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# Multi-Criteria Decision Analysis Approach to the Assessment of the Utilization Pathway of Hermentia Illucens Oil as an Environmentally Friendly Raw Material

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**ABSTRACT**

Inadequate disposal of organic waste results in adverse environmental impacts and financial losses. The aim was to determine the most profitable option, considering environmental, economic, technological, and regulatory issues. This approach involves appointing a team of organic waste management experts as decision-makers in the organic waste recycling sector. This method facilitates resource recovery while addressing the problem of organic waste disposal. This study used multicriteria decision analysis techniques to evaluate four potential recycling pathways for organic waste as feedstock in manufacturing biodiesel, bio-lubricants, animal feed, and bioproducts. The priority scale uses the paired comparison technique as a weighting approach to assess the selected criteria. Findings indicate that decision-makers prioritize environmental sustainability as the most essential assessment factor, followed by economic criteria. Conversely, process management elements are considered less critical. Among the options evaluated, using organic waste as a raw material for bioproduct synthesis was identified as the most effective organic waste recycling method. This option had the lowest coefficient of variation and was the most profitable. Bio-lubricant production was recognized as the second most preferred approach. The applied MCDA method demonstrated reliability and efficacy, identifying the preferred organic waste recycling alternative among the evaluated options. This was achieved through the application of decision-makers' skills and knowledge.

## 1. INTRODUCTION

Several methods have been evaluated globally in the past decade to address environmental challenges, including adopting a circular economy model across sectors to reduce carbon emissions by fifty percent by 2030 and attain carbon neutrality by 2050 [1]. Disposing of the organic portion of municipal solid waste (OFMSW) is a considerable difficulty, amounting to 900 million tons annually worldwide, and is projected to climb by 70% by 2050 owing to increased food waste [2]. Solid waste management (SWM) is a multifaceted issue that impacts several aspects of development across the three pillars of sustainability: environmental, economic, and social [3]. The fundamental principles of the Sustainable Development Goals (SDGs) can be broadly aligned with the objectives that have historically influenced the evolution of solid waste management (SWM) practices, specifically public health (SDG 3), environmental concerns (SDGs 6 and 13), and resource valuation (SDG 11), alongside the more recent emphasis on climate change (SDG 13). For instance, SDG 12.3 (to reduce per capita global food waste at retail and consumer levels) and SDG 14 (addressing the indiscriminate use and disposal of plastic waste that leads to marine litter and microplastic issues) cannot be achieved without fulfilling the objectives of sustainable solid waste management. Accumulated garbage and improperly discarded refuse pose considerable health and environmental risks (SDG 6 & 13). Mitigating these effects significantly exceeds the real expenditure of establishing and maintaining basic, sufficient waste management systems [4]. The SWM is directly associated with 12 of the 17 UN-SDGs, serving as the primary utility system for over 2 billion people [3, 5].

Global trash is projected to increase to 3.4 billion tonnes by 2050, up from 2.01 billion tons. Without advancements in the solid waste industry, emissions will rise to 2.38 billion tons of $CO_2$-equivalent by 2050 [4]. A paradigm shift is essential from the depletive 'produce-consume-dispose' model of the linear economy to the 'reduce-reuse-recovery-recycle-redesign-remake' model of the circular economy, which is more regenerative and restorative, potentially benefiting SDGs 1, 3, 6-9, 11, and 13-15 [6]. The circular economy signifies a structural transformation that fosters long-term stability and optimizes the utilization and circulation of commodities, resources, and nutrients (SDG 12) while delivering economic, environmental, and societal advantages (SDG 1, 2, 9, 13−15) that assist both public and private sectors in achieving short- and long-term SDG objectives (Ellen MacArthur Foundation, 2020). Waste management based on a circular economy may be a fundamental element in advancing the three pillars of sustainable development: economic growth, social inclusion, and environmental conservation [7].

