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Food industry waste - An opportunity for black soldier fly larvae protein production in Tanzania

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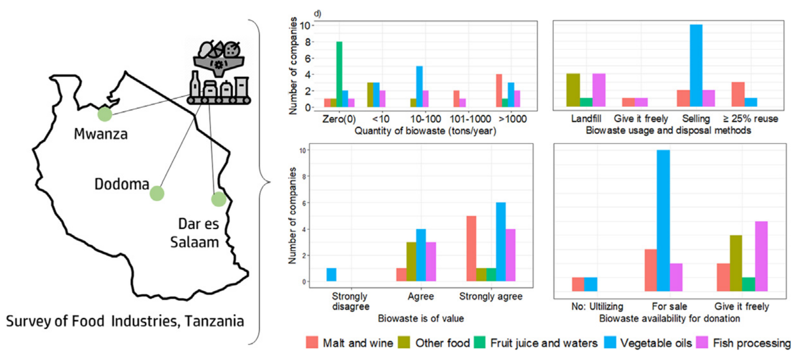
HIGHLIGHTS

- Food industry waste is generated in Tanzania and needs valorization technologies.
- Tanzania food companies can produce 100,000 to 1,000,000-ton y^{-1} of biowaste.
- Fly larvae composting can close nutrient loops of food industry biowaste.
- Blending of different types of biowaste can improve BSF larvae biomass production.

GRAPHICAL ABSTRACT

The status of food industry waste production, management and perceptions in Tanzania.



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ABSTRACT

Black soldier fly larvae composting is an emerging treatment option with potential to improve biowaste valorization in cities of low-income countries. This study surveyed the current generation and management status of food industry biowaste and their availability and suitability as potential feedstock for black soldier fly larvae (BSFL) composting treatment in three Tanzania cities, Dar es Salaam, Mwanza, and Dodoma. Biowaste-generating food industry companies ($n = 29$) in the three cities were found to produce banana peels, mango seeds, sunflower press cake, brewery waste, and coffee husks in large quantities (~100,000–1,000,000 kg y^{-1}). Around 50 % of these companies (16/29), primarily vegetable oil companies (10/11), either sold or gave away their waste as animal feed, while most companies (9/11) with unutilized food industry waste landfilled the generated biowaste. Multi-criteria analysis based on substrate availability criteria identified banana peels, mango seeds, and coffee husks with total score points of ≥10/12 as the most suitable feedstock for BSFL composting. However, multi-criteria analysis based on physical-chemical criteria identified brewery waste and sunflower press cake with total score points of ≥11/15 as the most suitable feedstock. Combined availability and physical-chemical properties of individual biowastes showed that all identified types of food industry biowaste can be suitable feedstock for producing BSFL biomass for protein production, but certain waste streams needed to be mixed with other waste streams prior to BSFL-composting to ensure sufficient availability and provide a balanced nutritional profile compared with the single-source biowastes. This study concluded that large volumes of food industry waste are being generated from food industry companies in Tanzania and there is need to establish new biowaste management interventions for resource recovery. Furthermore, for interested stakeholders in the waste management business, multi-stream BSFL-composting can be a suitable solution for managing and closing nutrient loops of the unutilized food industry biowaste in Tanzania and in other similar settings globally.

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1. Introduction

Waste management in low-income countries such as Tanzania is currently inadequate or lacking, with most biodegradable waste (biowaste) being abandoned in open dumps and landfill (Ferronato and Torretta, 2019; Kaza et al., 2018). This contributes to greenhouse gas emissions, eutrophication, acidification, and transmission of diseases (Ferronato and Torretta, 2019; Pariatamby et al., 2019). Waste management in large cities in low-income countries is particularly challenging, since these cities are experiencing rapid urbanization and existing waste treatment facilities are struggling to cope with the volumes of waste generated by the growing urban population (Kazuva et al., 2018; Pariatamby et al., 2019). The amount of municipal solid waste generated daily in Dar es Salaam is estimated to be around 4100 tons, of which >50 % is biodegradable (Huisman et al., 2016). Other cities in Tanzania, such as Mwanza, Mbeya, Arusha, Dodoma, Tanga, and Moshi, are also reported to generate municipal solid waste containing a high (35–80 %) biowaste fraction (Yhdego and Kingu, 2016). The biowaste in Dar es Salaam, and in other cities in sub-Saharan Africa, mainly originates from production, post-harvest handling, processing, and distribution of agricultural crops, meat, fish, and seafood (Kaza et al., 2018). Valorization of biowaste is still minimal, despite biowaste often being easily accessible directly from e.g., food industry companies (Kaza et al., 2018; Ravi et al., 2020; Aryampa et al., 2019).

Municipal councils typically manage solid waste in cities in low- and middle-income countries (LMICS), but actors in the informal and private sector also perform some waste management, filling gaps where the municipal authority fails to meet the needs of urban dwellers (Aryampa et al., 2019; Cheng and Urpelainen, 2015; Pariatamby et al., 2019). However, informal and private sector recycling and waste management actors generally aim for profit making (Cheng and Urpelainen, 2015; Kazuva et al., 2018). Thus waste fractions with higher market value, such as high-quality plastics and metals, are usually collected and taken for recycling (Hettiarachchi et al., 2018; Kaza et al., 2018), while the biodegradable fraction is left behind (Aryampa et al., 2019; Kazuva, 2017). The biodegradable fraction is difficult to collect and utilize efficiently, as there is no waste separation at source (Hettiarachchi et al., 2018). Furthermore, the cost of treating this fraction is reported to exceed the value of the products generated, discouraging actors from handling biowaste (Lohri et al., 2014). Consequently, the total amount of biowaste arriving at landfill and dump sites continues to increase (Komakech et al., 2014; Kazuva, 2017). Biowaste contains valuable resources, such as nutrients (e.g., carbohydrates, fiber, proteins, lipids) and energy (Katinas et al., 2019; Torres-León et al., 2018). Introducing waste management technologies that can extract the resources in biowaste and concentrate them into high-value products could shift the waste value chain and act as an incentive for adequate waste management and better utilization of this valuable resource (Kazuva and Zhang, 2019).

