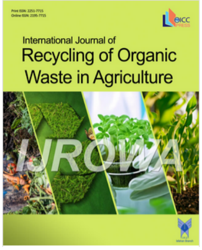

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A review of vegetable waste bio-processing techniques in rural areas

Noorafizah Murshid, Junidah Lamaming, Sariah Saalah, Mariani Rajin, Abu Zahrim Yaser*

Chemical Engineering Programme, Faculty of Engineering, University Malaysia Sabah, Jalan UMS, Malaysia.

***Corresponding author**: zahrim@ums.edu.my

Review paper

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Abstract:

Purpose: Vegetable waste (VW) could cause environmental problems if not properly managed. Due to rural living conditions and a relatively low residence density, VW is usually disposed of in landfills. Waste management should be engineered in a way to process the waste into value-added products in a sustainable manner. This review evaluates four bioprocessing techniques for this purpose: anaerobic digestion (AD), vermicomposting (VC), black soldier fly composting (BSFC), and composting.
Method: A systematic search involved databases from Scopus using keywords like "vegetable waste; anaerobic digestion; composting; vermicomposting; black soldier fly". By reviewing and synthesizing 173 articles (with 162 from 2019 – 2023), this paper summarizes and illustrates the information collected.
Results: In a systematic search, AD and composting easily surpassed 2000 publications (from 2013 to January 2023). Besides composting emerged as a cost-effective (for MYR 1.40/kg) bio-processing technique in terms of production cost. This review on VW composting is based on an acceptable C/N ratio (30 – 50), moisture content (50% – 80%), ratio of VW to additives (typically 30:70), efficient additives, and inoculation strategy. This review also summarizes the maturity index and illustrates the usage of compost and leachate as fertilizer.
Conclusion: VW composting in rural areas is reliable and beneficial because it uses a small-scale reactor and has the potential for a circular economy in the community.

Keywords: Composting; Vegetable waste; Waste management; Compost maturity; Organic fertilizer; Agriculture economy

1. Introduction

Global waste production is increasing due to urbanization, population growth, and economic growth. In Malaysia, the COVID-19 pandemic has led to increased agricultural expansion and unplanned vegetable waste (VW), posing threats to food security, health, economics, and environmental sustainability. The Food and Agriculture Organization (FAO) reports 1.6 billion tons of food waste annually, with 1.6 kg per capita per week in Malaysia, which produces about 38,000 tons daily, of which 45%, or 17,000 tons, are organic waste in 2019 (Nadhirah et al., 2021) and has not changed much since the 1980s (Jamaludin et al., 2022), of which around 4,080 tons are still edible. Sustainable management practices (Fig. 1) (Lu et al., 2022), such as composting, can prevent resource exhaustion (Guarnieri et al., 2021), mitigate environmental loads, and promote environmental sustainability (Kumar et al., 2020).

Numerous research has been conducted on VW, but only a few are reviews of VW. Gowe (2015) reviewed the production and processing of VW besides highlighting the possibility of extracting bioactive compounds for use as natural additives. Peng et al. (2019) reviewed the development of an anaerobic digester for the usage of fruit and VW in China for energy, fertilizer, and feed. Malenica and Bhat (2020) reviewed bioactive compounds in VW man-

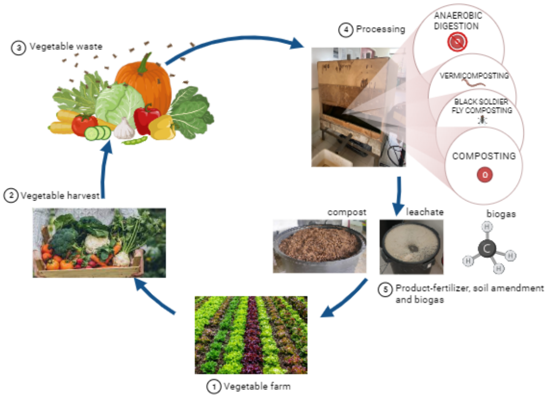

Figure 1. Vegetable waste management.

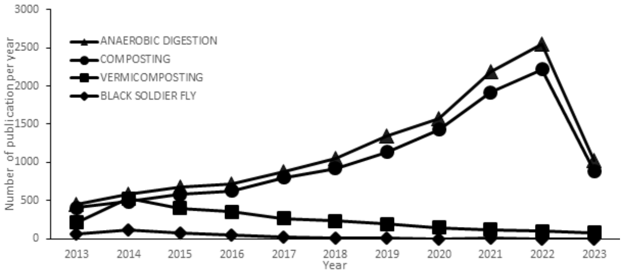

Figure 2. Trend of indexed papers containing the word "vegetable waste; anaerobic digestion", "vegetable waste; composting", "vegetable waste; vermicomposting", and "vegetable waste; black soldier fly" from 2013 to January 2023.

agement in Europe, particularly Estonia. Lastly, Esparza et al. (2020) provided a systematic review of the conventional and valorization techniques of VW, summarizing progress on microbiological, biochemical, and bioreactor engineering aspects.

The increasing number of research publications (in Scopus) on VW anaerobic digestion and composting between 2013 and January 2023 (Fig. 2) indicates its growing significance and relevance, which is expected to continue in the future. Meanwhile, vermicomposting and black soldier fly composting have decreased, possibly due to a shift in interest toward composting and anaerobic digestion since they offer greater benefits.

This review explores the economic feasibility of VW bioprocessing techniques in rural communities, examining optimization parameters, additives, and technologies. It identifies promising areas for further study and emphasizes the need for compost and liquid fertilizer for sustainable biowaste management. The focus is on experimental initiatives and knowledge gaps within the last 10 years, with a special emphasis on reports published between 2013 and 2023.

2. Overview of vegetable waste management

Population expansion and periodic supply chain instabilities fuel the exponential rise in worldwide organic waste, including vegetable waste (VW) (Du et al., 2018). The emergence of pandemic COVID-19 has exacerbated and disturbed the worldwide food system, necessitating actions to lessen the threat (Jribi et al., 2020). Addressing the problem of VW requires attention to storage practices (Amicarelli and Bux, 2021) and handling at each stage, from farm-level harvest and post-harvest (farmers), through wholesale and retail handling (suppliers), processors, and residuals at housing (warehouse), food outlets (wholesale), and business premises (retail markets) (Ganesh et al., 2022).

VW accounts for a sizeable share (42% of global food waste) (Ganesh et al., 2022). It encompasses various parts of vegetables, such as peel, seed, crop, stem, root, leaf, straw, or tubers (Obuobi et al., 2022). Retailers play a crucial role in VW management as they store vegetables for extended periods before reaching consumers (Cantera et al., 2018). Minimizing financial and environmental costs is essential in handling VW, and regulatory actions should focus not only on cutting-edge technology but also on the behavior of retailers to reduce food waste (Céline et al., 2020).

Vegetables constitute 75% of biodegradable organic matter (sugar and hemicellulose), 15% of resistant organic matter (cellulose and lignin) (Balaji et al., 2020) and complex chemical content (carbohydrates, proteins, lipids, organic acids, phytoncides, antimicrobial substances, minerals and vitamins) essential for the human body (Alam et al., 2022).

However, they are deficient in key nutrients like nitrogen ($0.5-1.5\%$), phosphorous ($0.1-0.2\%$), and potassium ($0.4-0.8\%$) (Haouas et al., 2021). The C/N ratio of vegetables is often below 20 due to low recalcitrant organic matter, causing rapid hydrolysis (Lu et al., 2022). Table 1 depicts the composition of important vegetable lignocellulosic sub-

Table 1. Composition of important vegetable lignocellulosic substrates.

Type of vegetable	Cellulose (%)	Hemicellulose (%)	Pectin (%)	Lignin (%)	Ref.
Cabbage	63	15	7	15	(Andres et al., 2017)
Cauliflower	35 – 67	14 – 21	6	14	
Carrot	52	12	4	32	
Tomato	19	12	8	36	
Potato	17 – 21	14	2	3	
Cucumber	28	11	NA	6	(Chang et al., 2019a)
Corn	28	22	NA	6	

*Remark: %: Dry weight basis, NA: Not available.

strates.

VW, rich in polysaccharide (Ramírez-Pulido et al., 2021) can be fermented to produce ethanol and butanol (Khandaker et al., 2020), useful in various industries and as liquid fuel supplements (Topi, 2020). It has been transformed into functional food ingredients Bas-Bellver et al.'s (2020), but valorization methods (Esparza et al., 2020) are needed to avoid destroying nutrients. VW is a potential animal feed option, but it poses significant risks (Torok et al., 2021) of containing toxic compounds that can transmit diseases or be unbalanced in terms of dietary intake (Sahoo et al., 2021).