The Ellen MacArthur Foundation delineates three principles of Circular Economy (CE): (1) safeguard and augment natural capital by managing finite resources and equilibrating renewable resource flows; (2) maximize resource yields by perpetually circulating products, components, and materials at optimal utility within both technical and biological cycles; (3) enhance system efficacy by identifying and eliminating negative externalities [8]. Circular Economy (CE) is an overarching concept aimed at reducing material inputs and minimizing waste production [9]. Despite being a term that has been discussed since 1960, significant disparities remain regarding its conceptualization [10], characteristics [11], definition of objectives [12], implementation, and performance evaluation indicators [13]. Furthermore, its genuine contribution to sustainable development is perpetually scrutinized as its goals have predominantly focused on economic prosperity and environmental quality [10], neglecting the social equity aspect that must address the needs of both present and future generations [14].

One of the efforts to implement the CE concept in general organic waste management can be done through bioconversion. Bioprocesses provide a viable and eco-friendly alternative to the conventional chemical methods now used to manufacture platform chemicals, fuels, and many commercial items [15]. Extensive research is underway to enhance bioconversion processes and biorefineries, which now cohabit to a degree alongside traditional refineries. Various choices and technologies are now being researched and are available to produce diverse beneficial end-products using bioprocesses. Numerous processes prioritize renewable resources, biomass, or contaminants as principal feedstocks. The latter circumvents food-fuel rivalry, in contrast to some feedstocks evaluated before and, at times, continue in contemporary discussions. Appropriate feedstocks include biomass [16, 17], solid waste [18-20], sludge [21], wastewater [22], waste gases [23], and byproducts such as glycerol from other biorefineries [24].

Commercially valuable goods derived from the sustainable conversion of biomass in a biorefinery are known as bio-products or bio-based products [25]. Along with the efficient use of resources and the sustainability of the environment, the significance of producing bioproducts is centered on making sure that there are good effects on the economic sector. Moreover, insect-mediated bioconversion is one of the newly suggested alternate ways for recycling organic waste. The black soldier flies (BSF), Hermetia illucens, are regarded as the most promising insect for valorizing waste and byproducts from the agri-food value chain [26]. Recent research efforts to integrate CE principles through BSF larvae cultivation to improve organic waste management and with ecological benefits [27-29].

The Black Soldier Fly (BSF), a detritivorous insect, has garnered considerable attention due to its capacity to thrive on a variety of organic wastes, including livestock manure [30, 31], human feces [32], the organic fraction of municipal solid waste [33, 34], food waste [35], agricultural residues [36], compost leachate [37], landfill leachate [38], insect farm waste [39], fish offal [40], This process results in the production of protein- and fat-rich larval, prepupal, or pupal biomass, henceforth referred to as BSF biomass, for applications in animal feed and biofuel. Furthermore, the BSF is neither recognized as a vector for infections nor a nuisance to companion animals or people [40].

Products generated from black soldier fly larvae (BSFL), and black soldier fly (BSF) protein powder have garnered interest in recent years owing to their potential as a sustainable and nutrient-dense food source, characterized by high protein and fat content and a favorable amino acid profile [41]. Acquiring four from insects is one method to incorporate edible insects into their diet or to create new dishes. These four items may be used for food fortification due to their high protein and mineral content (Ca, P, Cu, Fe, Mg, Mn, K, etc.) and their antioxidant properties. This protein has a high digestibility and a superior amino acid profile [42]. The protein component of BSF resembles a soybean meal and is mostly composed of amino acids. Furthermore, BSFL demonstrates crude protein levels comparable to or marginally above those of some plant-based proteins, such as linseed, sunflower, cottonseed, lupins, or fava beans [43]. The amino acid profile of BSF is similar to that of superior animal and plant proteins, such as egg white and soybean, while exhibiting higher concentrations of tyrosine, phenylalanine, and histidine relative to these protein sources [44].

