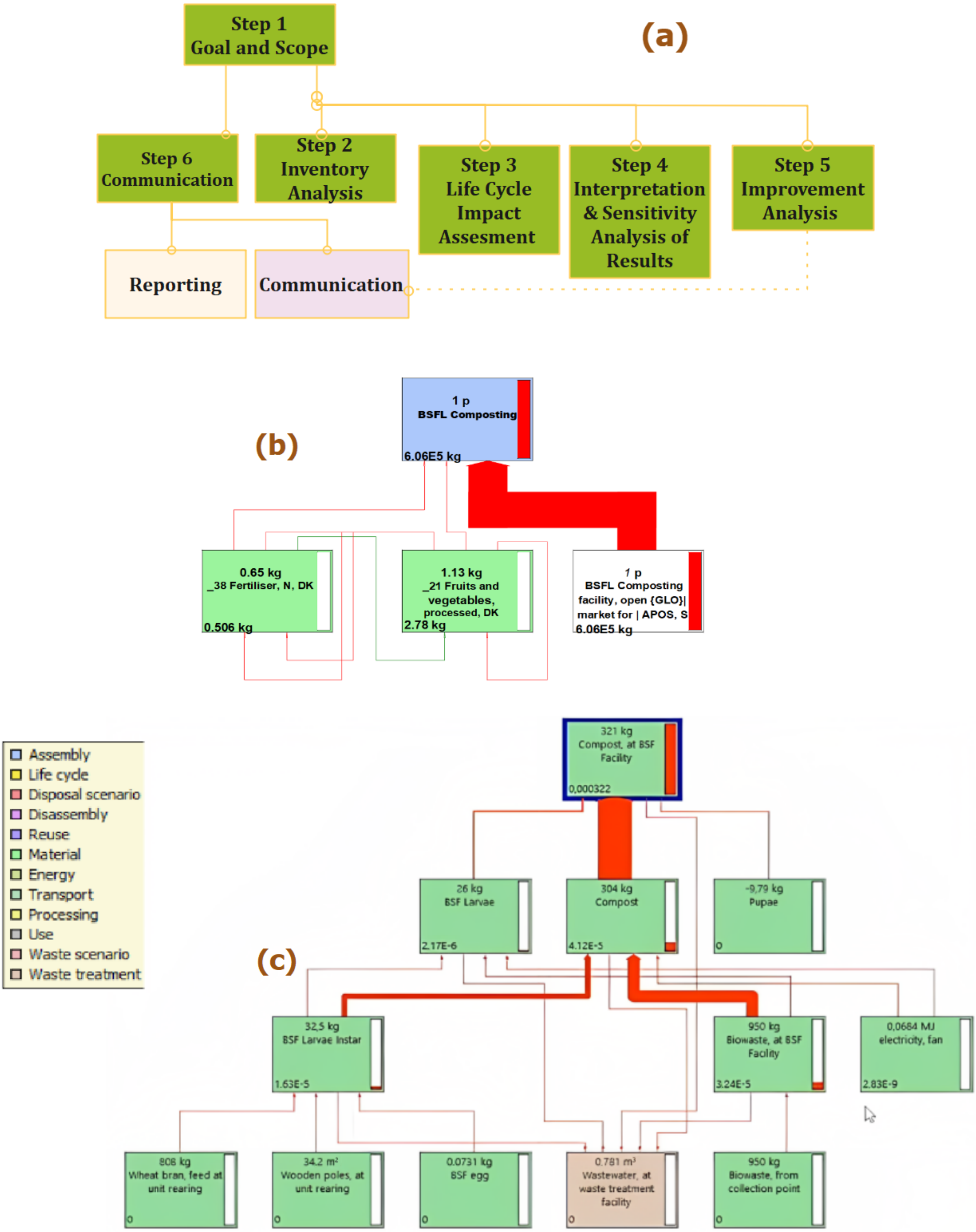

Figure 6. (**a**) Flow Chart of LCA Sima-Pro tool (**b**) Experimental conditions of LCA (**c**) LCA at extended scale-up conditions.