Black soldier fly (*Hermetia illucens* (L.), Diptera: Stratiomyidae) larvae (BSFL) composting is an emerging technology with potential to convert biowaste into high-value products, while decreasing the adverse impacts of inadequate waste management (Lohri et al., 2017; Lalander et al., 2018; da Silva and Hesselberg, 2020). In BSFL composting, amino acids, lipids, and energy are concentrated in the larval biomass, which can be recycled in the food cycle as animal feed (Heuel et al., 2021; Henry et al., 2015; Gold et al., 2018). The treatment residues contain plant nutrients, making them interesting for use as an organic fertilizer (Beesigamukama et al., 2020; Chirere et al., 2021). Black soldier fly larvae can process different types of raw biowastes, e.g., animal manure (Newton et al., 2005) and food waste (Lalander et al., 2019; Nyakeri et al., 2017), and agro-industrial biowastes such as brewery waste (Chia et al., 2018; Jucker et al., 2020), vegetable and fruit waste, and abattoir waste (Lalander et al., 2019). The technology is versatile and composting can be performed in a rather simple way, without a need for highly skilled personnel (Zurbrügg et al., 2018). In fact, BSFL composting has been demonstrated to generate products that are as valuable as those generated in anaerobic digestion, a considerably more complex treatment technology (Lalander et al., 2018). Thus BSFL composting has the potential to support adequate handling of biowastes, especially in low- and middle income countries, preventing it from ending up in open dumps and landfill (Purkayastha and Sarkar, 2021; Lohri et al., 2017).

While the larvae can consume many different types of biowaste, the nutritional composition of the substrate has a great impact on BSFL composting efficiency, measured as e.g., waste-to-biomass conversion efficiency (BCE), final larval weight, waste reduction efficiency, and larval survival during composting (Kawasaki et al., 2019; Lalander et al., 2019; Gold et al., 2020). To achieve high BCE ($\geq$12 % dry matter (DM)) and high final larval weight ($\geq$200 mg larva^{-1}), the substrate needs to have a sufficiently high protein content ($\geq 15\%_{DM}$) (Lalander et al., 2019; Gold et al., 2020) and a balanced protein to carbohydrate ratio (~1:1) (Cammack and Tomberlin, 2017; Gold et al., 2020), while the fiber and lipid content should not be too high (Gold et al., 2021; Lopes et al., 2020; Rehman et al., 2017). For example, low BCE ($<12\%_{DM}$) has been reported when treating vegetable and fruit waste with a low protein content ($\leq 13\%_{DM}$) (Isibika et al., 2019; Jucker et al., 2017; Lalander et al., 2019; Nyakeri et al., 2017) and no BSFL survival has been reported when composting pure fish waste with a high fat content ($>50\%_{DM}$) (Lopes et al., 2020; Isibika et al., 2021). Therefore in most cases, two or more types of biowaste must be mixed (multi-stream composting), to complement each other, providing the nutritional components lacking in single-source biowaste (Isibika et al., 2021; Nyakeri et al., 2019; Lopes et al., 2020).

Extensive research has been conducted on the conversion efficiency of different biowaste types in BSFL composting, but little is known about the actual feasibility of implementing this technology in practice, especially based on locally available waste streams. Reports on available biowaste streams in cities in sub-Saharan African countries, including those in East Africa, indicate that large volumes of sorted agricultural waste and food industry waste are available for waste entrepreneurs to utilize (Aryampa et al., 2019; Ravi et al., 2020; Kaza et al., 2018; Mbuligwe and Kaseva, 2006). For example, Mbuligwe and Kaseva (2006) estimated that industrial waste side-streams in Tanzania amount to 39,000 t per year, with 91.7 % originating from the food and beverage industry. Thus there appears to be great potential for waste management authorities and private sector entrepreneurs in LMICS cities to valorize BSFL composting of unutilized, segregated biowaste streams from the food sector. Matching waste management entrepreneurs interested in BSFL composting with available waste sources could help create a more extensive and environmentally and economically sustainable waste management solution in LMICS. As a first step in enabling such development, there is a need to acquire information on how existing food industry companies in a typical LMICS setting generate, utilize, and manage their waste today. Thus, the aim of this study was to assess the conditions for implementing BSFL treatment technology based on the available food industry biowaste, using Tanzanian cities as a study case for a LMICS setting. The assessment comprised: i) a survey of the current rate of generation, usage, and management of biowaste at food industry companies in densely populated cities in Tanzania; and ii) multi-criteria analysis with a traffic lights approach, using criteria based on availability and physical-chemical properties of the biowaste produced in the industries to assess its suitability as feedstock for BSFL composting.

2. Methodology

2.1. Study area

The study was conducted between November 2019 and January 2020 in the cities of Dar es Salaam, Mwanza, and Dodoma, located in south-east, north-west, and central Tanzania, respectively. At the time of the study, these cities were first, second, and fourth most populous cities in the country, with high numbers of food industry companies.

2.2. Study design

A survey targeting all food industry companies likely to generate biowaste in their production process was conducted. A list of established

Table 1
Distribution of the food industry companies surveyed ($N = 42$) according to food category, region in Tanzania, and company size.

	Region				Company size		Total
	Dar es Salaam	Mwanza	Dodoma	Small	Small-medium	Large	
Manufacture of malt liquors and wines	3	4	0	2	2	3	7
Manufacture of other food products	4	1	0	1	3	1	5
Manufacture of soft drinks, mineral water, and other bottled water	5	4	0	2	1	6	9
Manufacture of vegetable and animal oils and fats	2	1	10	11	0	2	13
Processing and preserving of fish, crustaceans, and mollusks	3	5	0	3	1	4	8
Total	17	15	10	19	7	16	42

food companies in Tanzania was obtained from the Ministry of Industry, Trade and Investment. This list covered food companies located in the 25 regions of Tanzania, arranged in 18 different categories based on type of product production, but only five of the 18 categories on the list refer to food industry companies with types of food production that would generate biowaste (Table 1). A total of 42 food companies in the three urban regions, out of 91 companies listed under the five relevant categories, were selected for the survey. The remaining 49 companies were excluded because they no longer existed, were not found, or were temporarily not operating. Seventeen of the selected food industry companies were located in Dar es Salaam, 15 in Mwanza, and 10 in Dodoma (Table 1). A wide range of products was produced by the food industry companies in Dar es Salaam and Mwanza, while all companies located in Dodoma produced sunflower seed oil (Table 1).