The BSFL contains significant quantities of lauric, oleic, myristic, palmitic, and palmitoleic acids [44]. Lauric acid, a principal component of coconut oil, constitutes the bulk of the oil content in BSF [41]. The proportion of unsaturated fatty acids in BSFL is modest (19–37%). In comparison to fish oil, black soldier flies larvae (BSFL) exhibit reduced levels of eicosapentaenoic acid (EPA, 20:5n–3) and docosahexaenoic acid (DHA, 22:6n–3) while displaying elevated levels of polyunsaturated fatty acids (PUFA) [45].

The utilization of Hermentia Illucens as a bioproduct in industrial applications significantly benefits the environment and economy. Furthermore, it helps reconcile social disputes regarding land use for landfills. Thus, this manuscript evaluates several different utilization routes of BSF oil for use as a feedstock in the production of biodiesel (Alt1), bio-lubricant (Alt2), animal feed (Alt3), and bioproducts (Alt4). The main objective of this study is to determine the most appropriate option to assess the utilization of BSF oil, considering technological, economic, and environmental factors. This article was achieved by applying multi-criteria decision analysis (MCDA) methodology and involving a team of experts as decision-makers.

## 2. METHOD

Various strategies and processes for delineating the decision-making process are present in the literature. This domain encompasses several scientific fields, including operational research, computer science, cognitive science, decision theory, psychology, management, economics, sociology, political science, and statistics [46]. The issue of decision-making may be articulated using mathematical language and models that represent actual realities. The methodologies used in this domain originate from econometrics and its related scientific fields, including statistics (the analysis and processing of data representing reality) and operational research (the optimization of choices) [47]. In operational research, decision-makers are the focal point. They use the established evaluation criteria to evaluate decision-making scenarios according to their preferences. They encounter a decision-making dilemma that often necessitates the consideration of opposing objectives. This scenario is characterized as a multi-criteria decision dilemma. Multi-criteria decision-making support techniques endorse this methodology. Using statistical methods for a multi-dimensional representation of reality, known as multi-dimensional comparative analysis, enables objective and automated analysis to address the issue. The involvement of a decision-maker is negligible in such a context. This methodology relies on aggregate metrics and may be used, for instance, to categorize and rank decision alternatives [48]. Depending on the methodology utilized, various ideas and approaches for addressing choice issues are used. The concept of multi-dimensional comparative analysis derives from techniques and taxonomic approaches used for the ranking and categorizing of intricate and diverse multi-dimensional entities. They enable the implementation of investigations on intricate economic issues. They are mostly intended to rank and use patterns for their creation. This collection of methodologies includes TOPSIS [49, 50], VIKOR [51, 52], HELWIG [53], VMCM [48], and PVM [48].

The advantages of the VIKOR method include ranking based on appropriate compromises for conflicting criteria, managing qualitative and quantitative standards, not requiring an explicit preference structure, theoretical foundations and basic calculations, producing a complete ranking of choices, and being widely applied in all fields. Meanwhile, the disadvantages of the VIKOR method include sensitivity to criteria weights, instability between alternatives and ranking reversals, limitations in handling inherent uncertainty, and complexity of interpretation with many criteria [54].

The VIKOR approach (Serbian: VIsekrzterijumska Optimizacijai Kompromisno Resenje) facilitates the identification of decision alternatives and selecting a compromised solution, accommodating competing assessment criteria. Solutions (variants) are assessed based on their proximity to the ideal and anti-ideal points. For individual decision-making alternatives, the weighted average distance from the ideal answer, the maximum weighted distance from this point, and the comprehensive indicator are calculated. The variations are prioritized using the values derived in this manner, resulting in three distinct rankings. The compromise solution suggestion represents a choice option characterized by the minimal value of the comprehensive indicator, contingent upon the simultaneous fulfillment of acceptable advantage and acceptable stability constraints. If any or both of these requirements are unmet, the solution comprises an appropriate collection of variations [48, 51].