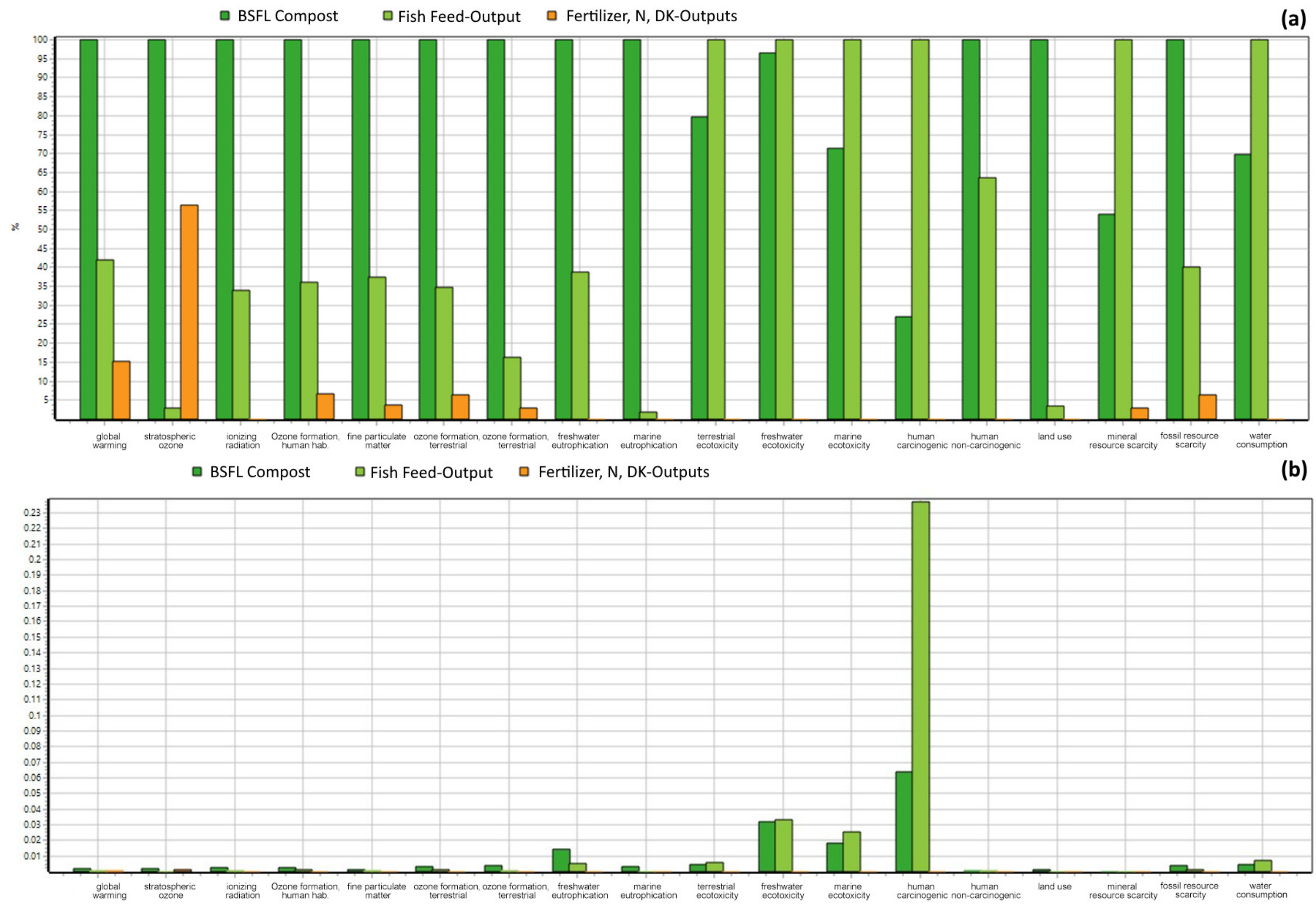

Figure 7. (**a**) Impact Assessment of End Products on experimental conditions at t = 0 (**b**) At normalization, excluding long-term emissions.