2.3. Questionnaire design and data collection

The questionnaire (Appendix 1) comprised four sections designed to investigate the food industry companies' practices pertaining to biowaste generation, storage, collection, processing, and final disposal, and perceptions on management of these streams. The questionnaire was developed in English and then translated into Swahili. It consisted of close-ended questions that required respondents to choose from a distinct set of pre-defined responses, such as 'yes/no' or multiple-choice questions. Both qualitative and quantitative data were requested from the food industry companies. The questionnaires were distributed physically to the 42 selected companies, with a request for voluntary responses by employees with overall responsibility and knowledge of company waste production and management practices. All 42 questionnaires sent out were completed and returned. The time taken for submission of completed filled questionnaires from the companies varied from 0 to 7 days, depending on the time available for respondents at different companies to complete the questionnaire.

2.4. Data analysis

2.4.1. Current biowaste generation and management in food industry companies

The first step in the data analysis consisted of describing current generation and management of biowaste by the food industry companies. The questionnaire responses were entered into Statistical Package for Social Sciences (SPSS) software (version 23) by assigning numerical values to all responses. Positive responses with a 'yes' response were assigned a numerical value of '1' and negative responses with a 'no' response were assigned a numerical value of '2'. All other responses in multiple choice questions with a, b, c, d, e, f, and g options were assigned a numerical value of 1, 2, 3, 4, 5, 6 and 7, respectively. Questions that had Likert-type response options were assigned a value of 1 (strong disagreement) to 5 (strong agreement). The data were then analyzed on SPSS descriptive statistics using frequency tables and cross-tabulations to measure different variables and relationships between the variables. R statistical software (R Core Team, 2016) was used for graphical representation of the data.

2.4.2. Biowaste suitability as feedstock in BSFL composting

The second step in data analysis assessed the suitability and availability of the companies' biowaste to be managed by interested stakeholders outside the company as a potential raw material for BSFL composting and production of larval biomass. The assessment was based on two categories: A) biowaste availability and B) biowaste suitability for use in BSFL composting.

Biowaste availability was assessed in terms of four sub-criteria: i) willingness of the company to allow any stakeholder/s outside the company to utilize and/or manage their biowaste (accessibility), ii) amount of waste generated, iii) whether any cost of purchase was involved, and iv) whether the waste was currently being used (competing use) (Table 2).

Biowaste suitability for BSFL composting was assessed in terms of physical-chemical properties. Physical-chemical properties of biowaste considered were: i) moisture content, ii) protein content, iii) carbohydrate content, iv) volatile solids (VS) content, and v) ratio of protein to carbohydrate (Table 2). Data on the physical-chemical properties of all biowastes were obtained from the literature. An average value was computed for different nutritional parameters based on 3–5 values for each waste taken from individual papers in the literature (Table 4). Protein to carbohydrate ratio (Prot:Carb) was calculated by dividing the percentage protein content (DM basis) by the percentage carbohydrate content (DM basis).

A multi-criteria analysis (MCA) procedure including the score evaluation method from Lohri et al. (2015) was adapted and modified to analyze both categories (A and B) and their respective sub-criteria. Criteria in category A were set to assess if the food industry waste were freely accessible and available as feedstock for BSFL composting treatment, while criteria in category B assessed if each type of biowaste had physical-chemical properties that can promote BSF larvae growth and desirable BSFL composting efficiencies. Unlike in Lohri et al. (2015), in this study the relative relevance of all sub-criteria was given a similar weighting; there was no total score summation of the criteria coupled with a ranking procedure to compare the biowaste types; and there were no focus group discussions with solid waste experts.

Data obtained from the survey (category A) and the literature (category B) were converted into scores ranging from 1 to 3 (1: low suitability; 2: moderate suitability, 3: high suitability), with a clearly defined attribute-to-score key (Table 2). For the accessibility (Question 40 in the questionnaire) sub-criterion in category A, a low score (1) was assigned when less than one-third (<0.33) of the companies responded 'NO' to making their waste

Table 2
Attribute-to-score keys used for suitability assessment of biowaste from food industry companies in terms of biowaste availability (category A, sub-criteria i–iv) and biowaste physical-chemical properties (category B, sub-criteria i–v) (score 1: lowest suitability; score 3: highest suitability).

A: Availability	Score 1	Score 2	Score 3
i. Accessibility	<0.33	0.33–0.67	>0.67
ii. Waste amount (kg/year)	<100,000	100,000–1,000,000	1,000,000 +
iii. Cost of purchase	<0.33	0.33–0.67	>0.67
iv. Competing use	<0.33	0.33–0.67	>0.67

B: Physical-chemical properties	Score 1	Score 2	Score 3
i. Moisture content (%)	>80	<65	65–80
ii. Protein content ($\%_{DM}$)	<15	>30	15–30
iii. Carbohydrate content ($\%_{DM}$)	<15	>30	15–30
iv. Volatile solids content (%)	<65	>85	65–85
v. Prot:Carb ratio	<1:1	>4:4	1:1–4:4

Table 3
Average suitability scores obtained for the four availability sub-criteria (accessibility, amount, purchase cost, competing use) by different food industry waste types. Companies producing similar types of biowaste gave different responses for the sub-criteria, so an average score for each sub-criterion is presented based on fractions of the companies' responses under each food industry company category that responded 'YES' or 'NO'.