The performance values $R_{ij}$ of the options related to specific criteria were analyzed to determine the minimum $(R_{ij})$min and maximum $(R_{ij})$max values in the decision matrix.

a. Pairwise comparisons of each criterion

$$w_i = \frac{1}{n}\sum_{j} a_{ij} \tag{1}$$

b. The maximum and minimum values were used in normalizing and linearizing the score set for each Maggot BSF development factor according to the equation:

$$R_{ij} = \left(\frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}\right) \tag{2}$$

where $R_{ij}$ and $X_{ij}$ ($i$ = 1,2,3,…m and $j$ = 1,2,3,…n) are the elements of the decision-making matrix (alternative i to criterion j), and $X_j^+$ is the best factor of criterion j. $X_j$ is the element values of each criterion.

c. Determine the values of S and R using the following equation:

$$S_i = \sum_{j=1}^{n} w_j \left(\frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}\right) \tag{3}$$

And,

$$R_i = Max\, j\left[W_j = \left(\frac{x_j^+ - x_{ij}}{x_j^+ - x_j^-}\right)\right] \tag{4}$$

where $W_j$ is the weight of each criterion, j.

d. Determine the index value with the equation

$$Qi = \left[\frac{S_i - S^+}{S^+ - S^-}\right]v + \left[\frac{R_i - R^+}{R^+ - R^-}\right](1-v) \tag{5}$$

where,

$S$ = min $S_w$
$S^+$ = max $S_i$
$R^-$ = min $R_i$
$R^+$ = max $R_i$
$v$ = 0.5

The ranking result is the result of sorting S, R, and Q. The best alternative solution based on the minimum Q value becomes the best ranking with the following conditions:

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \tag{6}$$

where,

$A^{(2)}$ = alternative with second order in Q ranking
and
$A^{(1)}$ = alternative with the best order in Q ranking
DQ = 1- ($m$-1) where $m$ is the number of alternatives.
Alternative $A^{(1)}$ must be ranked best on S and/or R.

**Table 1.** Criteria and alternatives for utilization pathway of Hermentia Illucens oil as an environmentally friendly raw material or make choices

| Criteria | Code | Alternative | Code |
|---|---|---|---|
| The production process is simple and easy | CRT_1 | Animal Feed | ALT_1 |
| Process management | CRT_2 | Biolubricants | ALT_2 |
| Product quality complies with standards | CRT_3 | Biodiesel | ALT_3 |
| Environmentally aware | CRT_4 | Bioproducts | ALT_4 |
| High investment costs | CRT_5 | | |
| Lack of policies supporting renewable materials | CRT_6 | | |
| Changes in strategy and policy | CRT_7 | | |
| High potential for conflict of interest | CRT_8 | | |
| Low coordination between stakeholders | CRT_9 | | |
| Lack of financial support | CRT_10 | | |
| Supporting Circular Economy | CRT_11 | | |

## 3. RESULT

Decision criteria refer to the guiding principles, objectives, standards, benchmarks, and conditions used by a team or organization to refine alternatives or make choices. These features empower the team to select a course of action from among several alternatives. These features enhance the quality, uniformity, and fairness of collective judgment. Criteria are used to evaluate alternatives. Criteria are based on the type and quality of alternatives, which may vary across projects. Criteria should be determined by stakeholders and policymakers, taking into account each stakeholder's preferences and the components of the situation. Table 1 summarizes the criteria and alternatives derived from the experts' responses to the questionnaire. The initial stage of the criteria assessment is a pairwise comparison using Eq. (1) on each of the predetermined criteria. The results of the pairwise comparisons are presented in Table 2. Next, the normalization determination is carried out from the results of the pairwise comparison, and the results are shown in Table 3.