Furthermore, global warming potential is a crucial category for assessing the climate change impact. LCA indicated that the BSFL composting process generates 17.671 kg CO_2 equivalent, fish feed production generates 7.406 kg CO_2 equivalent, and fertilizer production generates 2.715 kg CO_2 equivalent. These values provide insights into the carbon emissions associated with each process. Nonetheless, fertilizer with a higher percentage of production and minimum CO_2 makes the process environmentally and financially sustainable.

LCA offers a comprehensive overview of the environmental impacts associated with the BSFL composting process, fish feed production, and fertilizer production. The results highlight variations in water consumption, fossil resource scarcity, land use, ecotoxicity, and global warming potential among the different processes and is shown in a bar-plot at three point of normalization, weighted results, and with factor = 0 in Figures 7a,b and 8a–c. In addition to the experimental findings at optimum conditions and further process sustainability, KPIs and the tedious index are enabled by LCA tools. These findings can inform decision-making processes and guide efforts toward more sustainable waste treatment and resource utilization practices. ML provides the best well-informed tool for both onsite and future predictive assessments based on major experimental and software results dataset.

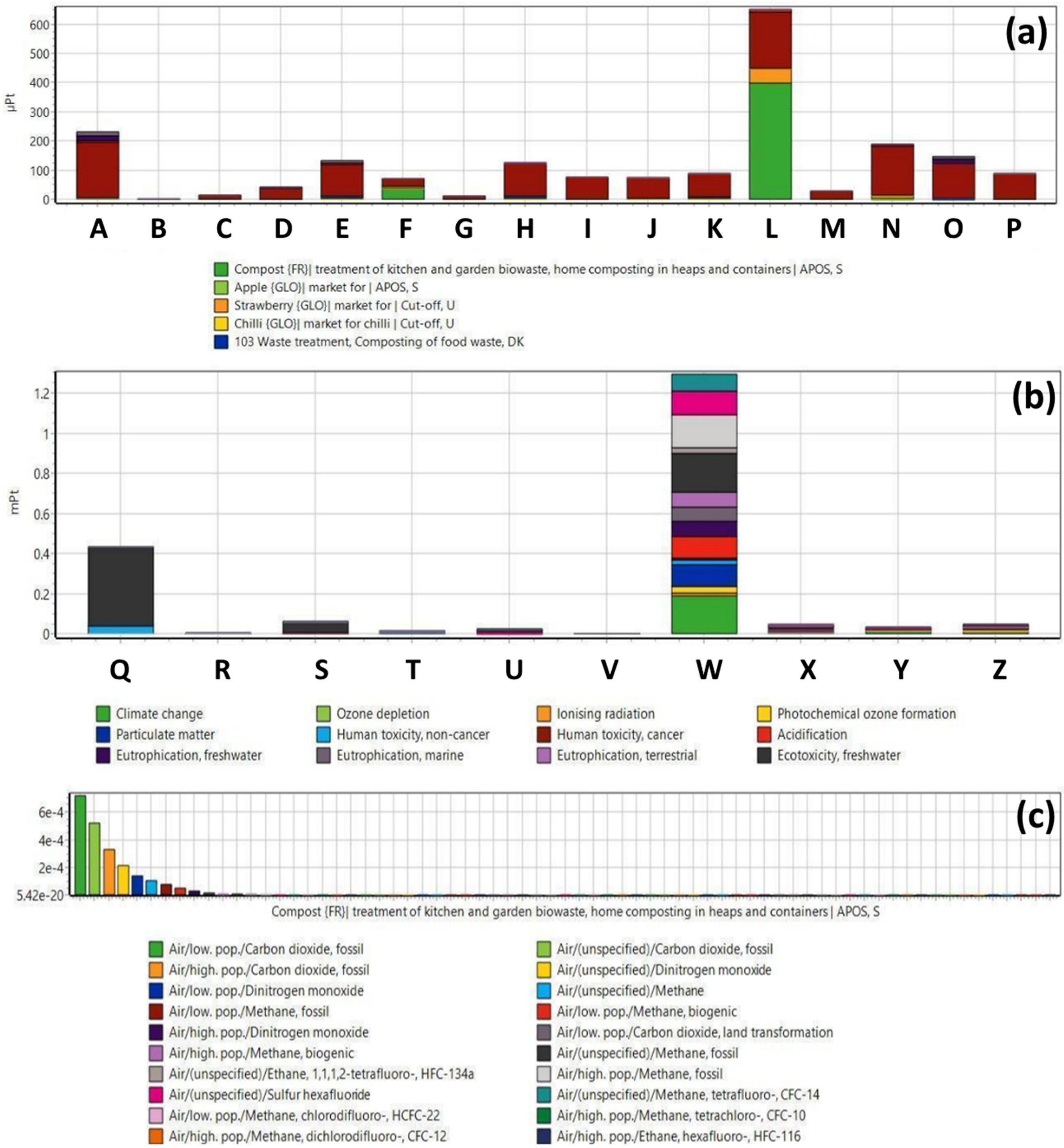

Figure 8. (**a**) Impact Assessment of End Products on scale-up conditions (**b**) Impact Assessment of End Products on scale-up conditions at Normalization, excluding long-term emissions (**c**) Global Emis-sions and Impact bar chart at Normalization. (**A**—Climate