VW is primarily disposed of in landfills (Nanlin et al., 2023) or incinerators (Chen et al., 2019), with 60% in developing areas and over 80% in rural areas. This habitual practice, influenced by human behaviors (Adamu et al., 2023), can lead to dioxin production, CO_2 emissions, air pollution, and methane release. Current methods are economically and environmentally unfriendly, necessitating the development of innovative, long-term solutions to minimize VW production (Facchini et al., 2023).

3. Vegetable waste bio-processing techniques

Bio-processing techniques (Table 2) like anaerobic digestion (AD), vermicomposting (VC), black soldier fly composting (BSFC), and composting are promising methods (Chaher et al., 2020) to minimize VW. Ugak et al. (2022) conducted an economic analysis of the composting system in Malaysia for approximately 1 ton of organic waste daily resemblance (Table 2) and showed operational costs (a,b,c, and d) of 0.75 hectares^2 reasonably assumes treatment for two months per batch including labor, raw material, transportation, machinery maintenance, nutrient analysis, and bagging of compost. For VC (a) (Alege et al., 2021) and BSFC (b) (Liu et al., 2022) including the purchase, shipping, and pretreatment of insects before and after treatment. Contingencies for operational costs are 10% of the total operational costs for locals performing their work in Kundasang Composting Community Site, Sabah.

The capital cost includes site preparation, construction of an office, toilet, pathway, fencing, a planting stand complete with piping, wiring, and a solar panel with a temperature reader, along with machinery such as a shredder, mixer, and weighing scale (Ugak et al., 2022). AD (e) (Sanaye and Yazdani, 2022) the cogeneration unit uses an on-site engine, alternator (2- to 5-cylinder engines), and transformer to generate electricity for treatment plants and neighboring facilities, transfer electrical energy from the alternator to the electricity (HV) cable, and supply the power grid with renewable energy. The contingencies for capital costs are 10% of the total capital cost.

In Table 2, VC and BSFC operational costs are higher due to the pretreatment of insects before and after the process. Alege et al.'s (2021) study showed that the cost of material (approximately 115 000 MYR/year) constituted the highest expense (approximately 42%) for a 1 ton feedstock, similar to Table 2, where the VC operational cost is wholly 186 000 MYR/year. Thirunavukkarasu et al. (2022) provided the production cost of the VC in India for 0.60 MYR/kg for 24, 000 kg of compost, and in Table 2 (i), they stated that the production cost is approximately 1.90 MYR/kg for 56, 000 kg.

Liu et al. (2022) estimated the cost of small-scale production from BSFC and demonstrated that labor accounts for up to 65% (45, 000 MYR/year) of the total operation cost.

Table 2. Comparison between vegetable waste bio-processing techniques.

				
Conversion agent	Anaerobic microorganism	Worms	Black soldier fly larvae	Aerobic microorganism
Optimum temperature (° C)	30 – 70	25 – 30	25 – 30	> 50
Duration (Months)	3 – 6	3 – 6	3 – 12	6 – 12
Operational cost (MYR/yearly)	95, 000. 00[a]	88, 000. 00[b]	80, 000. 00[c]	74, 000. 00[d]
Capital cost (MYR)	550, 000. 00[e]	186, 000. 00[f]	186, 000. 00[g]	179, 000. 00[h]
Production cost (MYR/kg)	3.50[i]	1.90[j]	1.80[k]	1.40[l]

1) Comparison made based on a case study at Kundasang Composting Community Site with 1 ton of vegetable waste/cycle (Data reproduced with permission from Murshid et al. (2022) and Ugak et al. (2022).

2) Operational and capital cost are similar items as listed in Ugak et al. (2022) economic analysis. Production cost is based on total of operational cost divide the total of compost (j, k & l) and biogas product (i).

Table 2 shows the approximately 80, 000 MYR/kg of labor required for managing the insects before, during and after the composting. Nanlin et al.'s (2023) studies sell compost at 2.50 MYR/kg, and Table 2 shows the production cost at 1.80 MYR/kg.

Pera et al. (2023) stated that AD is an expensive process to complete compared to composting due to equipment construction, which includes equipment to weigh, a digester, and energy generation equipment including an engine, alternator, transformer, and HV cable. Tian et al. (2023) reported total annual operating expenses of approximately 210, 000 MYR/year for a new facility (2.5 hectare^2) in China compared to 95, 000 MYR/year (0.75 hactare^2) in Table 2. Hanum et al. (2019) stated that Malaysia has three modern wastewater treatment plants that are equipped with AD, and the production cost is around 4.50 MYR/kg, comparable to 3.50 MYR/kg as in Table 2.

Lin et al. (2019) evaluate the techno-economic feasibility of commercial-scale AD and composting, and the advantage of composting is that the heat generated could kill harmful bacteria and pathogens within the process. Meanwhile, composting is effective in minimizing organic waste on a small or large scale; it also produces useful end products at a low production cost. Rahman et al. (2020) studies show that composting in 0.50 hectare^2 consumes roughly 75, 000 MYR/year, similar to the assumption in Table 2 (74, 000 MYR/year) with 0.75 hectare^2 of composting space. Rahman et al. (2020) sold compost in bulk for an estimated value of 1.50 MYR/kg, which is close to the selling price in Table 2 of 1.40 MYR/kg.

Keng et al.'s (2020) economic analysis showed that substituting chemical fertilizers with organic compost produced in-house is a viable option and that for Malaysia, the composting system would be able to self-sustain financially only when the landfilling cost is increased 2.3 times. Therefore, it is advantageous to adapt composting to start managing the waste with a feasible capital cost at the beginning, minimal operational costs yearly, and a low production cost of compost.

Anaerobic digestion

Anaerobic digestion (AD) is a biochemical process that converts organic waste into biogas and highly concentrated sludge via hydrolysis, acidogenesis, acetogenesis, homoacetogenesis, and methanogenesis with the help of microbes as shown in Eq. 1 (Assis and Gonçalves, 2022).

$$\text{Waste} + \text{Anaerobicmicrobes} + \text{Moisture} = \text{CO}_2 + \text{Biogas} + \text{Digested} \tag{1}$$

Factors affecting AD include seeding, temperature, C/N ratio, pH, mixing speed, organic loading rate (OLR), volatile fatty acids (VFA), and hydraulic retention time (HRT) (Berhe and Leta, 2023). VW, with high moisture (total solids (TS) concentration of 10%) and volatile solids (VS), is suitable for AD as presented in Table 3 (Silva et al., 2022). However, high cellulose content (Chatterjee and Mazumder, 2020) may cause acidification and methane formation. Semidry ($1-20\%$ TS concentration) and dry AD VW can be used in mesophilic temperature ($49-57°$ C) regimes, but fast carbohydrate breakdown at thermophilic temperatures limits methanogenic activity (Chatterjee and Mazumder, 2020).

Zhang et al. (2020) using a batch reactor found potato peels (452 mg COD/g VS) had the highest VFA production in a batch anaerobic fermentation reactor, surpassing carrots, celery, and Chinese cabbage by equivalent margins of 40.1%, 21.5%, and 124.9%. The quick acidification of carrots hindered VFA formation, while the low starting pH of Chinese cabbage inhibited VFA yield. Tsigkou et al. (2020) investigated the pH influence on biohydrogen production, finding that co-digestion of mixed waste streams increased H_2 levels by three times and increased biohydrogen production at pH 7.5.

Shi et al. (2021) and D'Silva et al. (2022) found that anaerobic co-digestion (AcoD), achieved a higher methane production (388 ± 131 mL g^{-1} VS), performance index value (1.04) and satisfactory biodegradability (77%) with potential for full-scale implementation. Quadros et al. (2022) found that biochar significantly increased ($17-28\%$) methane generation in AcoD using VW and chicken manure due to biochar's redox-active compounds that facilitated the microbiological syntrophic and adherence of microbes to the biochar's surface. Jiang et al. (2022) found that carbon recovery from sewage sludge and VW increased biogas production rates by $1.3-3$ times, with an optimal OLR of 2.083 kg L^{-1} d^{-1} and the greatest VBPR at 2.04 L/Day. Mixed substrates improved hydrolytic acidification, methanogenesis, and ammonia nitrogen inhibition while preventing excessive humification of organic materials.

Vermicomposting

Vermicomposting (VC) (Fig. 3) use worms, oxygen, and moisture to safely decompose organic material (OM) with little odor, as in below Eq. 2 (Chaher et al., 2020; Das et al., 2020); however, it comes at a significant cost in terms of both energy and money. Worms help take over both the turning and maintenance of the material, reducing the need for mechanical operations (Kumari et al., 2022).

$$\text{Waste} + \text{O}_2 + \text{worms} + \text{moisture} = \text{vermicast} + \text{CO}_2 + \text{H}_2\text{O} + \ldots + \text{vermicompost} \tag{2}$$

According to Pierre-Louis et al. (2021), earthworms used in VC (Table 4) are typically classified as '*epigeic*' species, or 'surface dwellers', because of their high reproductive rates, endurance, tolerance for living close to one another, and propensity to produce large volumes of vermicompost. Manual earthworm extraction is a bottleneck in large-scale VC technologies due to high labor, time, cost, and low efficiency (Ghorbani and Sabour, 2021). Walling and Vaneeckhaute (2021) propose a novel approach, centrifugation for 84% worm recovery while Grasserová et al. (2020) suggest combining, with composting being used first (to remove pathogens) followed by VC (to prolong decomposition and improve aeration).