**Table 2.** Pairwise comparisons on each criterion

| Criteria | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| CRT_1 | 1.000 | 2.646 | 0.416 | 0.416 | 0.416 | 0.379 | 0.416 | 0.416 | 0.416 | 2.159 | 1.823 |
| CRT_2 | 0.378 | 1.000 | 0.402 | 0.402 | 0.520 | 0.379 | 0.402 | 0.546 | 0.546 | 0.546 | 0.546 |
| CRT_3 | 2.401 | 2.489 | 1.000 | 2.159 | 2.159 | 2.159 | 0.454 | 2.159 | 0.454 | 2.088 | 0.494 |
| CRT_4 | 2.401 | 2.489 | 0.463 | 1.000 | 0.402 | 0.454 | 0.454 | 0.477 | 2.019 | 0.402 | 0.379 |
| CRT_5 | 2.401 | 1.924 | 0.463 | 2.489 | 1.000 | 1.540 | 2.019 | 1.918 | 2.197 | 2.197 | 0.379 |
| CRT_6 | 2.642 | 2.642 | 0.463 | 2.204 | 0.649 | 1.000 | 2.273 | 2.197 | 2.474 | 2.392 | 2.474 |
| CRT_7 | 2.401 | 2.489 | 2.204 | 2.204 | 0.495 | 0.440 | 1.000 | 0.494 | 0.494 | 0.494 | 0.494 |
| CRT_8 | 2.401 | 1.830 | 0.463 | 2.096 | 0.521 | 0.455 | 2.023 | 1.000 | 2.474 | 2.392 | 0.416 |
| CRT_9 | 2.401 | 1.830 | 2.204 | 0.495 | 0.455 | 0.404 | 2.023 | 0.404 | 1.000 | 0.494 | 0.416 |
| CRT_10 | 0.463 | 1.830 | 0.479 | 2.489 | 0.455 | 0.418 | 2.023 | 0.418 | 2.023 | 1.000 | 0.416 |
| CRT_11 | 0.549 | 1.830 | 2.023 | 2.642 | 2.642 | 0.404 | 2.023 | 2.401 | 2.401 | 2.401 | 1.000 |
| Total | 19.440 | 22.998 | 10.581 | 18.597 | 9.715 | 8.032 | 15.109 | 12.433 | 16.499 | 16.567 | 8.838 |

**Table 3.** Normalizing and linearizing the score set

| Criteria | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CRT_1 | 0.051 | 0.115 | 0.039 | 0.022 | 0.043 | 0.047 | 0.028 | 0.033 | 0.025 | 0.130 | 0.206 | 0.741 | 0.068 |
| CRT_2 | 0.019 | 0.043 | 0.038 | 0.022 | 0.053 | 0.047 | 0.027 | 0.044 | 0.033 | 0.033 | 0.062 | 0.422 | 0.038 |
| CRT_3 | 0.124 | 0.108 | 0.095 | 0.116 | 0.222 | 0.269 | 0.030 | 0.174 | 0.027 | 0.126 | 0.056 | 1.347 | 0.123 |
| CRT_4 | 0.124 | 0.108 | 0.044 | 0.054 | 0.041 | 0.056 | 0.030 | 0.038 | 0.122 | 0.024 | 0.043 | 0.685 | 0.063 |
| CRT_5 | 0.124 | 0.044 | 0.134 | 0.103 | 0.192 | 0.134 | 0.154 | 0.133 | 0.133 | 0.043 | 0.043 | 1.235 | 0.113 |
| CRT_6 | 0.136 | 0.115 | 0.044 | 0.119 | 0.067 | 0.125 | 0.150 | 0.177 | 0.150 | 0.144 | 0.280 | 1.506 | 0.137 |
| CRT_7 | 0.124 | 0.108 | 0.208 | 0.119 | 0.051 | 0.055 | 0.066 | 0.040 | 0.030 | 0.030 | 0.056 | 0.886 | 0.081 |
| CRT_8 | 0.124 | 0.080 | 0.044 | 0.113 | 0.054 | 0.057 | 0.134 | 0.080 | 0.150 | 0.144 | 0.047 | 1.026 | 0.094 |
| CRT_9 | 0.124 | 0.080 | 0.208 | 0.027 | 0.047 | 0.050 | 0.134 | 0.033 | 0.061 | 0.030 | 0.047 | 0.839 | 0.077 |
| CRT_10 | 0.024 | 0.080 | 0.045 | 0.134 | 0.047 | 0.052 | 0.134 | 0.034 | 0.123 | 0.060 | 0.047 | 0.779 | 0.071 |
| CRT_11 | 0.028 | 0.080 | 0.191 | 0.142 | 0.272 | 0.050 | 0.134 | 0.193 | 0.146 | 0.145 | 0.113 | 1.494 | 0.136 |
| | | | | | | | | | | | | 10.959 | |