Change; **B**—Ozone Depletion; **C**—Ionising Radiation; **D**—Photochemical Oxidant Formation; **E**—Particulate Matter; **F**—Human Toxicity Non-carcinogenic; **G**—Human Toxicity Carcinogenic; **H** –Acidification Potential; **I**—Eutrophication; **J**—Eutrophication Freshwater; **K**—Eutrophication Marine; **L**—Eutrophication-Terrestrial; **M**—Ecotoxicity Freshwater; **N**—Land Use; **O**—Resource Use Minerals; **P**—Resource Depletion—Metals; **Q**—Compost {FR} | treatment of kitchen and garden biowaste, home composting

inn heaps and containers | APOS, S; **R**—Apple, market for {GLO}; **S**—Strawberry, market for {GLO}; **T**—Chilli, market for {GLO}; **U**—Waste treatment, 103 {GLO}; **V**—Waste Paper, Sorted, production mix {C}; **W**—Enzymes, market for {GLO}; **X**—Potato Starch, market for {GLO}; **Y**—Electricity, high voltage {GLO}; **Z**—Municipal Collection of Non-hazardous Waste {GLO}).

3.8. Machine Learning and Modeling for BSFL Composting

ML accounted for the same dataset as the At3 dataset for the shortlisting of the ANN algorithm, modeling, and ANN black box simulations. The Epoch was arbitrarily selected as 85, while the number of hidden layers was 20. The dataset was divided into 50% training, and 25% each for testing and validations. The ANN matrices shown in Appendix A include that Mean square error and R were selected. The error bin for LM and SCG was 20 bins. LM showed the minimum Mean Squared Error (MSE) for all the three distinctive datasets. The same trend was confirmed for R-metrics. LM had a value of R = 1 for training datasets. However, the testing and validation had a brief variation of up to 0.09. Figure 9a,b shows the training, testing and validation of input and sample datasets.