	Accessibility		Amount		Purchase cost		Competing use	
	Response	Score	(kg y^{-1})	Score	Response	Score	Response	Score
Brewery waste (n = 4)	Yes	2.5 ± 1.0	100,000–1,000,000	2.7 ± 1.0	Yes	1.0 ± 0.0	Yes	1.0 ± 0.0
Sunflower press cake (*n* = 12)	Yes	3.0 ± 0.0	100,000–1,000,000	1.5 ± 0.9	Yes	1.2 ± 0.6	Yes	1.2 ± 0.6
Banana peels (*n* = 2)	Yes	3.0 ± 0.0	100,000–1,000,000	2.5 ± 0.7	No	2.5 ± 0.7	No	2.0 ± 0.0
Mango seeds (n = 2)	Yes	3.0 ± 0.0	100,000–1,000,000	2.0 ± 1.4	No	3.0 ± 0.0	No	3.0 ± 0.0
Coffee husks(n = 2)	Yes	3.0 ± 0.0	<10,000	1.0 ± 0.0	No	3.0 ± 0.0	No	3.0 ± 0.0
Fish waste (*n* = 7)	Yes	3.0 ± 0.0	100,000–1,000,000	1.7 ± 1.0	Yes	2.4 ± 1.0	Yes	1.9 ± 0.9

accessible (i.e. allowing others to utilize and/or manage their waste), while a high score (3) was assigned when more than two-thirds (>0.67) of the companies responded 'YES'. Conversely, the 'NO' and 'YES' fractions of responses for the cost of purchase (Question 40 in the questionnaire) and competing use (Question 12 and 14 in the questionnaire) sub-criteria were assigned a value of 3 and 1, respectively. A high score (3) was assigned when company biowaste generation (Question 9 in the questionnaire) was >1,000,000 kg/year, while a low score (1) was assigned when company biowaste generation was <100,000 kg/year (category A). An average score, obtained by averaging the scores given by all companies for a particular type of biowaste and a particular criterion, was computed and used for biowaste suitability assessment (Table 3).

Part B of Table 2 presents the attribute-to-score key for the physical–chemical properties evaluated. Protein content of the waste substrate is one of the limiting factor that affect the BSFL growth development especially in agro-industrial substrates (Lalander et al., 2019). Moreover, the balance of protein and available carbohydrates similarly influence the BSFL growth development and final products of the BSFL composting (Gold et al., 2020; Barragan-Fonseca et al., 2019). For category B (physical-chemical properties), a low score (1) was assigned when the biowaste had a very low content of nutrients, a score of 2 was assigned when the biowaste had more than the optimal amount of nutrients, and a high score (3) was assigned when the biowaste had nutrient composition in the optimal range to support production of larval biomass in BSFL composting (Table 2). For moisture content, a dry substrate was given a higher score than a very wet substrate, since it has been demonstrated that substrates with moisture content >80 % cannot easily be dry-separated (Cheng et al., 2017) and that BSFL composting efficiency declines with increasing moisture content (Lalander et al., 2020b). Water can easily be added to a dry substrate to achieve optimal moisture content.

Overall biowaste suitability for production of animal protein using BSFL composting was assessed using a three-color traffic light method (Caddy, 2015), with a score of 1 represented by red, a score of 2 by yellow, and a score of 3 by green (Tables 3 and 4). Red color indicated nutritional parameter values that were critically low or high, yellow indicated intermediate values and green indicated that the nutritional parameter values were in the optimal range to support BSFL growth.

3. Results

3.1. Characteristics of production

Of the 42 food industry companies surveyed, 18 produced one single product, around half (21/42) produced >1000 tons of product per year, and over half (26/42) used unprocessed raw material (Fig. 1a–c). Malt-wine and soft drink companies relied on a wide variety of products and high volumes of production, with each producing five or more products, and most (6/7 malt-wine and 7/9 soft drink companies) produced 1000 tons or more of products per year. Most of the soft drink companies (7/9) used only processed raw material and thereby did not generate any biodegradable waste fractions, while vegetable oil and fish processing companies (11/13 and 8/8, respectively) used only unprocessed raw material.

3.2. Status of biowaste generation, collection, usage, and disposal in the food industry companies

Thirteen of the companies surveyed did not produce biowaste. In particular, most of the soft drink companies (8/9) had no waste (Fig. 1d). The amounts of waste generated varied throughout the year for most of the remaining companies (25/29), mainly due to

Table 4
Calculated average scores attributed to physical-chemical properties of food industry waste (values obtained from various published studies).

	Moisture content (%)	Score	Protein (% DM)	Score	Carbohydrates (% DM)	Score	Volatile (%)	Score	Prot:Carb*	Score
Brewery waste	5.5 ± 2.1[a]	2.0 ± 0.0	23.5 ± 1.2[a]	3.0 ± 0.0	51.5 ± 7.9[a]	2.0 ± 0.0	91.8 ± 7.6[a]	2.3 ± 0.6	1:2	3
Sunflower press cake	8.69 ± 0.5[b]	2.0 ± 0.0	30.5 ± 6.5[b]	2.3 ± 0.5	41.1 ± 14.6[b]	2.3 ± 0.5	91.6 ± 3.5[b]	2.0 ± 0.0	1:1	3
Banana peels	87.1 ± 1.9[d]	1.0 ± 0.0	6.7 ± 3.4[c]	1.0 ± 0.0	29.2 ± 20.7[c]	2.3 ± 1.0	87.0 ± 2.8[c]	2.0 ± 0.0	1:4	3
Mango seeds	47.1 ± 4.0[e]	2.0 ± 0.0	5.7 ± 0.6[e]	1.0 ± 0.0	35.0 ± 25.2[e]	1.8 ± 0.5	97.8 ± 0.7[e]	2.0 ± 0.0	1:6	2
Coffee husks	12.2 ± 3.0[g]	2.0 ± 0.0	10.8 ± 4.1[f]	1.5 ± 0.6	70.1 ± 3.2[h]	2.0 ± 0.0	91.0 ± 9.3[f]	2.3 ± 0.5	1:7	2
Fish waste	68.0 ± 3.3[j]	3.0 ± 0.0	47.2 ± 17.3[i]	2.3 ± 0.5	5.5 ± 1.7[k]	1.0 ± 0.0	93.5 ± 6.2[j]	2.0 ± 0.0	8:1	2