**Table 4.** Alternative weights for each criterion

| Alternative | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Animal Feed | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Biolubricants | 75 | 70 | 80 | 75 | 70 | 80 | 80 | 80 | 70 | 60 | 70 |
| Biodiesel | 75 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 70 | 70 | 80 |
| Bioproducts | 75 | 80 | 80 | 80 | 80 | 80 | 80 | 80 | 70 | 80 | 80 |

**Table 5.** Alternative normalization calculations for each criterion

| Alternative | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Animal Feed | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Biolubricants | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Biodiesel | 1 | 0.5 | 1 | 0.666667 | 0,5 | 1 | 1 | 1 | 1 | 0.666667 | 0.5 |
| Bioproducts | 1 | 0.5 | 1 | 0.666667 | 0,5 | 1 | 1 | 1 | 1 | 0.333333 | 0.5 |

**Table 6.** Calculation result of normalized weights

| Alternative | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Animal Feed | 0 | 0 | 0.123 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Biolubricants | 0.067 | 0.038 | 0.123 | 0.062 | 0.113 | 0.137 | 0.081 | 0.094 | 0.077 | 0.071 | 0.136 |
| Biodiesel | 0.038 | 0.061 | 0.062 | 0.075 | 0.069 | 0.081 | 0.094 | 0.077 | 0.071 | 0.091 | 0.5 |
| Bioproducts | 0.123 | 0.031 | 0 | 0.092 | 0.040 | 0.094 | 0.077 | 0 | 0.136 | 0.333 | 0 |

The questionnaire results showed that 11 criteria influenced the choices related to the utilization of Hermentia Illucens oil as a raw material. The responses to the questionnaire also showed the significance attributed to each criterion. Alternatives are potential ways, options, and strategies that must be identified to achieve the objectives. Alternatives are usually selected collectively by the government, and stakeholders generally provide information on the development of Hermentia Illucens oil (BSF).

Table 4 contains criteria data where alternative assessments will be calculated based on the assessment criteria that have been given weights for each criterion, and these weights are given by expert respondents. Moreover, expert respondents provided alternative assessments for each criterion using the following thresholds: excellent (90−100); good (75–89); sufficient (60–74); and poor (0–59). The results of the expert assessments are shown in Table 4.

Based on Table 4, the next step is to carry out the normalization and weight normalization assessments shown in Tables 5 and 6.

The next step is to calculate the Utility Measures (S) and Regret Measure (R), which are shown in Table 7.

**Table 7.** Calculation of S and R values

| Alternative | Score S | Score R |
|---|---|---|
| Animal Feed | 0.122881 | 0.123 |
| Biolubricants | 1 | 0.137396 |
| Biodiesel | 1.219225 | 0.5 |
| Bioproducts | 0.925976 | 0.333333 |

Based on the results obtained by the VIKOR method in Table 7, it is known that the main choice of experts related to the use of maggot oil is animal feed, which is around 0.123, and biodiesel is around 0.5. Furthermore, the next choices are bioproducts and biolubricants with values of 0.333 and 0.137, respectively.

## 4. DISCUSSION

The discussion revealed that the main priority in the strategy for utilizing BSF Maggots is as animal feed. The use of BSF Maggots as animal feed is based on their abundant protein and fat content. According to food futurists, a civilization that prioritizes sustainability will gradually accept insects as a substitute protein source [52]. The demand for feed resources is expected to increase due to the predicted increase in consumption of animal products by 60–70% by 2050. However, conventional feed ingredients such as fish meal and soybean meal are expensive and may eventually become scarce. In this regard, insect farming has emerged as a sustainable substitute, providing an effective way to meet the growing demand for animal feed while reducing dependence on traditional resources [55].