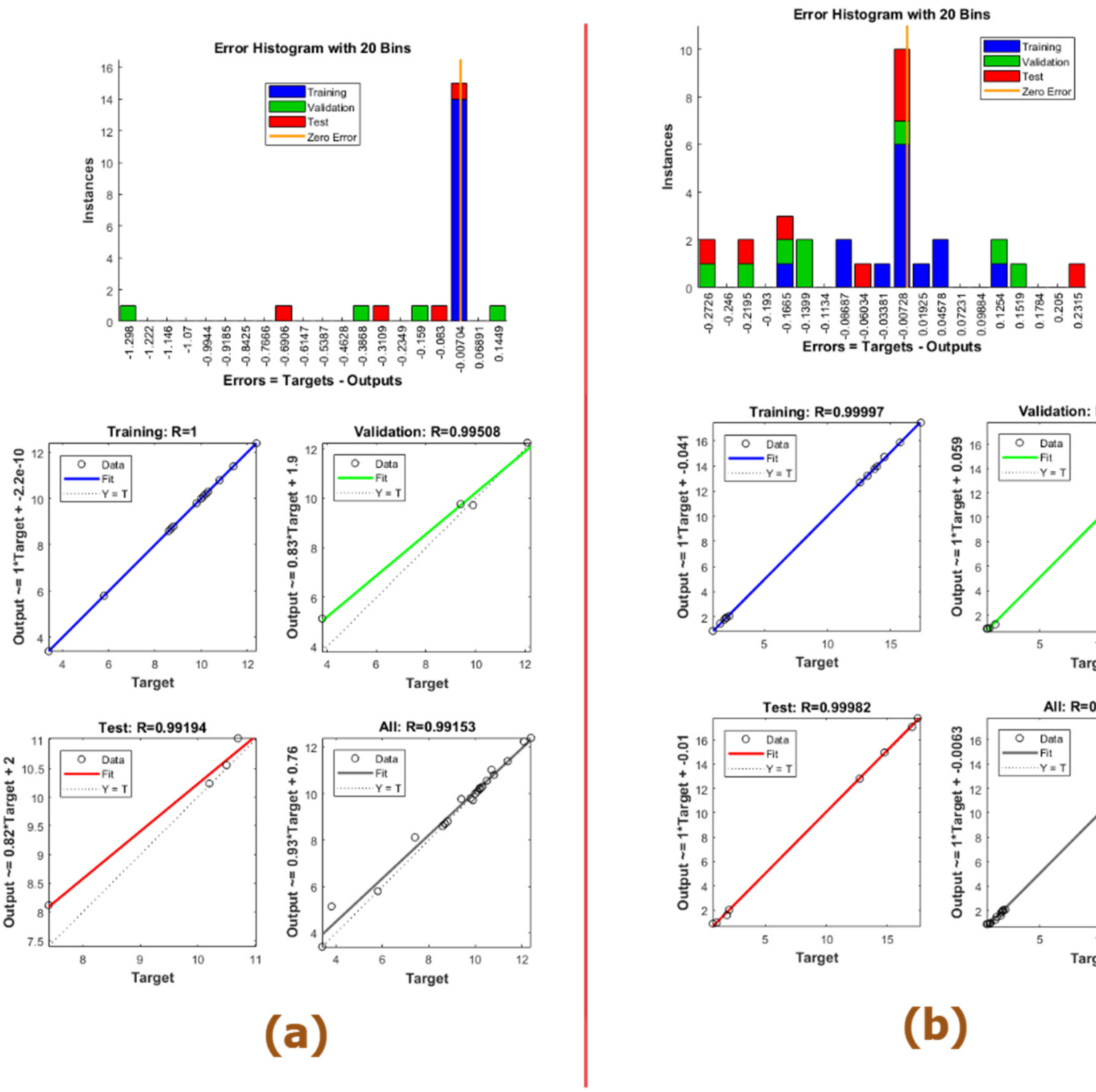

Figure 9. (**a**) ANN–Levenberg Algorithm (**b**) ANN Scaled Conjugate Algorithm for Training, Testing, and Validations of Input and Sample Datasets.

