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ORIGINAL PAPER

Physicochemical changes and emissions impact during co-composting of grease trap solid waste and rice husk

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Abstract

Despite the challenges encountered in grease trap solid waste (GTSW) composting reported in previous studies, a new composting strategy to utilise GTSW effectively was not developed yet. Therefore, this study proposed co-composting GTSW with rice husk and aimed to investigate the physicochemical properties changes, gaseous emission and biocompost quality of GTSW-rice husk co-composting. The process was conducted in 120 L in-vessel composting reactor at 30:1 initial C/N ratio, 60% (v/w) initial moisture content and turning frequency of one to three times a week. Results showed that GTSW-rice husk co-composting reached maturity in 70 days. During thermophilic phase, a temperature of 40–50 °C was sustained for 46–47 days, oxygen level was relatively low but maintained above zero, and methane was found below the detection limit. Active composting led moisture content and C/N ratio decreased from 60 and 63% to 47–53% (v/w) and 30:1–32:1 to 21:1–23:1, whereas pH and EC increased from 4.9–5.9 to 7.8–8.0 and 292–400 µS/cm to 1050–1240 µS/cm, attributing to microbial decomposition of organic matter. A significant positive association ($p < 0.01$) was found between moisture and carbon, moisture and C/N ratio, pH and EC, carbon and C/N ratio. The final biocompost produced complied with U.S. EPA compost standard, being nutritious and non-phytotoxic. However, phosphorus and potassium contents of biocompost needed enhancement before application. This study could serve as a basis to reshape GTSW management into a sustainable operation.

Keywords Grease trap waste · Co-composting · Biomass utilisation · Gaseous emission · Circular economy

Introduction

Grease trap waste (GTW) was the waste collected by grease trap, a plumbing device connected to kitchen sink functioning as to trap fats, oil and grease (FOG) and solid food residue, preventing them from flowing into the sewerage system along with wastewater and caused blockage. It consisted of three main components, FOG, wastewater and solid residue. Inadequate grease trap maintenance by food premises operators was found causing FOG and solid residue to escape into sewerage system and led to sewer pipe blockages. This has been a worldwide concern as the blockages not only caused sanitary sewers and manholes overflow, but also polluted clean water bodies, threatening environmental and public health (Povera 2020; Aghdam et al. 2023; Yusuf et al. 2023). To prevent sewer pipe clogging and its subsequent cascade of negative impacts from happening, most countries' municipalities developed strategies to promote responsible GTW management practices within food premises, including Malaysia.

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According to Malaysia's current GTW management strategies, FOG was collected and used as a raw material for biodiesel production, however, the solid residue was being disposed to landfill after collection (Lee et al. 2025). Notably, the potential of GTW's solid fraction has not been explored, and no industry has developed strategy to valorise it yet. While financial incentives upon gathering FOG encouraged food premises operators to properly handle FOG for biodiesel production, the lack of comparable incentives for solid residue disposal hindered its effective management. Apart from that, landfilling waste posed significant environmental and human health risks despite being a widely use solid waste management practice. These risks included greenhouse gas emissions, toxic gas release, leachate generation and breeding of disease-carrying vectors (Abubakar et al. 2022). Carbon dioxide (40–50%) and methane (50–60%) were the major greenhouse gases released from the decomposition of waste dumped in landfills. Due to their heat trapping ability, their generation raised the atmospheric temperature, leading to global warming and eventually climate change (Ramprasad et al. 2022; Siddiqua et al. 2022). With the growing concerns on climate change, sustainable approaches should be developed to repurpose GTW's solid fraction, transforming it into a valuable resource and diverting it from landfill disposal. Hereinafter, the solid fraction of GTW would be identified as grease trap solid waste (GTSW).