Huang et al. (2022) stated that VC (10 days) and room drying (10 days) have been shown to improve the stabilization

Table 3. Initial and final parameter reported in vegetable waste anaerobic digestion related publications.

Operational condition				Material	Inoculum	Ratio	Initial condition					Compost quality										Ref.
Composting system (L)	Stage	Duration (Day)	Aeration	amendment		(%)	pH	MC	C/N	EC	PS	pH	MC	C/N	EC	Opt Temp	OM Loss	PS	G.I	Nutrient	Biogas (mg/L)	
R (200)	Single	60	NA	NA	NA	100	6.7	50	38	NA	< 5	5.3	54	10	NA	46	53	NA	NA	N:1	64000	(Arhoun et al., 2019)
R (75)	Single	60	NA	Cattle manure: Water	NA	1:1:2	7.8	NA	NA	NA	< 5	4.1	NA	NA	NA	35	NA	NA	NA	NA	12000	(Stephen et al., 2020)
Semi-CTS (0.5)	Single	NA	NA	Mixed waste activated sludge	NA	1:3	6.4	NA	NA	NA	NA	7.8	NA	NA	NA	NA	NA	NA	NA	NA	280	(Ambrose et al., 2020)
Batch (40)	Two	NA	NA	Cattle manure: Leaves	NA	60:20:20	5.6	NA	22	2.7	NA	7.0	NA	NA	0.02	NA	NA	NA	NA	NA	815	(Silva et al., 2022)
Semi-CTS (25)	Single	103	2.5 kgVS/ L^{-1}day	Pig manure: Sewage sludge	NA	60:20:20	7.6	NA	NA	NA	< 2	6.1	NA	NA	NA	NA	NA	NA	NA	NA	2040	(Jiang et al., 2022)
CTS (5)	Single	6	NA	Carrot: Cattle manure	NA	90:10	5.7	NA	NA	NA	NA	3.9	NA	NA	NA	37	NA	NA	NA	NA	321	(Zhang et al., 2020)
				Cedery: Cattle manure			5.6	NA	NA	NA	NA	5.3	NA	NA	NA		NA	NA	NA	NA	372	
				Chinese cabbage: Cattle manure			4.8	NA	NA	NA	NA	3.8	NA	NA	NA		NA	NA	NA	NA	201	
CST (0.12)	Single	60	NA	Cattle manure	Digested inoculum	(75:25) + 0.5%	7.5	NA	NA	NA	< 5	7.5	NA	NA	NA	37	NA	NA	NA	NA	607	(Quadros et al., 2022)

Abbreviation: R=Reactor; NR=Non-reactor; Semi-CTS=Semi-continuous stirred tank; CST=Continuous stirred tank; MC=Moisture content in wet weight basis (% wb); EC=Electrical conductivity (dS/m wb); PS=Particle size (cm); Opt Temp=Optimum temperature (° C); OM Loss=Organic matter loss (% wb); G.I=Germination index (%); N=Nitrogen (% wb); NA=Not Available; Ref=References.

Table 4. Initial and final parameter reported in vegetable waste vermicomposting-related publications.

Operational condition				Material amendment	Inoculum	Ratio (%)	Initial condition					Compost quality									Ref.
Composting system (L)	Catalyst	Duration (Day)	Aeration				pH	MC	C/N	EC	PS	pH	MC	C/N	EC	Opt Temp	OM Loss	PS	G.I	Nutrient	
R (20)	Eisenia fetida	84	NA	Goat manure	NA	50:50	8.1	NA	45	3.1	NA	7.7	NA	20	0.04	NA	NA	NA	NA	NA	(Katakula et al., 2021)
R (16)	Eisenia fetida	NA	NA	Dewatered sludge	NA	70:30	5.7	84	10	308.0	< 2	5.3	75	8	1.35	25	6	NA	NA	N:6 P:10	(Li et al., 2020)
R (1)	Eisenia	30	NA	Cattle manure: Sawdust	NA	50:40:10	7.1	NA	NA	1.4	< 2	7.0	NA	NA	0.02	NA	13	NA	NA	N:3	(Paul et al., 2020)
R (550)	Eisenia fetida	27	Turn daily	Cattle manure: Sawdust	NA	50:40:10	6.4	77	NA	7.0	NA	8.0	67	NA	0.02	25	17	NA	98	N:4 P:15 K:30	(Pottipati et al., 2022)
R (12)	Eisenia fetida	20	Turn daily	NA	NA	100	NA	65	NA	153.0	< 2	NA	49	NA	3.10	28	13	NA	NA	NA	(Huang et al., 2022)

Abbreviation: R=Reactor; NR=Non-Reactor; MC=Moisture content in wet weight basis (% wb); EC=Electrical conductivity (dS/m wb); PS=Particle size (cm); Opt Temp=Optimum temperature (° C) ; OM Loss=Organic matter loss (% wb); G.I=Germination index (%); N=Nitrogen (% wb) ; P=Phosphorus (% wb); K=Potassium (% wb); NA=Not available; Ref=References.

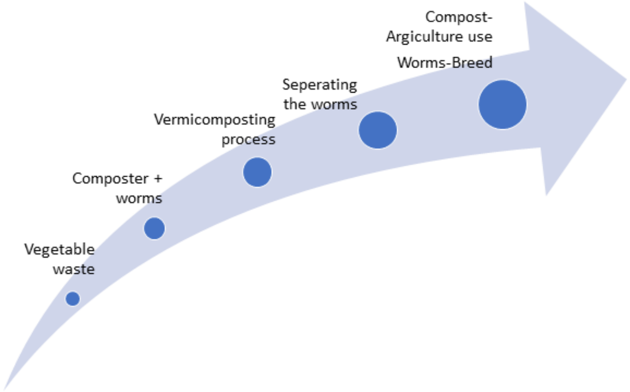

Figure 3. Vermicomposting process and worm life.

process of dewatered sewage sludge and reach satisfactory maturity. Earthworms have been found to accelerate nitrification and enhance the number and variety of ammonia-oxidizing bacteria and archaea (AOB and AOA) in VC. Mago et al. (2022) found that combined VC with cattle manure can efficiently manage cruciferous vegetable residual biomass, leading to sustainable management. Katakula et al. (2021) employing *Eisenia fetida* earthworms in VC with goat manure (GM) increased concentrations of *Olsen* phosphorus by 0.98 and 0.96 g per kg of compost, respectively, which were 113% and 109% higher than the control (100% GM). Paul et al. (2020) found by adding biochar to VC would decrease heavy metals, oxygen uptake rate (below 0.96 mg/g VS/day), pathogens (to levels < 1.1103 MPN/g dry weight) and CO_2 evolution rate (below 1 mg/g VS/day).

VC reactors have been shown to enhance operating conditions and speed up biodegradation rates (Ramprasad and Alekhya, 2021). Pottipati et al. (2022) studied in-vessel rotary drum composting (RDC) and VC for the transformation of improved nutritional content (in 27 days), nitrogen content (from 1.4% to 4.15%), and total organic carbon (TOC) (52.5%). Smart vermicompost reactors can speed up worm growth by 30% and shorten compost production time by half (Ghorbani and Sabour, 2021). Future solutions for large-scale vermicompost facilities include thermal cameras, microcontrollers, and machine learning to regulate water delivery (Balasubramani et al., 2022). VC is also being considered as a viable approach for producing high-quality nutrients for lettuce cultivation in urban farming plans (Arumugam et al., 2022).

Black soldier fly composting

Hermetia illucens, or the black soldier fly, has been used as an organic waste converter thanks to its larvae (Eq. 3) (Attiogbe et al., 2019).

$$\text{Waste} + O_2 + \text{Moisture} + \text{BSF} \ \ \text{larvae} = CO_2 + H_2O + \ldots + \text{Frass} + \text{BSF} \tag{3}$$

The black soldier fly (BSF) is a common fly belonging to the family *Stratiomyidae* (Rehman et al., 2023), and it originates in South America, with four phases of life cycle: eggs, larvae, pupas, and adults (Fig. 4) (Beyers et al., 2023). Its life cycles are influenced by population density (whether wild or domestic) and environmental conditions (temperature, humidity, light intensity, and the quality and amount of food available) (Priyambada et al., 2021).

BSFL can eliminate harmful germs like *E. coli* and *Salmonella enterica*, preventing the spread of house flies and disease (Song et al., 2021), and BSF adults are regarded as non-pathogenic (Rehman et al., 2023). BSF consumes various organic waste (as reflected in Table 5), reducing its weight and leaving behind a residue called frass, which can be used as compost and contains nutrients including phosphorus ($60 - 70\%$) and nitrogen ($30 - 50\%$) (Lindberg et al., 2022).