Table 3 shows results for the Levenberg–Marquardt algorithm; during the training segment, the MSE is extremely low at 1.23×10^{-19}, indicating a very small difference between the predicted and desired outputs. The correlation coefficient (R) is 1.000, suggesting a perfect linear relationship between the predicted and desired outputs. The predicted volume reduction is 64.87%, while the experimental volume reduction is slightly higher at 65%. The predicted CO_2 equivalent is 16.67, and the actual CO_2 equivalent is 99.8%, resulting in high accuracy of prediction.

Table 3. ANN Machine learning Modeling Input/Output and Predictions Results.

ANN Algorithm	ANN Segment	MSE	R	Predicted Volume Reduction	Experimental Volume Reduction	Predicted CO_2 Equivalent	Actual CO_2 Equivalent	Accuracy
Levenberg–Marquardt	Training Validation Testing	1.23×10^{-19} 4.23×10^{-1} 0.137	1.000 0.999 0.991	64.9%	65.0%	17.64	16.67	99.8%
Scaled Conjugate Gradient	Training Validation Testing	0.004 0.016 0.674	0.997 0.998 0.990	62.2%	65.0%	16.90	16.67	95.6%

In the validation segment, the MSE increases to 0.423, indicating a slightly higher difference between the predicted and desired outputs compared to the training segment. The correlation coefficient (R) remains high at 0.999. In the testing segment of the Levenberg–Marquardt algorithm, the MSE is 0.137, indicating a higher difference between the predicted and desired outputs compared to both the training and validation segments. The correlation coefficient (R) is 0.991, still indicating a strong linear relationship satisfying our assumption of comparison between LM and SCG algorithms for linearity.

For the Scaled Conjugate Gradient algorithm during the training segment, the MSE is 0.004087, indicating a relatively low difference between the predicted and desired outputs. The correlation coefficient (R) is 0.997, indicating a strong linear relationship. The predicted volume reduction is 62.2%, which is slightly lower than the experimental volume reduction of 65%. The predicted CO_2 equivalent is 16.90, while the actual CO_2 equivalent is 16.67, resulting in an accuracy of 95.6%.

In the validation segment, the MSE is 0.015932, indicating a higher difference between the predicted and desired outputs compared to the training segment. In the testing segment of the Scaled Conjugate Gradient algorithm, the MSE is 0.674, indicating a higher difference between the predicted and desired outputs compared to both the training and validation segments. The correlation coefficient (R) is 0.990, indicating a strong linear relationship, as keenly observed in Figure 9a,b. Overall LM shows greater affinity for handling robust experimental and LCA parameters for both onsite and scale-up studies predictions, owing to lower MSE and higher R values.

3.9. Comparative Analysis of Current BSFL, LCA, and Data-Driven Research Work with Conventional Systems

The waste treatment efficiency of BSFL was also compared with one of the conventional methods i.e., bin composting. All the inputs such as waste type, quantity, number of larvae, and surface area were kept the same as the optimized value for BSFL. Two samples were used, one with BSFL and the other without BSFL in a similar container. The BSFL reduces waste much faster than the conventional method. The percentage weight and volume reduction by both the BSFL and bin composting are shown in Figure 10.

From Figure 10 is it evident that by composting with BSFL for 15 days the total waste was reduced by almost 70%, while the percentage weight reduction of the bin system was around 20%. The volume was reduced by 20% in the case of a bin, and in the case of BSFL the volume was reduced by almost 90% in 15 days The normal time for bin composting is 4 to 8 weeks [46].