Furthermore, a study conducted by Suryati et al. [56] demonstrated several advantages of BSF maggot oil, such as ease of cultivation, non-competition for land use for food crops, higher oil productivity, and circular economic applications for organic waste. On the other hand, maggot oil also faces disadvantages such as the technology being unfamiliar to the public, oil quality being affected by the type of organic waste, and difficulties in cultivating BSF maggots in some areas [57]. The protein in BSFL is rich in essential amino acids, which are important for the growth and development of ruminants, and is easily digested, with protein digestibility ranging from 72.78 to 78.67 percent [58]. In addition, the apparent metabolizable energy (AME) value of BSF larvae is high [54]. The most common essential amino acids in prepupal biomass are arginine, valine, and lysine. The amount of amino acids remains constant despite changes in the substrate. The nutritional reliability of BSF prepupae (6) is demonstrated by the persistent presence of threonine, isoleucine, methionine, and tryptophan, despite methionine, cysteine, and tryptophan deficiencies [59].

Conventional procedures, including water-based extraction, salt, detergent, and alkaline solvents, as well as non-conventional procedures such as microwave, ultrasound, enzyme, and pulsed electric field-assisted extraction, can be used to recover proteins from BSF larvae [60]. Furthermore, by using carbohydrates as the primary source of acetyl-CoA, BSF are able to synthesize some fatty acids through de novo biosynthesis. However, BSF cannot produce polyunsaturated fatty acids; instead, they absorb them from the diet and convert them to saturated versions [61]. Up to 76% of the total fatty acids in larvae are saturated fatty acids (SFAs), followed by polyunsaturated fatty acids (PUFAs) up to 23% and monounsaturated fatty acids (MUFAs) up to 32%. Lauric acid (C12:0) is the most common SFA, accounting for up to 52% of the total fatty acid content regardless of diet composition. Palmitic acid (C16:0) and oleic acid (C18:1 n-9) provide 12–22% and 10%–25%, respectively [62].

The availability of sustainable feed that enables livestock farmers to meet the growing demand for highly nutritious animal products is a challenge in animal nutrition. Fishmeal is the primary protein source in livestock feeds, which also contains soybeans, fish oil, and some grains. The fact that land for soybean cultivation is dwindling worldwide and marine overexploitation continues to reduce the abundance of small pelagic forage fish, which are the source of fishmeal and fish oil, poses a significant barrier to the sustainable production of increasingly sought-after fish and meat products [63]. The prices of fishmeal and soybean meal have risen due to increased demand and a lack of resources to produce them, while feed costs, which account for 60–70% of livestock production costs, are already prohibitive and unaffordable for resource-poor livestock farmers [64]. The livelihoods of livestock farmers in Indonesia, particularly small-scale farmers, are also affected by this situation. Therefore, continuing to use fishmeal and soybean meal as protein sources in feed production is not a sustainable alternative [6]. There is considerable interest in potential replacements for these expensive ingredients as Indonesian industries seek alternative protein sources for their growing aquaculture, swine, and poultry subsectors. Therefore, practical and sustainable substitutes are needed.

The availability and willingness to pay of target consumers for proposed new insect products are crucial factors to consider in research, policy, and commercial production. Creating products that target those most likely to accept and benefit from them will be aided by a thorough understanding of the factors influencing consumer demand [65]. Therefore, livestock farmers' knowledge and willingness to pay will be crucial to the acceptance and use of insect-based feeds for livestock production and the consumption of the resulting livestock products [66]. Although little is known about these attitudes, they are crucial for commercial livestock production in Indonesia.

In integrated fish-livestock farming systems, smallholder farmers can increase the supply of local insects for animal feed by cultivating insects. Crop residues and other agricultural waste can be used as inputs for BSF development, and the resulting fly larvae can then be added to animal feed. As a result, the farm's nutrient cycle is closed using a circular strategy. Insect farming can help resource-constrained farmers control waste and increase yields on limited land [67].