Composting is a recognised environmental-friendly approach that has been reshaping the management of various solid organic wastes by converting it into a usable product. This technology not only mitigated environmental harm and reduced greenhouse gas emission, but also allowed the nutrients from the waste to be recycled to the land, supporting circular economy for sustainable development (Li et al. 2023; Nordahl et al. 2023). To date, there are limited studies researched on utilising GTSW as feedstock in biocompost production. In fact, these existing studies used FOG layer and solid fraction of GTW in combined form as one of the feedstocks in their co-composting study (Lemus et al. 2004; Belyaeva and Haynes 2010; Rojas-Vargas et al. 2022; Chitthaluri and Venkateswara Rao 2023). These four studies added co-substrates such as yard trimmings, poultry manure, food waste, grass clipping waste or vegetable waste to FOG + GTSW mixture and performed co-composting because FOG + GTSW mixture contained high carbon content, exceeding the desirable carbon to nitrogen (C/N) ratio to initiate composting (25:1–35:1) (Azis et al. 2023). Chitthaluri and Venkateswara Rao (2023) reported that FOG + GTSW mixture employed in their studies contained a higher carbon content (99.14%) than grass clipping waste (16.72%) and vegetable waste (72.97%).

Although these studies demonstrated that the co-composting process of FOG + GTSW mixture with co-substrates could be performed and established temperature of more than 50 °C during thermophilic phase, the presence of FOG was found affecting composting efficiency and final biocompost quality. Lemus et al. (2004) found that adding FOG + GTSW mixture to food waste decreased organic matter degradation rate when the overall mixture's lipid content exceeded 5% as the increasing lipid content reduced the porosity of composting mixture. In addition, Belyaeva and Haynes (2010) also reported that the presence of FOG interfered the decomposition of other organic matter such as carbohydrates and proteins. This is because FOG was more easily degradable than other organic materials, its presence diverted the degradation focus to FOG, reducing the microbial activity involved in degradation of carbohydrate and protein- rich organic materials and inhibited humus formation during composting (Liu et al. 2023). Considering the challenges associated with including GTW's FOG in composting, a new composting strategy should be developed to utilise GTSW effectively without FOG.

Preliminary investigations of GTSW conducted prior to this study found that utilising GTSW solely might not be ideal for efficient composting due to its relatively high moisture content (70–80%), low C/N ratio (20:1–22:1), and low porosity. Incorporating additional feedstocks to GTSW was necessitated to initiate composting. Co-composting multiple feedstocks with complementary properties was also preferable than single feedstock composting as it was known to enhance composting performance by improving the overall physicochemical properties and nutrient composition of feedstock mixture (Aydin Temel 2023). Rice husk was one of the renowned feedstocks used as co-substrate in composting, especially during the composting of moist, compact and low C/N ratio feedstocks. This is because not only its naturally low moisture content could balance overall mixture's moisture level, but also its larger particle size and highly porous structure could provide structural support to feedstock mixture, increasing its porosity and improved aeration (Aydin Temel et al. 2018; Duan et al. 2021). Despite being utilised as co-substrate in various composting studies, incorporating rice husk into GTSW composting has not been explored yet. Given that co-composting GTSW with rice husk demonstrated the potential of offering a promising alternative to current GTSW management practice, this study investigated the physicochemical properties changes, gaseous emission and final biocompost quality of co-composting GTSW with rice husk.

In this study, a 120 L in-vessel composting system was first designed and constructed. Co-composting was then performed in the reactor at initial C/N ratio of 30:1 and 60% (v/w) initial moisture content at Universiti Putra Malaysia (UPM) between April–September 2023. The physicochemical parameters, carbon dioxide and methane emitted were monitored throughout composting. The initial mixture and matured biocompost were then characterised based on their physical and physicochemical properties. Results from this study would provide a valuable insight into the efficiency, stability and final product quality of GTSW co-composting with rice husk. In this paper, the information about the physicochemical parameters changes and gaseous emission occurred during co-composting of GTSW and rice husk as well as their product's characteristics are reported for the first time.

Materials and methods

Feedstock preparation

GTSW was obtained from local restaurants situated in Seri Kembangan, Malaysia. To collect large amount of GTSW, restaurants operating for a minimum of 12 h/day, adopting both a la carta and cafeteria serving styles, and using underground grease interceptor were selected (Lee et al. 2025). As GTSW sedimented in grease trap, the entire content of grease trap was collected by tank truck and separated gravitationally in containers for two days. After that, the FOG and wastewater were removed from the containers using extraction pump. GTSW was then subjected to dewatering by laying it on a sieve to drain out excess wastewater for 18 h before using it in composting. From collecting GTSW to using it in composting, it was done within four days consecutively. Rice husk was obtained from local rice processing mill located in Malacca, Malaysia. The characteristics of GTSW and rice husk used in this study were shown in Table 1.