* Prot:Carb ratio, calculated from average literature values for carbohydrates and protein on a dry matter (DM) basis. Letters on each physical-chemical property indicate the source of the data listed immediately below:
[a] Farcas et al. (2021), Ajanaku et al. (2011), Naibaho and Korzeniowska (2021).
[b] Rincón et al. (2011), Petraru et al. (2021), Chauhan (2021).
[c] Isibika et al. (2019, 2021), Hassan et al. (2018), Ogunlade et al. (2021).
[d] Isibika et al. (2019, 2021), Khan and Perveen (2010).
[e] Elegbede et al. (1995), Nzikou et al. (2010), Tesfaye (2017).
[f] Setter et al. (2020), Oliveira and Franca (2015), Murthy and Madhava Naidu (2012), Elsawy et al. (2021).
[g] Setter et al. (2020), Oliveira and Franca (2015), Murthy and Madhava Naidu (2012).
[h] Murthy and Madhava Naidu (2012), Oliveira and Franca (2015), Elsawy et al. (2021).
[i] Isibika et al. (2021), Lopes et al. (2020), Shanthi et al. (2021), Nguyen et al. (2015).
[j] Isibika et al. (2021), Lopes et al. (2020), Shanthi et al. (2021).
[k] Isibika et al. (2021), Shanthi et al. (2021), Nguyen et al. (2015).

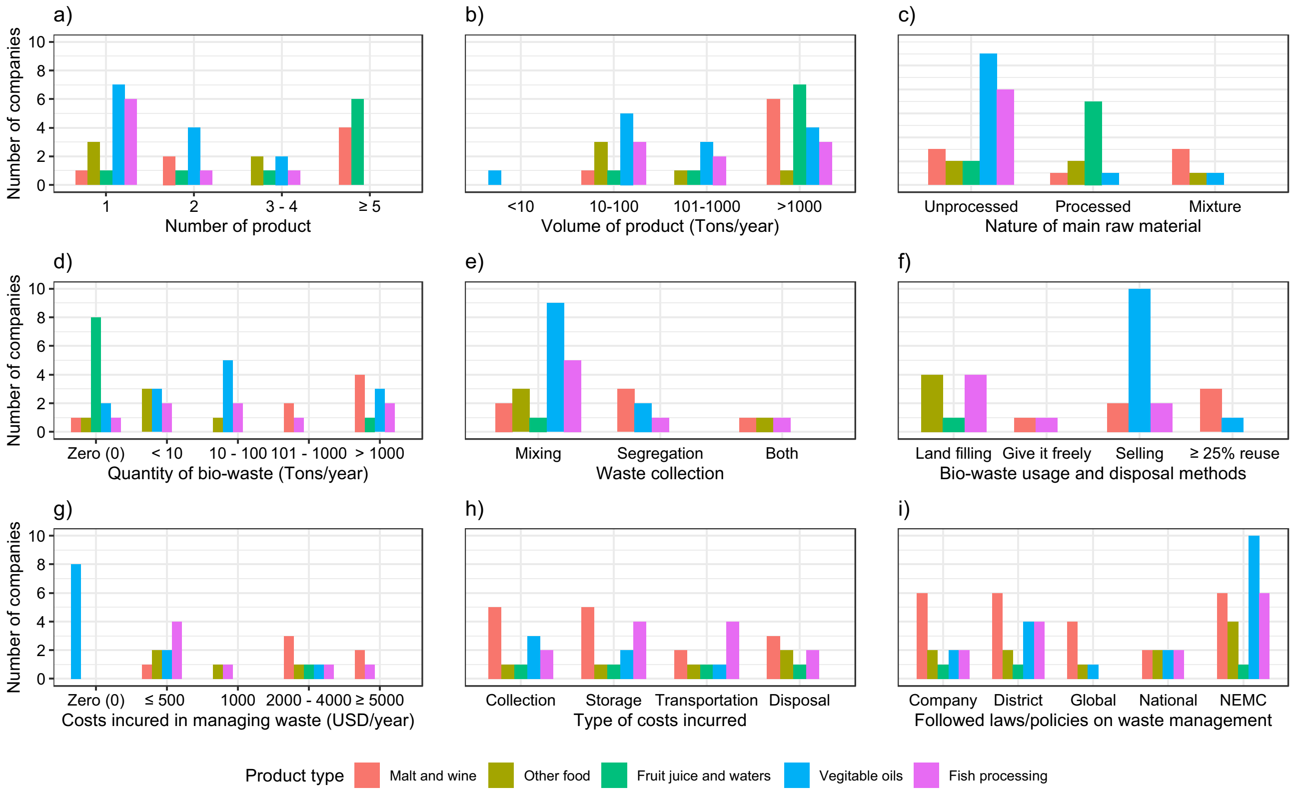

Fig. 1. Graphical presentation of current production and management of biowaste in the 42 food industry companies surveyed.

the type and nature of raw materials used (22/25). Most malt-wine companies (6/7) generated 1000 tons or more of biowaste per year (Fig. 1d).

Around two-thirds of the food companies that produced biowaste (20/29) mixed their biowaste streams during collection (Fig. 1e). More than half of the companies (17/29) monitored and documented the quantity of biowaste