With limited resources, smallholder farmers can launch creative ventures to produce insect meal as animal feed, and waste from insect production can be converted into organic fertilizer for crops [68]. The sale of crops and animal products (fish, meat, eggs, and insect meal) can provide food or supplement household income. Thus, by converting waste into resources, insects can efficiently end the nutrient cycle and prevent food waste. Legal restrictions on the use of insect meal as an animal feed ingredient are crucial factors to consider when completing this cycle [69]. Insect meal is currently permitted in Kenya and Uganda for use in fish and livestock feed [70], and is being developed in the European Union. Therefore, regulators are now also beginning to accept this viable concept.

Affordable goods and services related to sustainable livelihoods and participation in value chains in a profitable and sustainable manner are available to individuals, households, entrepreneurs, and micro, small, and medium enterprises through inclusive business models (IB) [71]. Sustainable business solutions that increase low-income communities' access to products, services, and employment opportunities in a profitable manner are known as inclusive business models [72]. By selling these insects to nearby cattle farmers and feed mills, smallholder farmers can engage with the local economy while divesting themselves from expensive external inputs such as fishmeal-based feed.

Several Sustainable Development Goals (SDGs) are interconnected, and the application of creative and sustainable food production techniques, including the use of insect farming for animal feed with smallholder farmers, can contribute significantly to some of them [68]. Globally, the ability of rural populations to earn a decent living, avoid hunger, participate in decision-making, and overcome social and economic marginalization is influenced by their access to and control over natural resources [73]. Resource-poor individuals can establish small-scale insect farms with few inputs to produce, both for their own consumption and for local markets, thereby reducing poverty (SDG 1) and hunger (SDG 2) [66].

Malnutrition is exacerbated by water scarcity, poor water quality, and inadequate sanitation, which negatively impact food production and livelihoods. Preliminary trials conducted in South Africa have shown that BSF larvae can be used to manage human waste in urine-diverting dehydration toilets while conserving water, thereby alleviating sanitation issues that predominantly impact the rural poor (SDG 6). A new industry for job creation and economic expansion is commercial insect farming (SDG 8). In addition to improving gender equality (SDG 5), inclusive insect farming can promote sustainable industrialization, provide employment, and support local technology development in low-income communities (SDG 9). Sustainable use and reduction of food waste can be achieved through insect bioconversion (SDG 12). A sustainable alternative to fishmeal could be increased insect production, which would mitigate the impacts of overfishing and forest conversion for agriculture on biodiversity (SDGs 14 and 15).

## 5. CONCLUSION

Environmental, economic, and social growth are the three pillars of sustainability, and solid waste management (SWM) is a complex topic that impacts all three. The objectives that have historically shaped the development of solid waste management (SWM) techniques can be broadly equated with the core ideas of the Sustainable Development Goals (SDGs). Bioconversion is one way to apply CE principles to organic waste management in general. Platform chemicals, fuels, and many other industrial products are currently produced using traditional chemical methods; bioprocessing offers a practical and environmentally friendly alternative. Using a multicriteria decision analysis approach to assess the utilization pathways of Hermentia Illucens oil as an environmentally friendly raw material, the highest score was obtained for its use as animal feed. The use of maggot oil as a raw material in animal feed can significantly contribute to achieving sustainable development. The implications of this study can encourage all stakeholders to participate in achieving sustainable development. Furthermore, this study still requires further research on system models that can be further developed for the implementation of BSFL oil in animal feed production.


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## NOMENCLATURE

| | |
|---|---|
| $S$ | min $S_w$ |
| $S^+$ | max $S_i$ |
| $R$ | min $R_i$ |
| $A^{(2)}$ | alternative with second order in Q ranking |
| $A^{(1)}$ | alternative with the best order in Q ranking |
| DQ | 1- (m-1) where m is the number of alternatives |
| CRT | Criteria |
| Alt | Alternative |