Attiogbe et al. (2019) stated that high mercury removal

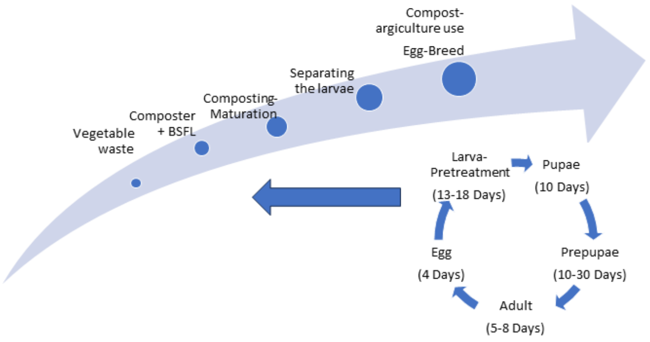

Figure 4. Black soldier fly larvae composting process and black soldier fly life cycle.

Table 5. Initial and final parameter reported in vegetable waste black soldier fly-composting related publications.

Operational condition				Material	Inoculum	Ratio	Initial condition					Compost quality									
Composting system (L)	Media	Duration (Day)	Aeration	amendment		(%)	pH	MC	C/N	EC	PS	pH	MC	C/N	EC	Opt Temp	OM Loss	PS	G.I	Nutrient	Ref.
R (57)	BSF	32	NA	Sawdust	NA	94:6	NA	71	19	13.0	< 2	6.0	31	21	0.16	36	40	NA	NA	N:2 P:3 K:1	(Wu et al., 2023)
NR	BSF	11	NA	NA	NA	100	5.3	67	NA	3.6	< 5	6.3	62	NA	0.05	NA	46	NA	NA	N:4 P:2 K:1	(Deng et al., 2022)
R (30)	BSF larvae	12	Thrice daily	Soybean curd residue: Rice husk	NA	50:40:10	6.5	75	NA	NA	NA	7.5	21	18	NA	32	60	NA	60	N:1	(Chang et al., 2022)
NR	BSF	13	NA	Chicken manure: Sawdust	NA	60:30:10	NA	71	NA	NA	NA	7.2	45	NA	NA	27	NA	NA	NA	N:2 P:1 K:2	(Attiogbe et al., 2019)
R (0.5)	BSF larvae	30	Active	NA	Digested	50:50	6.0	70	NA	NA	< 2	6.8	NA	NA	NA	30	46	NA	NA	N:7 P:8 K:2	(Fu et al., 2022)

Abbreviation: R=Reactor; NR=Non-Reactor; MC=Moisture content in wet weight basis (% wb); EC=Electrical conductivity (dS/m wb); PS=Particle size (cm); Opt Temp=Optimum temperature (° C) ; OM Loss=Organic matter loss (% wb); G.I=Germination index (%); N=Nitrogen (% wb) ; P=Phosphorus (% wb); K=Potassium (% wb); NA=Not available; Ref=References.

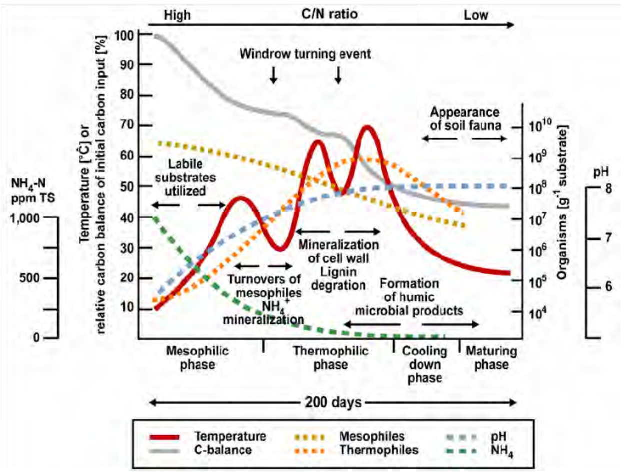

Figure 5. Different phases during composting as function of time, temperature, and further process (Fischer and Glaser, 2012).

rates (after 13 days) from high-mercury VW compost are below the EU's threshold limits (0.7 – 10 mg Hg/kg). Kabir et al.'s (2021) study found fruit waste is a better medium for larval growth (1700%) and an efficient way to decrease waste quantity entering landfills.

Deng et al. (2022) studied the effect of compost thickness and 40% carbohydrate content on survival rate and the 47.6% increase in the average weight of the BSF. They found that *Firmicutes* (95.77%), *Proteobacteria* (2.54%), *Actinobacteria* (0.74%), and *Chloroflexi* (0.6%) were the most prevalent phyla in BSF sand following BSF treatment. Fu et al. (2022) studied that BSF grown on digestates had maximum body weight growth rates (28.28% – 47.10%) and a reduction in OM (40.97% – 46.07%) that outperformed BSF reared on raw VW. Chang et al.'s (2022) study demonstrated that VW and RH co-composting with BSF had a maximum OM degradation (31.9%), rate constant (0.14 d^{-1}) and germination indices (188.6%), with 6.02 kg (from 20 kg) of mature compost, which complied with Taiwan's compost criteria.

Lindberg et al. (2022) found that adding enzyme pretreatment to BSF treatment led to a 22% greater biomass conversion in larvae. Wu et al. (2023) found that adding 4% straw increased larval growth and conversion rates, resulting in fresh frass with higher humification that also passed the organic fertilizer criterion following a 32-day secondary composting procedure. Composted frass fertilizer applications (0% to 6%) increased soil organic matter, nutrient availability, and enzyme activities. Applying 2% frass improved growth, weight, root movement, total phosphorus content, and net photosynthetic rate in maize seedlings. BSF in organic waste treatment offers increased yield and short production time, making it a promising option for sustainable waste management.

Composting

Composting is an aerobic decomposition process carried out by microorganisms. Composting offers several advantages (Table 2), including lower operating costs compared to other waste management methods and easier implementation for small communities. The system requires less labor with high skills and is very manageable. The bacteria feed on organic matter while consuming oxygen (O_2) during composting. According to Eq. 4, active composting produces a lot of heat and releases a lot of carbon dioxide (CO_2) and water vapor into the atmosphere (Yaser et al., 2022; Finore et al., 2023).

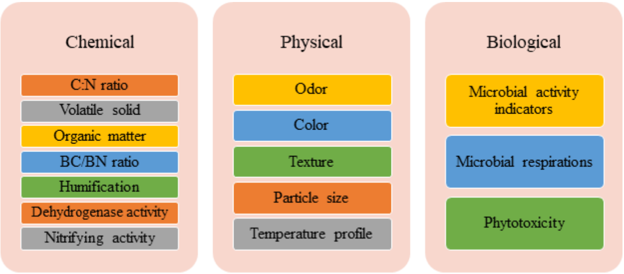

Figure 6. Maturity and stability index parameter for VW compost.

$$\text{Waste} + O_2 + \text{Aerobic microorganism} + \text{Moisture} = CO_2 + NH_3 + \text{Product} + \text{Heat} + H_2O \quad (4)$$

The CO_2 and water losses can account for as much as half the weight of the original components, significantly reducing the volume and mass of the final product. Organic materials break down into smaller molecules (polyphenols, polysaccharides, and amino acids), contributing to the formation of humic substances. The process (Fig. 5) involves mesophilic (25 – 40° C), thermophilic (40 – 65° C), cooling, and maturation (10 – 40° C) stages, with fungi and bacteria being the most prevalent microorganisms. Proper sanitization requires a defined temperature regime such as 10 days at > 55° C (with 3 turnings in between) or > 65° C for 6 days (with 1 turning). Composting can produce humic substances and contribute to the formation of humic substances (Mahapatra et al., 2022).

Composting using VW has been described by Esparza et al. (2020) in a review that is comparable to the Arvanitoyannis and Varzakas's (2008) review. While Agrawal et al. (2022) thorough critical review concluded that eight (8) important parameters influence anaerobic digestion (AD), this review will expand their explanation and provide more details on the important parameters of VW in composting, including C/N ratio, moisture content, particle size and porosity, turning frequency, temperature, pH value, electrical conductivity, and microorganisms. Table 6 depicts an overview of parameters during VW composting. Proper management and control of key parameters are crucial for successful composting operations. Temperature, additives, moisture content, aeration, and article size and porosity all influence microbial activity, temperature, and compost stability, ensuring efficient and effective composting.

C/N ratio

The optimum carbon-to-nitrogen (C/N) ratio is crucial for successful composting, as microorganisms require the right balance of carbon and nitrogen for energy (Lalremruati

Table 6. Initial and final parameter reported in vegetable waste composting-related publications.