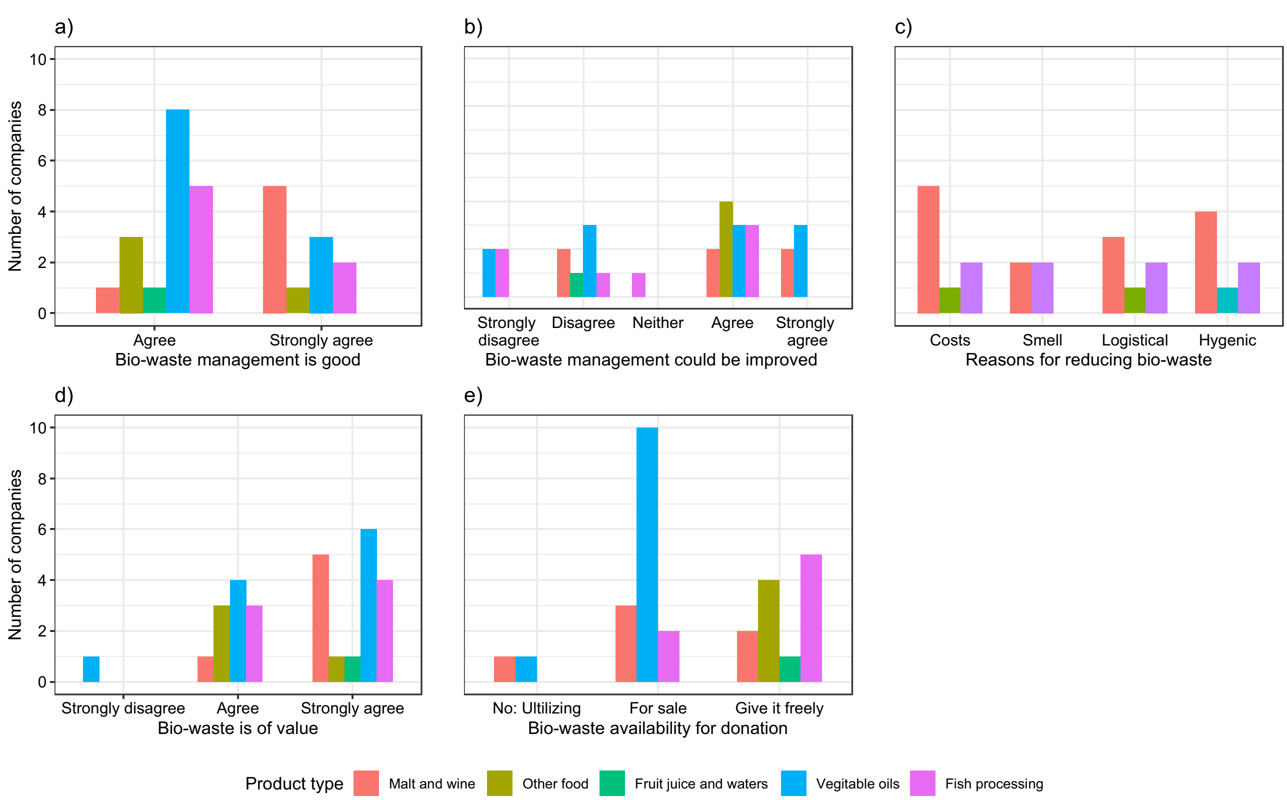

Fig. 2. Graphical presentation of food industry companies' (n = 29) perceptions on their current waste management.

generated. As regards disposal, landfilling was used by 9/29 companies, while 16/29 reported handing their biowaste over to outsiders, either by giving it away free of charge (2) or by selling it (14) (Fig. 1f). Selling biowaste was by far the most common option for vegetable oil companies (10/11). Only 4/29 companies re-used internally a proportion of the total waste generated (25 % or less). Having no usage (11), high cost involved in usage (9), and waste contamination (5) were reasons cited for not using the biowaste produced. The majority of the vegetable oil companies (8/11) reported zero cost for waste management (Fig. 1g). In fact, this was a distinctive feature, as the vegetable oil companies reported no costs for waste disposal (Fig. 1h). All food industry companies reported that they followed existing company, district, National Environmental Management Council (NEMC), national, and/or global waste management laws and policies (Fig. 1i).

3.3. Current waste management perceptions of the food industry companies

All the food industry companies that generated biowaste ($n = 29$) were of the opinion that their current waste management practice was good or very good (Fig. 2a), although the majority (17/29) also believed that there was room for improvement (Fig. 2b). Around one-third of these companies (10/29) identified a need to reduce the amount of biowaste generated. Specifically, cost reduction, hygiene, and logistical challenges (cited by 8/10, 7/10, and 6/10, respectively), were given as reasons behind the need for waste reduction (Fig. 2c). On the other hand, almost all the biowaste-generating food companies (28/29) agreed that their biowaste streams have value if managed properly (Fig. 2d). Almost all the biowaste streams (27/29) were reported to be available for utilization if other stakeholders outside the company were interested in managing them (Fig. 2e).

3.4. Biowaste suitability for production of animal protein by BSFL composting

The food industry companies that generated biowaste produced five types of waste: banana peels, mango seeds, sunflower press cake, brewery waste, and coffee husks (Table 3). The amount of waste that was available to interested stakeholders ranged from 100,000 to 1,000,000 kg y^{-1} (Table 3). All biowaste streams were accessible to interested stakeholders, and thus all biowaste had a high (≥ 2.5) accessibility score (Table 3). Only the coffee husks were not available in large quantities, so that biowaste scored lowest on the 'amount of waste' criterion. Unlike other types of waste, brewery waste and sunflower press cake waste scored low in terms of purchase cost and competition criteria. This implies that utilization of brewery waste and sunflower press cake waste in production of animal protein in BSFL composting would entail a purchasing cost, while competing with existing uses (Table 3).

Brewery waste was the only biowaste with an optimal protein content ($23\%_{DM}$) (Table 4). Banana peels, mango seeds, and coffee husks had the lowest score for protein content ($\leq 11\%_{DM}$). Brewery waste, sunflower press cake, and banana peels had the highest Prot:Carb ratio (range 1:1 to 1:4). Fish waste scored lowest for carbohydrate content ($<7\%_{DM}$). Fish waste had the highest amount of protein ($47\%_{DM}$) and an optimal moisture content, while banana peels had the highest moisture content (87 %) (Table 4).