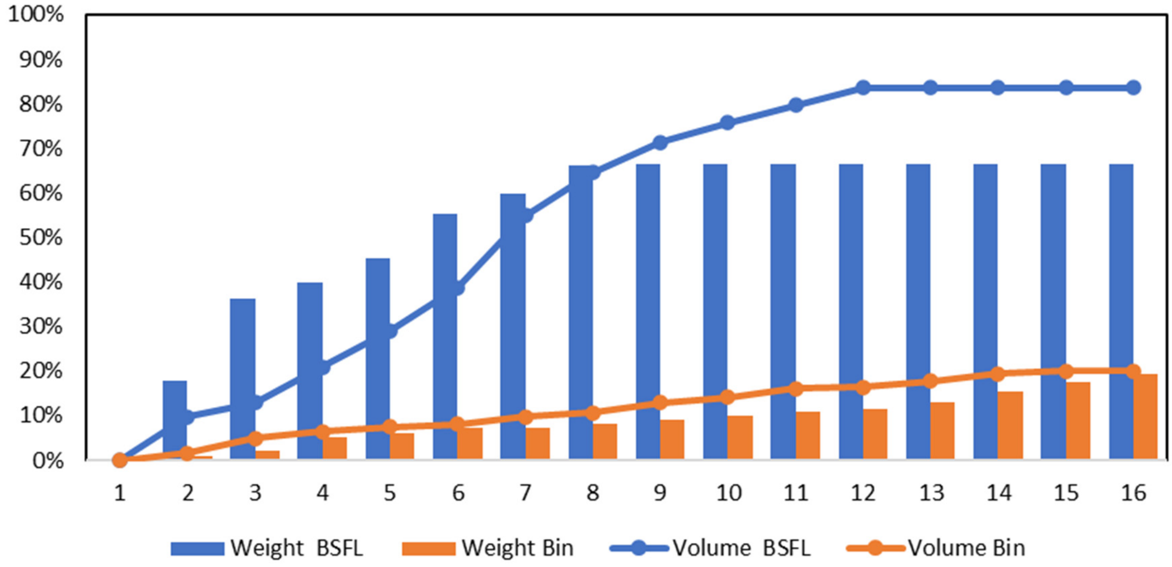

Figure 10. Percentage Weight and Volume Reduction with BSFL vs. Bin Composting (conventional method) for kitchen waste (Optimum conditions 16 days, aeration frequency four times a day, number of larvae was 600 with kitchen waste composition).

The characteristics of the compost produced are also an important basis to compare both methods. Table 4 displays the compost quality produced by BSFL in comparison to that produced by bin composting and the best compost values. Since BSFL and bin composting are evaluated in this work, a comparison was made between the literature of earlier research and the current study (BSFL) and bin composting.

Table 4. Quality of compost produced by Kitchen Waste using BSFL and bin system in comparison to conventional methods.

Parameters	Current Study (Bin Composting)	Current Study (BSFL)	Best Quality Value by Conventional Method [18]
pH	5.4	8.5	7.2–7.8
Moisture Content	63.4%	67%	60
C/N	14.5	12.1	>11.0
N (mg/L)	20.6	33.6	>18.7
P (mg/kg)	70	350	>200
TDS (mg/L)	960	1250	2000
Conductivity (dS/m)	2.04	2.5	2–6
Na (mg/kg)	800	1700	>1500
K (mg/kg)	500	1100	2000

The pH and C/N ratio of the compost articulates that the compost produced by the bin composting was not matured enough yet to be applied, as the pH was in the acidic phase. Moreover, the nutrient quantity in the compost produced by BSFL was better than the bin composting. The Levenberg–Marquardt algorithm generally shows better performance with lower MSE, and higher correlation coefficients compared to the Scaled Conjugate Gradient algorithm and predicts an accurate result for the experimental and calculated LCA parameters such as CO_2 equivalents.