Operational condition				Material		Ratio	Initial condition					Compost quality									
Composting system (L)	Turning frequency	Duration (Day)	Aeration	amendment	Inoculum	(%)	pH	MC	C/N	EC	PS	pH	MC	C/N	EC	Opt Temp	OM Loss	PS	G.I	Nutrient	Ref.
R (50)	Every 3 day	60	Passive	NA	NA	100	NA	67	15	NA	< 5	7.1	54	10	NA	45	53	< 5	NA	N:1	(Pandebesie et al., 2022)
R (250)	Daily	20	Active-	Soil	Baikal Effective Microorganisms	NA	6.4	NA	35	NA	< 2	7.1	NA	25	NA	55	53	< 2	190	N:1	(Sokolova et al., 2021)
R (50)	Every 3 day	60	Passive	Diaper	NA	30:70	7.9	79	20	NA	< 5	8.0	54	11	NA	43	62	< 5	NA	N:2	(Pandebesie et al., 2022)
R (500)	Daily	45	Passive	Garden	VWinoculum	10:90	6.3	72	26	2.7	< 1	7.3	54	15	0.04	71	67	< 1	94	N:2 P:5 K:9	(Mishra and Yadav, 2021)
R (2200)	NA	1	Active	Chicken manure: Rice husk	NA	30:60:10	8.5	68	NA	NA	< 2	8.1	44	NA	NA	75	NA	NA	NA	N:1 P:1	(Bian et al., 2019)
NR (300)	Weekly	95	Passive	Chicken manure: Rice husk	NA	30:30:30	4.4	84	27	5.7	NA	8.6	45	16	0.03	70	50	NA	NA	N:2 P:1 K:3	(Tratsch et al., 2019)
R (2200)	NA	1	Active	Chicken manure: Rice husk	NA	35:55:10	7.5	55	24	NA	2	8.3	26	29	NA	55	58	< 0.3	NA	N:1 P:1	(Ajmal et al., 2020)
R (300)	Twice daily	21	Active	Horse manure: Leaves	NA	77:8:15	5.7	84	27	NA	< 3	8.5	81	15	NA	40	60	< 3	NA	N:2 P:1 K:2	(Dayananda and Shilpa, 2020)
R (1)	NA	70	Passive	Sawdust	NA	62:38	3.9	72	50	8.5	< 3	7.0	40	28	0.04	NA	15	< 3	NA	N:1.4	(Ghinea and Leahu 2020)
						94:6	4.0	83	45	8.4		8.5	42	20	0.03		12			N:1.9	
						92:8	4.0	83	31	8.3		8.0	41	18	0.04		12			N:1.9	
R (100)	Daily	9	Active	Rice husk	Enzyme (Jaggery + Curd)	90:5:5	6.8	80	14	NA	< 2	7.8	18	24	NA	60	85	< 2	NA	N:1	(Murugesan and Amarnath, 2020)
R (360)	Daily	9	Passive	Leaves: Paper	Inoculum	NA	6.8	68	26	NA	< 1	6.9	50	NA	NA	61	NA	< 1	NA	NA	(Resmi and Vinod, 2022)

Abbreviation: R=Reactor; NR=Non-Reactor; MC=Moisture content in wet weight basis (% wb); EC=Electrical conductivity (dS/m wb); PS=Particle size (cm); Opt Temp=Optimum temperature (° C) ; OM Loss=Organic matter loss (% wb); G.I=Germination index (%); N=Nitrogen (% wb) ; P=Phosphorus (% wb); K=Potassium (% wb); NA=Not available; Ref=References.

and Devi, 2021). Researchers have found that the dominant range of C/N for composting vegetable waste (VW) is 25 – 30, with the highest reaching up to 50 and the lowest reaching 10 (Table 6). VW has a low C/N ratio of 17 – 20 (Pottipati et al., 2022), thus adding dry materials as bulking agents can increase the C/N ratio and facilitate composting (Rich et al., 2018).

Findings by Resmi and Vinod (2022) indicate that the presence of the anaerobic condition in 100% VW is because more moisture is present, thus the addition of bulking agents is required. Sarabhai et al. (2019) found that adjusting the C/N ratio by adding kitchen waste (KW) 1:1 VW led to more effective decomposition, reducing the C/N ratio to 23 (54% reduction). Ghinea and Leahu (2020) observed higher initial C/N ratios, exhibiting rapid carbon and nitrogen losses of 28.

Mishra and Yadav (2021) also used single-addition material of garden waste similar to Dayananda and Shilpa (2020), and the results showed the C/N ratio decreasing from 26 to 15 with a 42% reduction after 45 days of composting. In conclusion, maintaining the appropriate carbon-to-nitrogen (C/N) ratio is crucial for enhancing microbial activity, accelerating degradation, and improving compost quality. Adding bulking agents has also been found to save time and reduce costs in the composting process.

Moisture content

Moisture content (MC) during composting impacts microbial activity and degradation rate through its influence on oxygen uptake. Murshid et al. (2022) and Pottipati et al. (2022) stated that VW MC is more than 80%, so bulking agents, often fibrous materials, can help regulate high MC in VW and absorb part of the leachate (Al-Nawaiseh et al., 2021).

VW composting (in Table 6) often sees MC levels of 50 – 80% due to the inherent water content of vegetables, as suggested in the Mengqi et al.'s (2021) review. When too dry, compost decomposition slows, while exceeding 70% MC can restrict oxygen flow and encourage anaerobic conditions (Resmi and Vinod, 2022). Tratsch et al. (2019) reported a drop from an initial 85% to 55% MC (35% decreasing rate) when VW was mixed with chicken manure (CM) and rice husk (RH) and after 95 days, this further decreased to 45% (18% decreasing rate). They found that while temperature increases, it reduces moisture content.

Bian et al. (2019) reported that VW MC decreased from 87% to 55% with CM and RH, further dropping to 45% (18% decrease rate) after composting due to high temperatures, extended time, and evaporation. They also noted a sudden temperature drop during leachate production in the active thermophilic phase, slowing moisture loss. Meanwhile, Resmi and Vinod (2022) found that the initial MC of 84% in vegetables was reduced to 68% (16% decrease) with bulking agents and to 50% (34% decrease) after 85 days of composting.

The initial water loss can impede composting, requiring water addition or the use of high water-retention materials like clays, bentonite, ash, or phosphate rock, which increase water-holding capacity (Ghinea and Leahu, 2020). Conversely, eggshells have no such impact and may even hinder biological activity (Wang et al., 2021). In the composting process, controlling MC is key, given its influence on microbial activity, the rate of degradation, and oxygen uptake, thereby ensuring composting efficiency.

Particle size and porosity

Particle size (PS) as well as distribution are important in striking a good balance between surface area for microbial growth and porosity for sufficient aeration. Mengqi et al.'s (2021) review suggested that compostable materials should ideally be sized more than 2 cm, and Table 6 illustrates the dominant particle sizes obtained from various studies on vegetable waste, which are 2 cm and do not exceed 5 cm, with the lowest reaching 1 cm.

The properties of compost largely depend on its PS, with finer fractions less than 2 cm indicating better quality compost that contributes to higher maturity and cleaner compost with lower electrical conductivity (EC), sodium content (Na), C/N ratio, less glass, and impurities (Resmi and Vinod, 2022). Nevertheless, the nutrient content of this fine fraction is lower, negatively impacts aeration levels, and tends to accumulate heavy metals (Zhou et al., 2022), whereas the 2 – 10 cm fraction range is richer in nutrient content (Jakhar et al., 2022). More than 70% of the compost particles (< 5 cm) produced during the composting process can be used as compost for soil amendment, according to research by Chang et al. (2019b).

Bian et al. (2019) found that smaller particle sizes are more conducive to decomposition due to easier access for microorganisms, whereas larger particles decompose more slowly. The findings indicate that PS reduces during the composting process as a result of microbes consuming less organic waste, moisture, and other components. Particles that are relatively fine, on the other hand, condense the material and reduce porosity, as stated in Ajmal et al.'s (2020) research.

Resmi and Vinod (2022) showed that shredding waste accelerates moisture content reduction up to 10% only in 10 days, while bigger PS take 30 days to achieve the same results due to porosity. Qasim et al. (2019) found that controlling PS and porosity increases microbial activity, and an application rate higher than 20% may impede organic matter biodegradation. PS and porosity significantly enhance degradation and microbial activity, support proper aeration, and influence oxygen diffusion for efficient composting.

Aeration and turning frequency

Composting requires optimal aeration, as explained by Amrit et al. (2021). In an earlier year, a pilot-scale study conducted by Vallini et al. (1993) successfully composted market VW using a force-aerated reactor for 35 days while curing the premature product in a different reactor. However, insufficient or excessive aeration rates (AR) can cause problems such as anaerobic conditions, moisture and heat loss, and gas emissions (Amrit et al., 2021). Turning the composted material manually (Suhartini et al., 2020) or mechanically (Martínez et al., 2019), using forced aeration (Zhang et al., 2023) or through pipes (Murshid et al., 2022), are common ways to enhance aeration and microbial activity during composting. The initial conditions before composting, including the turning frequency (either passive or active), are presented in Table 6.