4. Discussion

4.1. Current generation, usage, and management of food industry waste

Food industry companies in Mwanza, Dodoma, and Dar es Salaam, Tanzania, generated varying quantities (<10,000 to >1,000,000 kg y^{-1}) of food industry waste (Fig. 1d, Table 3). The brewery companies re-used internally 25 % of the waste they generated, while the remaining fraction of the brewery waste, together with all vegetable oil waste, was sold for use as animal feed (Fig. 1d). This demonstrates that there is an existing market for these biowaste types. The biowastes generated from fish processing, soft drink manufacture, and coffee production did not have any use, and were mainly landfilled at a company or city council site (Fig. 1f). This is similar to results reported by Mbuligwe and Kaseva (2006) in an early study on industrial solid waste management in Dar es Salaam. They found that brewery waste and vegetable oil waste were used for production of animal feed, while peels and crushed spent seeds from fruit and vegetable processing companies ended up in landfill. This suggests that there has been little to no improvement in management of fruit processing waste over the past 15 years, while the utilization value of brewery and vegetable oil waste streams seems to have persisted. Our results indicated that large amounts of non-utilized biowaste from food industry companies located in Dar es Salaam and Mwanza still end up in landfill.

Many of the industries surveyed stated that there was room for further improvement in their waste management practices (Fig. 2b), but most also believed that their current practices were already good or very good (Fig. 2a) and in line with current waste management regulations (Fig. 1i). This suggests that most of the industries surveyed are unlikely to change the way they manage biowaste, if there is no incentive to do so.

4.2. Availability of food industry waste streams to interested stakeholders outside the company

All companies surveyed were willing to let their biowaste be managed by stakeholders outside the company wishing to manage these waste streams (Table 3). Based on experiences reported for a BSFL treatment facility in Indonesia, treating 1000 kg of waste per day has been suggested as a starting processing rate for a small-scale BSFL composting facility (Dortmans et al., 2017; Zurbrügg et al., 2018). This means that, with the exception of brewery waste and banana peels (Table 3), food industry biowaste from single companies in the three cities surveyed here may not be available in sufficient amounts to ensure operation of a small-scale BSFL treatment facility. Moreover, the accessibility of brewery waste and sunflower press cake was limited by competition from existing users in the animal feed production value chain (Table 3). Lohri et al. (2015) emphasized the importance of securing non-competing and free-of-cost biowastes to enhance reliability in procurement of sufficient feedstock volumes, for a biofuel production facility in their case. The results obtained in this study indicate that BSFL composting stakeholders interested in brewery waste and sunflower press cake should evaluate the impact of existing purchase cost and competition (see Table 3) on securing a sufficient supply of these two types of waste streams as main feedstock. Having a sufficient supply of feedstock is important, since e.g., problems in long-term operational performance of other technologies, such as biogas production, have been reported to arise due to lack of a continuous supply of feedstock (Tumusiime et al., 2019). Overall, banana peels, mango seeds, and fish waste were found to be the most suitable substrates in terms of accessibility, amounts, purchase cost, and competition (Table 3). However, it may be necessary to source food industry biowaste from two or more food industry companies in order to acquire sufficient volumes to meet the suggested daily requirement (1000 kg d^{-1}) of a small-scale BSFL treatment facility.

4.3. Physical-chemical properties of food industry waste for BSFL composting

Brewery waste and sunflower press cake were the only two types of biowaste with high suitability as potential feedstock in BSFL composting, as their nutritional parameters (score > 1) were all above the critical value (Tables 2 and 4). To our knowledge, sunflower press cake has not been tested yet as feedstock for BSFL. Brewery waste, with its balanced nutritional composition, has been recommended as potential feedstock for BSFL composting at small or large scale (Nyakeri et al., 2017; Jucker et al., 2020; Chia et al., 2018; Beesigamukama et al., 2021), due to its potential to support fast BSFL growth rates that result in high final larval weight (>200 mg $larva^{-1}$) (Beesigamukama et al., 2021; Chia et al., 2018) and BCE (>13 %) (Beesigamukama et al., 2021; Nyakeri et al., 2017).

Banana peels, mango seeds, and coffee husks were the biowaste types with the lowest ($\leq 11\%_{DM}$) protein content (Table 4). The carbohydrate content in mango seeds was also low (Table 4). Available literature on

BSFL composting of banana peels reports lower BCE (<12 %), final BSFL weight (<135 mg larva^{-1}), and material reduction (<56 %) (Isibika et al., 2019, 2021; Nyakeri et al., 2017) in comparison with feedstock such as food waste with higher protein content (~22 %) that resulted in higher BCE (≥14 %), final BSFL weight (≥200 mg larvae^{-1}) and material reduction (≥55 %) (Lalander et al., 2019). The high moisture content in banana peels (75 %) is also likely to have a negative impact on BSFL composting efficiency, by reducing BCE while also hindering dry separation of the BSFL biomass (Lalander et al., 2020a). Moreover, high concentrations of other chemical compounds, such as tannins and phenolics, in banana peels have been found to have a negative effect on BCE (Isibika et al., 2019). Apart from the critically low amount of carbohydrate in fish waste (Table 4), BSFL have been shown to be unable to process pure fish waste due to its high fat content, lack of structure, and sticky nature (Nguyen et al., 2013; Isibika et al., 2021; Lopes et al., 2020). However, the impact of other pre-existing factors, such as substrate structure and nutritional parameters including phenolic compounds, fats, fiber, and tannins capable of hindering BSFL growth, were not directly assessed in this study. The literature indicates a risk of these additional factors hindering BSFL growth, so they should be considered and evaluated when determining the suitability of all existing biowaste streams before actual implementation of BSFL composting.

Assessment of the different food industry waste flows based on criteria relating to their physical-chemical properties showed that brewery waste and sunflower press cake were the most suitable substrates, with prospects for resulting in high treatment efficiencies in BSFL composting based on the moisture, protein, carbohydrate, and volatile solids content of the waste (Table 4).

4.4. Feasibility of using food industry waste for BSFL composting based on combined availability and physical-chemical properties criteria

Our overall assessment of food industry wastes indicated that the potential of all types of biowaste for use as feedstock in BSFL composting was restricted by one or several criteria (Table 5). The first part of the multi-criteria assessment, concerning substrate availability, identified banana peels, mango seeds, and coffee husks as available biowaste streams. The second part, concerning physical-chemical properties, identified brewery waste and sunflower press cake as best suited for BSFL composting. Thus considering both availability and physical-chemical properties (Table 5), the food industry wastes identified as being available for BSFL composting were not sufficiently well balanced for BSF larvae production as a standalone feedstock.