4. Conclusions

Based on the current research outcomes, it has been demonstrated that Black Soldier Fly Larvae (BSFL) are highly effective and suitable for composting kitchen waste. The optimal time required for waste reduction using BSFL was found to be 15 days. By increasing the frequency of aeration and the number of larvae, the waste consumption process by BSFL can be accelerated. Additionally, increasing the surface area of the container leads to enhanced waste reduction. It was observed that layering the waste can effectively increase the surface area without occupying much space. Compared to conventional bin composting systems, waste reduction by BSFL occurs at a significantly faster rate. The compost produced through BSFL treatment of waste exhibits superior qualities, such as high nutrient value and other characteristics aligned with standard compost quality. The life cycle assessment (LCA) study demonstrated sustainable metrics for BSFL composting. When comparing different Artificial Neural Network (ANN) algorithms, it was evident that the Levenberg–Marquardt algorithm provided better predictive results, exhibiting the least Mean Squared Error (MSE) for intricate experimental and software tool parameters. The accuracy of predicting CO_2 equivalent reached up to 99.5%. This study contributes to optimizing and scaling up composting technologies for the treatment of organic waste, particularly kitchen waste, using BSFL. The outcome is the production of higher-quality compost and a clear understanding of the differences in treatment efficiency compared to conventional bin composting methods.

Author Contributions: Conceptualization, M.Y.A. and S.S.; methodology, M.Y.A., S.S. and L.N.; validation, M.Y.A., S.S. and A.R.; formal analysis, M.Y.A., S.S. and L.N.; investigation, M.Y.A., S.S. and A.U.; resources, M.Y.A., S.S., L.N., A.U. and M.J.; data curation, M.Y.A., S.S., A.R. and A.S.A.; writing—original draft preparation, M.Y.A. and S.S.; writing—review and editing, M.Y.A., S.S., A.U. and M.J.; visualization M.Y.A., S.S. and L.N.; supervision, M.Y.A., S.S., A.U. and M.J.; project administration, M.Y.A., S.S. and L.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Available on request.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

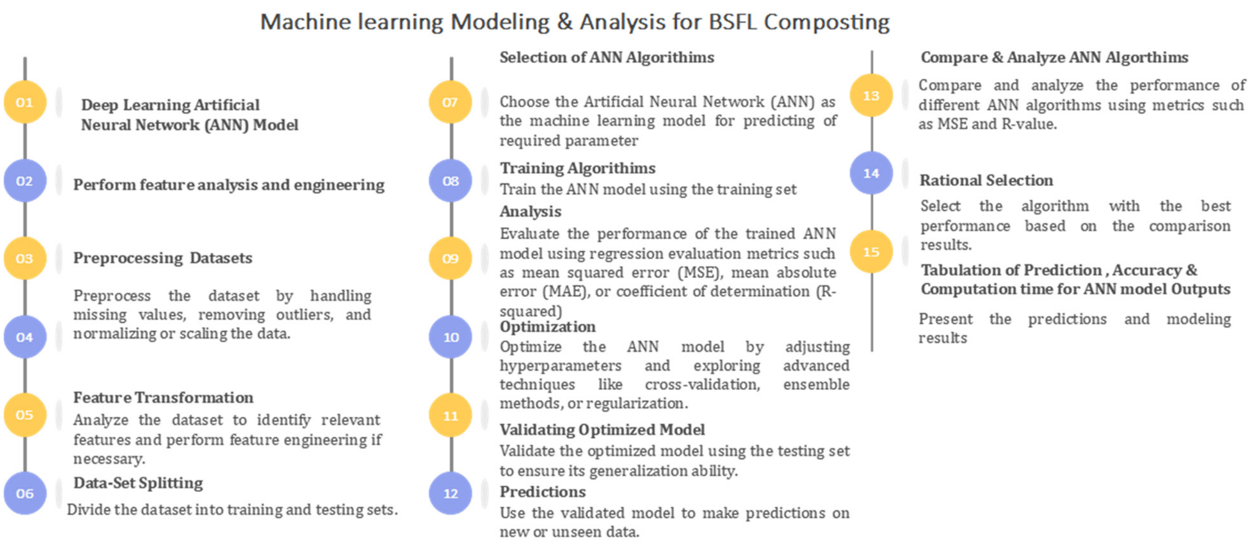

Figure A1. Machine learning timeline and working for the BSFL composting.

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