Qasim et al. (2019) show that composting with a high aeration rate (AR) (410 – 547 L air/kg TS/d) results in 60 – 100% more moisture and heat loss than composting with a low AR (74 – 210 L air/kg TS/d). When controlling intermittent aeration, employing the oxygen uptake rate as feedback might result in a 30% increase in oxygen consumption while using 50% less energy (Li et al., 2023). The duration of waste stabilization is reduced by increasing AR at the beginning stages of organic matter decomposition, but excessive aeration or turning might damage essential components in composting (Peng et al., 2023).

The turning frequency (TF) also affects the results obtained, but using bulking agents might cut down on the costs of pile turning or forced aeration (Balaganesh et al., 2022). Therefore, optimizing the TF regime is required to maintain the necessary nutrients or to accomplish other objectives, such as increased cleanliness (pathogen reduction) (Ma et al., 2022). The TF is also linked to some physio-chemical variables that could serve as indicators of compost maturity (Chang et al., 2019b). Ugak et al. (2022) studies show the TF every 3 days has a higher OM loss for in-vessel composting of VW and food waste.

Temperature

Composting temperature is typically managed through factors like pile conditions (C/N ratio, moisture, porosity) (Walling and Vaneeckhaute, 2021), pile configuration (depth, shape), and oxygen levels (ventilation or aeration) (Chen et al., 2020). Although studies have shown that thermophilic composting achieves the highest degradation rates (Zhan et al., 2022), some have discovered that mesophilic composting can yield higher organic breakdown rates.

Pathogen destruction is enhanced, and temperature increases were observed with biochar, mineral additives, polymer additives (zeolite, jaggery, and polyethylene glycol), and biological or organic additives during the composting of various wastes (Kumar et al., 2020; Murugesan and Amarnath, 2020). These additives likely enhance microbial biomass and activity, leading to temperature changes and shorter composting times at doses under 5%.

Ajmal et al. (2020) demonstrated that applying a temperature of 65° C for 18 h optimizes the degradation and mineralization rates of in-vessel composting of agricultural wastes. Non-dominant microbes in a commercial consortium impact compost microbial composition more than dominant ones. Cao et al. (2022) conducted a lab-scale experiment on composting with membrane-covered technology. It increased compost pile temperature, accelerated organic matter degradation, and achieved earlier (2 – 9 days) germination indexes (50% – 80%) compared to the control sample.

Finore et al. (2023) stated that the efficiency of composting is temperature, and as a prolongation of the thermophilic phase can improve the quality of compost itself, extracellular enzymes secreted by microorganisms have a fundamental role, being associated with the increase in temperature. In conclusion, proper management of temperature, whether in the thermophilic or mesophilic range and with or without additives, is essential for effective decomposition and pathogen destruction.

pH value and electrical conductivity

The optimal pH range for composting is more than 6, which supports microbial activity, as stated in Mengqi et al.'s (2021) review. Table 6 indicates dominant pH values between 6 – 7 during the initial composting of VW, which may reach 5 or 8 depending on the bulking material. pH tends to approach neutrality around 7 after composting. Jain and Kalamdhad (2019) observed a rapid pH increase from 6.8 to 7.1 during the thermophilic phase, reaching 7.6 at the end of 20 days of composting. pH decreases initially and increases later in composting, impacting microbial activities (Ajaweed et al., 2022). Additives can be incorporated to raise pH and improve the composting of acidic substrates like food waste (Ghinea and Leahu, 2020). Bulking agents like bagasse, paper, peanut shell, sawdust, and Ca-bentonite can also raise pH during composting (Tabrika et al., 2021), similar to fly ash or lime addition.

Lower pH can help reduce nitrogen loss through ammonia volatilization (Sokolova et al., 2021). Elemental sulfur addition lowers pH in poultry manure composting by producing H_2SO_4 and increasing H^+ ion concentration (Barthod et al., 2018). Inoculum consortium addition increases pH (from 4.3 to 6.3) during organic waste composting, possibly through enhanced biological activity and acid degradation (Kaur and Katyal, 2021).

Electrical conductivity (EC) is a valuable tool for understanding biochemical transformations in composting (Ajaweed et al., 2022). The ideal EC range for mature compost is typically considered to be below 0.02 dS/m (Mengqi et al., 2021), ensuring an appropriate level of nutrient availability and microbial activity while avoiding excessive salinity or leaching of nutrients. Table 6 shows that in the initial phase of composting VW, the EC values vary from 0.02 to 0.09 dS/m and might reach 4 dS/m depending on the bulking material added.

Composting boosts, the production of inorganic compounds and the discharge of ions, leading to rapid increases in EC (0.021 to 0.035 dS/m) as temperatures rise (Jain and Kalamdhad, 2019) similar to Zahrim et al. (2021) study (350 000 to 900 000 dS/m). Soluble components released during decomposition and mineralization of organic compounds cause an initial increase in conductivity, which is then maintained until the final EC reached 0.0087 dS/m. Composting matrix EC can be minimized through the production of volatile fatty acids and the conversion of NH_4^+ to NH_3 during organic biodegradation (Gao et al., 2022).

Additives

Recent research has focused on improving composting through various supplements, including microbial cultures, additives, activators, biochar, and microbial inoculation. These supplements can alter the compost's bulk density, temperature, pH profiles, carbon and nitrogen content, cellulase and dehydrogenase activity, and mineral nutrients (Chang et al., 2020).

An activator stimulates the composting process by providing additional nitrogen, with manure being the primary choice, which could reduce the composting time (Al-suhaibani et al., 2021). Al-suhaibani et al. (2021) stated that it is important to select from a variety of activators as it can affect the maturation process. Ouattara et al. (2022) and Radwan and Ashour's (2019) study show that compost matures after five months with the use of chicken manure (CM) as an organic activator, compared to other treatments like cattle manure or a mixture of sheep and camel manure.

Biochar, produced from dead leaves and cuttings, has been shown to promote the fermentation process of compost (Chen et al., 2020). Zhang et al. (2021) reported that co-composting CM with VW and biochar reduced ammonia (NH_3) emissions by $50-82\%$, stabilized heavy metals, and enhanced the microbial degradation of 17β-estradiol (E2). Additionally, biochar showed a removal rate ($k = 0.1582$) and a reduction in total coliform from 3.68 to 1.06 log10 CFU g^{-1} thus reducing the presence of antibiotic-resistant bacteria and decreasing heavy metal concentrations in composted CM, VW, and corn stalks (Ezugworie et al., 2022).

Recent research has shifted towards discovering novel supplements that enhance the composting process. Musa et al. (2020) found higher ammonium nitrogen release (77.98, 64.09, and 64.35%) and cumulative nitrogen availability with the application of homemade indigenous microorganisms (IMO), emphasizing the role of microbial inoculums in enhancing nutrient transformation and availability during composting.

Asadu et al. (2020) used actinomycetes as microbial inoculums in in-vessel composting and observed the highest cellulose degradation (21.6%) and nitrogen mineralization (6.87%) with Rothia spp. Murugesan and Amarnath (2020) achieved significant reductions in organic degradation (42%), composting period (from 45 to 9 days), size, and volume (from 0.012 m^3 to 0.003 m^3) with NPK levels of 0.9%, 0.5%, and 1.0%, respectively, in VW composting by using pre-cultured seed inoculums.

Research has shown that the use of microbial inoculants and metabolic regulators can enhance composting processes efficiency, safety, and maturity. Wang et al. (2021) stated that ATP supplementation reduces CO_2 emissions and increases humic acid content, while MA accelerates OM degradation. Kaur and Katyal (2021) evaluated different microbial inoculants in paddy straw and VW composting, finding that the fungal bacterial consortium produced the best compost quality parameters with pH (8.19), electrical conductivity (1.52 dS/m), moisture (45%), C:N ratio (15.66), and germination index (121.29%).

Ajmal et al. (2020) evaluated the effects of microbial inoculums added at different stages of Taguchi technique composting and found that the addition of inoculums at specific stages resulted in improved total nutrients ($9.9 \pm 0.5\%$ of N^+ K_2O^+ P_2O_5), including reduced carbon content (50%), increased nitrogen content (98% and 79%), and a lower C/N ratio (26%). Ameen and Al-Homaidan (2020) found that composting VW with fungal (*Penicillium vinaceum* and *Eupenicillium hirayama*) inoculation improved compost quality and plant vigor, as well as enhanced the disease-defense ability of the seeds. Similarly, in-situ composting with 300 tons/hectare of exogenous microbial agents, as studied by Yun et al. (2021), enhanced compost maturity, shortened composting time, and increased microbiome (*Proteobacteria*, *Firmicutes*, and *Ascomycota*) diversity.