It has been suggested previously that strategies for utilizing different food industry waste streams for BSFL conversion could consider blending of different types of biowaste during composting, to balance the nutritional components of single-source biowaste (Isibika et al., 2021; Lopes et al., 2020; Nyakeri et al., 2019; Lalander et al., 2019). Based on the characteristics of the different food industry wastes available in Dar es Salaam, Mwanza, and Dodoma, mixing of waste streams could have the potential to balance the biowaste nutritional composition and improve BSFL conversion efficiency in treating these food industry waste streams. For example, banana peels (low protein content, high moisture and carbohydrate content), could be mixed with fish waste (low carbohydrate content, high protein content) (Table 5). Similarly, coffee husks or mango seeds could be added to decrease the moisture content of a wet substrate. Isibika et al. (2021) found that BSFL composting a mixture of banana peels, as a carbohydrate-rich feedstock, with fish waste, as a protein-rich waste substrate, increased the BCE of banana peels from 6 % of VS to 13 % and 20 % for multi-stream composted fish waste: banana peels in a 1:1 ratio and 3:1 ratio, respectively. Similarly, Truzzi et al. (2019) found that BSFL composting a mixture of coffee husks with 10 % by mass of a fat- and protein-rich microalgal species (*Schizochytrium*) produced BSFL biomass containing higher amounts of nutritional compounds such as omega-3 oils and protein (necessary ingredients in feed and food production), in comparison with BSFL composting of 100 % coffee husks.

To our knowledge, sunflower press cake and mango seeds have not yet been tested as substrate in BSFL composting. However, increased growth rate, final body weight, and feed conversion ratio in hybrid Nile tilapia (*Oreochromis niloticus* × *O. mossambicus*) (Khieokhajonkhet, 2020) and broiler chickens (Beriso Ulo, 2020) have been reported following partial replacement of maize in the diet with 10 % and 15 % mango seed meal, respectively. Sunflower press cake also has potential to be a good substrate blends in BSFL composting, as shown previously for oilseed press cake from *Crambe abyssinica* and *Camelina sativa* (Schreven et al., 2021). In that study, BSFL performance in terms of larval development time and final growth weight in mixtures of chicken feed and oilseed press cake (up to 50 % *Camelina* and 25 % *Crambe*) was similar to that on chicken feed alone (control) and better than that of 100 % *Crambe* and 100 % *Camelina* press cakes (Schreven et al., 2021). Thus, previous literature on multi-stream composting of food industry biowastes indicates potential for feasible continuous operation of a BSFL composting treatment facility at high process efficiencies. Using multiple biowastes in BSFL composting could increase the revenue from the process, while the added complexity compared with single-stream BSFL composting could be justified by enabling a more stable process. In addition, smaller streams of biowaste (>10 %) that already have a market, e.g., sunflower cake and brewery waste, could be added at a cost to optimize the treatment process.

Blending of substrates in BSFL composting can be a suitable biowaste treatment method in managing and closing nutrient loops, enabling reuse of the resources contained in food industry waste streams in large cities in Tanzania and in other similar LMICS globally. Future studies should evaluate the impact of different blends, material availability throughout the year, and collection and transport costs, which can affect feedstock accessibility and the profitability of waste treatment facilities.

5. Conclusions

This study shows that food industry companies in the Tanzanian cities, Dar es Salaam, Dodoma, and Mwanza generate biowaste amounts mostly ranging from 100,000 to 1,000,000 kg y^{-1}. Banana peels, mango seeds, sunflower press cake, brewery waste, and coffee husks were the main biowaste types generated. There was not much reuse of the generated biowaste internally by the companies, only brewery companies reused

Table 5
Traffic light display showing the overview of the biowaste feedstock suitability in BSFL composting based on combined availability and physical chemical criteria. Red = critically low or high, yellow = more than needed (opposite of critical values) and green = optimal range.

	Brewery waste	Sunflower press cake	Banana peels	Mango seed	Coffee husks	Fish waste
Accessibility	green	green	green	green	green	green
Amount	green	yellow	green	yellow	red	yellow
Purchase cost	red	red	green	green	green	yellow
Competing use	red	red	yellow	green	green	green
Moisture content	yellow	yellow	red	yellow	yellow	yellow
Protein	green	yellow	red	red	red	yellow
Carbohydrates	yellow	yellow	yellow	red	yellow	red
Volatile solids	yellow	yellow	yellow	yellow	yellow	yellow
Prot:Carb ratio	green	green	green	yellow	yellow	yellow

25 % of their brewery waste. The biowaste with ready market for use in animal feed production were mostly the remaining 75 % of brewery waste and all vegetable oil waste streams. More than 50 % of the remaining types of food industry waste was not utilized and ended up in landfills. In multi-criteria analysis, an assessment based on availability criteria identified banana peels, mango seeds, and coffee husks with total score points of ≥11/15 as the most suitable substrates, while an assessment based on physical-chemical properties identified brewery waste and sunflower press cake with total score points of ≥11/15 as the most suitable substrates in BSFL composting. No single biowaste stream satisfied all criteria relating to availability and physical-chemical properties. Blending of the biowaste would be necessary to ensure provision of a nutritionally balanced substrate for the larvae and a feasible continuous operation of the BSFL composting treatment facility using the identified food industry biowaste as feedstock. The present study provides the current generation, usage and management status of existing types of food industry biowaste and their potential as resourceful feedstock in BSFL composting in the surveyed regions of Tanzania. More surveys, in depth contextual investigations and knowledge transfer to scaled up biowaste management operations are recommended for valorization of biowaste and for advancement of industrialization of BSFL composting treatment technology in Tanzania and other similar low-, and middle income countries globally.

CRediT authorship contribution statement

A. Isibika: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **P. Simha:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **B. Vinnerås:** Conceptualization, Methodology, Supervision, Writing – review & editing. **C. Zurbrügg:** Conceptualization, Supervision, Writing – review & editing. **O. Kibazohi:** Funding acquisition, Supervision, Writing – review & editing. **C. Lalander:** Conceptualization, Methodology, Formal analysis, Supervision, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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