Specific cold-adapted and heat-adapted strains improved VW composting at low temperatures, increasing thermophilic temperatures (±2° C), germination index (104.7%), humic acid to fulvic acid ratio (62.0%), and enzymatic activities (Shi et al., 2022). Traditionally available microbial inoculants expedited the composting of VW, resulting in improved degradation rates, a high germination index ($85-97\%$), an extended thermophilic phase duration ($3-8$ days), a fecal population below 1000, and optimal NPK values with a low C/N ratio ($14.5-20.2$) (Mishra and Yadav, 2021).

Haouas et al. (2021), who identified beneficial bacteria in VW composting, including *Alcaligenes aquatilis* GTE53 which is desirable for solubilizing inorganic phosphate (162.8 and 247.4 $mg \cdot mL^{-1}$), atmospheric nitrogen fixation, phenol degradation (99.2%), and pathogen inactivation (*Escherichia coli*, *Streptococcus sp.*, *Salmonella sp.*, and *Fusarium oxysporum albedinis*). In conclusion, these key parameters greatly impact the composting process and the production of high-quality compost. Multi-stage inoculation and substrate pre-treatment offer benefits but may complicate large-scale operations. Reducing odor and greenhouse gas emissions remains a challenge without a single effective additive.

Technology development

Research on composting technology has been significant, with Sokač et al. (2022) highlighting the use of different methods such as central composite, full factorial, and Box-Behnken designs in composting analysis over the past 15 years. However, most optimization procedures have relied on the one-factor-at-a-time method. Bian et al. (2019) have explored VW composting with CM and RH, similar to Tabrika et al. (2021) studies where the addition of sheep manure and olive pumice has improved the process.

A recent study by Wu et al. (2023) found that a combined hydrothermal optimized at 165° C for 45 minutes and 20 hours of biological treatment using Weissella bacteria effectively recovered nutrients, yielding 93.03 g of VW juice with compliant concentrations of organic matter (1.45%), primary nutrients (0.51%), and toxic components, suitable for liquid organic fertilizer. However, challenges remain, and further research is needed to develop innovative composting technologies that reduce environmental impact and produce high-quality compost according to the maturity index.

Maturity index

Sayara et al. (2020) identified two key characteristics determining compost quality: maturity and stability. Maturity is crucial for agricultural purposes, considering its impact on plant growth and phytotoxicity (Sarsaiya et al., 2019), while stability refers to the resistance of organic matter against extensive biodegradation or microbiological activity (Cerda et al., 2018). Parameters like temperature, C/N, and dissolved organic carbon are used for stability analysis, while seed germination and the Solvita compost emission test are used for maturity analysis (Thompson et al., 2002). Achieving stability or maturity is essential for safe soil application, preventing the presence of harmful pathogens (Mahapatra et al., 2022). Compost quality, as stated by Mahapatra et al. (2022) and Sayara et al. (2020) encompasses physical, chemical, and biological characteristics (Fig. 6).

Researchers have studied the relationship between microorganisms and physicochemical parameters, revealing dynamic changes in microbial communities during composting (Balaganesh et al., 2022). An increase in microorganism count indicates a more efficient biodegradation process, while a rapid decrease signifies compost maturity and stability (Ghinea and Leahu, 2020). Zhan et al. (2022) analyzed core bacterial communities in diverse composts and revealed distinct interactions, with Thermobifida emerging as a ubiquitous core bacterium, and structural equation modeling (SEM) further emphasized the significant positive and direct influence ($> 80\%$) of core bacteria on composting maturity (Zhang et al., 2023).

Maturity extends beyond biodegradation to include phytotoxic substances and suitability for plant growth (Yang et al., 2021). Despite ongoing research, there is a need for universally recognized indicators for measuring compost maturity. Several indicators have been employed, as illustrated in Table 7, and this review serves as a valuable resource for researchers in their pursuit of a standardized maturity index, facilitating composting practices, and quality of compost.

4. Compost and leachate application

The outcome of composting VW is an abundance of compost and leachate with promising future usage. Rynk (1992) stated that potential buyers (landscapers, farmers, commercial nurseries, or developers) of compost could be using it for a secondary purpose (replace topsoil, chemical fertilizer, or peat moss) besides soil fertility restoration and waste recovery.

Pellejero et al. (2017) concluded that the addition of compost to soils has a positive effect on the fresh weight of the plant, recommending the use of doses of 6 kg m^{-2}, while a dose of 8 kg m^{-2} could replace the use of chemical fertilizers such as urea. Haouas et al. (2021) use *P. ultimum* on cucumber in comparison to on-farm green composts made from VW, *Fusarium oxysporum f. sp. basilici* on basil, and *Sclerotinia sclerotiorum* on lettuce, showing results where compost supplementation improves soil structure, nutrient availability, water retention, and microbial activity while suppressing soil-borne pathogens (Corato, 2020). However, immature compost can lead to severe health issues (Corato, 2020) and phytotoxicity for plants (Ezugworie et al., 2022).

Leachates are liquid effluents from waste moisture and degradation products (Costa et al., 2019). Compost leachate (VWL) is generated during composting due to its high moisture content (Sanadi et al., 2021) and VW has 80% of it (Murshid et al., 2022), which is often discharged into wastewater treatment plants or released into the environment during rainfall. Treating VWL is costly due to its high nutrient and organic pollutant content (Bolyard et al., 2019). Limited information exists on the reuse of VWL as organic liquid fertilizer, but it is a low-cost liquid bio-fertilizer that enhances composting and is a sustainable "closed-loop nutrient" technology.

Sall et al. (2019) composting 6000 kg of VW generated about 400 L of leachate; however, applying raw or saturated VWL can disrupt plant growth and nutrient absorption. Dilution is a simple strategy to reduce organic carbon, preserve soil water storage, and maintain cation exchange capacity (Makkar et al., 2017). Dilution rates (DR) should be determined based on nutrient and pollutant limits for vegetable crops, such as the FAO and Malaysian Water Standards. Dilute VWL should adhere to threshold values (COD, micro-, and macronutrients) set by Malaysian Water Standards to avoid organic pollutant accumulation and ensure nutrient balance (Muhmood et al., 2019). Combining conventional and advanced treatments can remove contaminants from VW leachate, effectively recover nutrients, and produce fertilizer that meets regulatory standards (Nenciu et al., 2022).

5. Economic evaluation and benefit to users

Waste management strategies are crucial in transitioning to a circular economy (Närvänen et al., 2022), eradicating waste through prevention, regenerating biomaterials, and restoring technological materials (Malenica and Bhat, 2020). Studies have shown that converting VW into bio-compost (Cafiero et al., 2020), biodegradable detergents (Boni et al., 2022), and compost (Arumugam et al., 2022) can significantly outweigh the environmental impacts of waste treatment while contributing to the economy. The recycling rate in Malaysia reached 31.67% in 2021, and it is expected to increase at least 2% annually (Chin et al., 2022). 40% of the recycling rate could shrink by approximately 2.74×10^8 tons of CO_2 eq annually. The European Union (Lindberg et al., 2022) has proposed a circular economy monitoring framework to reduce environmental burdens and resource scarcity. Circular economy initiatives aim to halve organic waste at the retailer or consumer level by 2030, creating new businesses and job opportunities (Facchini et al., 2023).

As part of the Twelfth Malaysia Plan (RMK-12, 2021 – 2025), circular economy principles are being embraced, including the development of a composting site in Kundasang, a major vegetable producer in Wang et al. (2022) stated that rural areas with scattered living conditions and low residence density are conducive to the implementation of composting technology. However, there is a lack of sufficient data on compost from organic waste, especially in rural areas (Huang et al., 2023). Aerobic composting is a standard technology to treat these organic wastes in-situ. The shift in waste management practices is driven by the goal of reducing (Keng et al., 2020), recycling, and reusing materials throughout the production and consumption chain (Chin et al., 2022).

Aerobic composting in rural areas is a sustainable and decentralized approach to managing waste and generating profitable end-products, contributing to economic growth (Wang et al., 2022). This approach aims to manage waste effectively while generating profitable end-products, contributing to economic growth, which is particularly important in light of the COVID-19 pandemic (Ooi et al., 2021). Ac-

Table 7. Established standards for maturity index to define mature compost.

Factor	SIRIM MS1529 (Malaysia)	SNI 19-7030-2004 (Indonesia)	86/ 278/EEC (Europe)	NY 525–2021 (China)	AS 4454-2012 (Australian)
Physical Properties					
pH	NA	6.8 – 7.5	5.5 – 8.0	5.5 – 8.5	5.5 – 7.0
Moisture content, %	NA	< 50	< 75	< 30	NA
Foreign matter	NA	0.55 < 25 mm, $< 1.5\%$	max 0.5% > 2 mm	NA	$< 0.5\%$ for > 2 mm fraction
Conductivity, mS.cm^{-1}	NA	NA	NA	< 4	NA
Temperature, ° C	NA	NA	NA	55	> 55 for atleast 3 days
Organic matter, %	NA	NA	> 20	45	> 15
Volatile Solid, %	NA	27 – 58	NA	NA	NA
Chemical Properties					
C/N ratio	< 25	10 – 20	25 – 50	10 – 15	NA
Carbon (C), %	NA	NA	30 – 40	NA	NA
Nitrogen (N), %	> 1.5	0.4	> 0.6	NA	< 0.08
Phosphorus (P), %	NA	0.1	17.0	NA	< 0.08
Potassium (K), %	NA	0.2	12.0	NA	< 0.15
Total nutrient (NPK), %	NA	NA	NA	> 5.0	NA
Lead (Pb), mg/kg	300	NA	15	< 50	NA
Arsenic (As), mg/kg	50	NA	2.0	< 15	NA
Chromium (Cr), mg/kg	200	NA	NA	< 150	NA
Nickel (Ni), mg/kg	150	NA	21	NA	NA
Cadmium (Cd), mg/kg	5	NA	1.9	3.0	NA
Mercury (Hg), mg/kg	2	NA	0.85	< 2.0	NA
Biological Properties					
Germination index, %	NA	NA	> 80	> 80	NA
Plant Growth Test	NA	NA	25% & 50% compost in standard soil media; Barley seeds or Cress seeds must pass $> 90\%$	NA	100% Leached compost; radish Seeds; must pass at $> 60\%$.
PAH-polycyclic aromatic hydrocarbons	NA	NA	6	NA	NA
Salmonella sp.	Absent	NA	< 3 MPN/4g	NA	NA
E. coli (cfu/g)	< 10	NA	NA	NA	NA
Pseudomonas aeruginosa (cfu/g)	< 10	NA	NA	NA	NA
Fecal coliforms	NA	NA	< 1000 MPN	NA	NA

Abbreviation: NA=Not available; MPN=Most probable number.

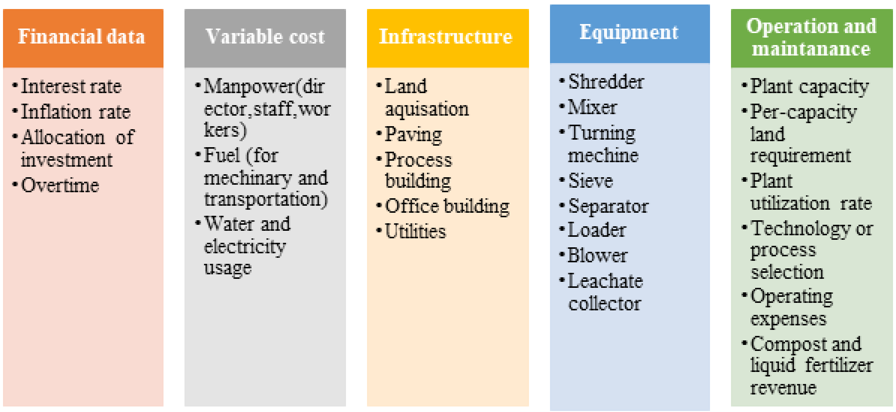

Figure 7. Cost-benefit analysis inventory data for VW composting.

cording to Yong et al. (2021), the average cost in Malaysia for municipal solid waste collection, transport, and landfill disposal is MYR 66/ton/day, MYR 40/ton/day, and MYR 42/ton/day, respectively. The total cost for landfilling is RM 148/ton. Renewable electricity generated from waste is sold to Tenaga National Berhad (TNB) at a rate of RM 0.3997/kWh, while organic fertilizer is sold at MYR 515/ton according to the Sustainable Energy Development Authority (SEDA).

The savings from landfilling are the same as the cost of landfill disposal, while the savings from leachate treatment are MYR 5.69/m^3 via a traditional wastewater treatment system (Yong et al., 2021). A composting farm in Kempas, Johor, converts 3 tons/day of organic waste into 1.2 tons/day of fertilizer (Ooi et al., 2021). The production of vegetable waste compost (VWC) and vegetable waste leachate fertilizer (VWLF) can be commercialized, promoting circular economy principles. Developing products that enhance agricultural productivity and soil conservation is crucial, as soil is a non-renewable resource. Methods such as nitrogen conservation (Awasthi et al., 2019), nutrient-rich feedstock supplementation, natural nutrient addition, and microorganism inoculation (Murugesan and Amarnath, 2020) can increase the nutrient concentration in compost, making it more beneficial for plant growth.

Thomson et al. (2022) stated that composting systems include windrows (Al-Nawaiseh et al., 2021), aerated static piles (AES), enclosed channels, forced aeration composting (FC) (Murshid et al., 2022), and hyper-thermophilic composting (Nenciu et al., 2022) Al-Nawaiseh. In rural areas, these technologies are used Wang et al. (2022), with state composting being more profitable at smaller scales and preferred for decentralized treatment (Lin et al., 2019). Static accumulation with forced ventilation is commonly used for larger (more than 1 ton of waste per 5-hectare area) on-farm systems producing significant organic waste.

The choice of composting technology depends on factors such as feedstock volumes, matrix types, and existing farm facilities (Silva et al., 2022). Large-scale (< 100 tons/day) composting has higher maintenance costs due to complex mechanical pre-processing technologies (Torrijos et al., 2021), resulting in low-quality compost. Chin et al. (2022) implemented a pilot-scale composting plant allowed a minimal return of 6 years with a capital and operation cost of 810,000 MYR/year and 23,000 MYR/year in revenue. A circular economy aims to maximize product utilization before disposal through anaerobic digestion. However, composting faces economic hurdles, including the lack of a market platform for selling compost. As stated by Boni et al. (2022), market acceptance depends on factors such as price, quality, consistency, and freedom from contaminants.

Operation and maintenance costs vary based on the chosen process, with smaller plants (> 5 tons/day) offering higher prices due to better quality and retail pricing (Liu et al., 2022). Larger plants handle mixed waste, resulting in lower market prices. Pelletizing compost outputs and implementing effective marketing strategies can increase value and demand. A circular economy aims to maximize product utilization before disposal (Chatterjee and Mazumder, 2020). Income sources vary among composting plants of different scales, but all generate revenue from selling compost products. Composting plant operational and maintenance costs vary based on the chosen process (Fig. 7) (Ooi et al., 2021). Operational costs include salaries for managers, technicians, and workers. It is essential to have a thorough understanding of the advantages and risks from diverse perspectives.

6. Final consideration and future direction

In conclusion, VW has been attracting researchers for decades, with bio-processing being the first step towards sustainable waste treatment. Between 2013 and January 2023 (Fig.2), anaerobic digestion and composting surpassed 2000 publications, while vermicomposting and black soldier fly composting decreased since 2014, possibly due to a shift in interest in beneficial bioprocessing. This pioneering review discusses composting as a cost-effective (for MYR 1.40/kg) technique (shown in Table 2) for rural areas, demonstrating its sustainability in handling organic waste and producing beneficial products.

VW composting is a sustainable approach to handling organic waste, reducing landfill usage, and producing beneficial products. However, the review also identified several challenges, such as optimal decomposition, odor or pest issues, and understanding ideal conditions for composting. Table 6 summarizes the dominant initial parameters, including the C/N ratio (between 25 and 30 with the highest reaching up to 50 and the lowest reaching 10), moisture content (between 50% and 80%), pH value (between 6 and 7 and may reach 5 or 8) and electrical conductivity (0.02 to 0.09 dS/m and might reach 4 dS/m). Advancements in composting through additives or technological advancements can enhance compost quality. Activators, multi-stage inoculation, and substrate pretreatment are common methods that increase microbial activities, leading to degradation. Exploring innovative technologies is crucial to maximizing VW's potential and minimizing its environmental impact. The maturity of the produced product is not generally possible, and research on finding a unity maturity index is limited. However, this review contributes for the first time to providing resourceful information (Table 7), featuring selected maturity parameters from several published maturity indexes. To our knowledge, studies that adopt leachate as an organic liquid fertilizer are not widely reported or very limited. Further research is needed to explore the use of VW leachate as an organic liquid fertilizer and develop fertilizer formulations that meet market requirements and regulatory standards.

VW composting contributes to the circular economy by closing the nutrient loop by recycling VW and transforming it into compost, which supports future plant growth. Local community engagement, government support, and effective policies are essential for successful waste management practices. Advancements in technology and community-level composting offer sustainable, energy-efficient treatment methods with a positive impact on society and the environment. As a result, this review can help to ensure that the idea is a sustainable and viable decision for the future.

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Ethical approval

This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions

All authors contributed equally in design the main sample, measure all the processes and also prepare the text.

Availability of data and materials

Data in this manuscript are available by request from the corresponding author.

Conflict of Interests

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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