Table 1 Characteristics of GTSW and rice husk

Parameter[1]	GTSW	Rice husk
pH	4.39–5.55	6.12–6.14
Electrical conductivity, EC (uS/cm)	340.21–488.59	447.57–532.43
Moisture (%)	74.65–83.50	10.26–14.85
Ash (%)	2.47–6.70	11.93–13.27
Total solid, TS (g/kg wet sample)	165.00–292.21	859.20–907.64
Volatile solid, VS (g/kg wet sample)	140.30–235.58	727.42–782.59
Carbon, C (%)	54.37–58.85	39.80–40.00
Nitrogen, N (%)	2.55–2.73	0.81–0.84
Hydrogen, H (%)	9.14–9.34	5.38–5.41
Sulphur, S (%)	0.43–0.67	0.00[2]
C/N ratio	20.00–23.00	47.00–49.00
Zinc, Zn (mg/kg)	9.50–11.64	2.43–2.76
Manganese, Mn (mg/kg)	1.54–2.76	9.30–9.66
Arsenic, As (mg/kg)	0.22–0.39	0.00–0.20
Cadmium, Cd (mg/kg)	0.00[2]	0.00[2]
Chromium, Cr (mg/kg)	1.65–2.96	0.00[2]
Copper, Cu (mg/kg)	2.10–3.35	0.00[2]–0.20
Lead, Pd (mg/kg)	0.44–0.79	0.00[2]–0.20
Nickel, Ni (mg/kg)	0.55–0.99	0.00[2]–0.20
Mercury, Hg (mg/kg)	0.11–0.20	0.00[2]

[1]All percentages, concentrations, pH and EC are by dry weight basis, except moisture, ash, TS and VS were measured using fresh sample

[2]A value of zero was recorded when the concentration was below the detection limit

Composting setup

A pilot scale in-vessel composting system was designed and constructed for the composting process as shown in Fig. 1. The system consisted of a closed reactor, an air supply tube and an air pump. The composting reactor has an operating capacity of 120 L and was positioned horizontally throughout composting. It was wrapped with a heat insulator formed by a thick layer of plastic bubble wrap and its opening was covered with a lid to facilitate heat trapping and reduce heat loss from the pile throughout composting. The air supply tube (32 mm in diameter) was punctured with holes of 3 mm in diameter at certain intervals and connected to the air pump (HP-40, HiBlow, United States). The tube was inserted into the composting mixture through the lid of reactor to supply aeration for 15 min, at 40 L/min in every two hours.

Composting was performed twice based on the method as described by Baharuddin et al. (2010) with slight modification. It was carried out at Biorefinery Complex, Faculty of Biotechnology and Biomolecular Science (FBSB), UPM (2.99°N, 101.71°E). The composting mixture was retained in the reactor until it reached maturity. To begin the composting process, the C/N ratio of each raw material was first determined. Then, the amount of respective biomass needed for composting at initial C/N ratio of 30:1 was calculated using Eq. 1 (Suhartini et al. 2020):

$$R = \frac{\left(R_1 x Q_1\right) + \left(R_2 x Q_2\right)}{\left(Q_1 + Q_2\right)} \quad (1)$$

where R = The ideal C/N ratio for composting feedstock mixture, R_n = C/N ratio of material n, Q_n = Mass of material n in wet weight (kg).

In this study, the raw materials were prepared at a total amount of 60 kg. When the mixture was loaded and mixed in the reactor, air supply tube connected to air pump was then inserted horizontally into composting mixture. Compost turning was conducted one to three times a week by rotating the reactor to aerate the pile and homogenise the mixture. The initial moisture content of composting mixture was adjusted using rainwater to approximately 60% (v/w) by using Eq. 2 (Suhartini et al. 2020):

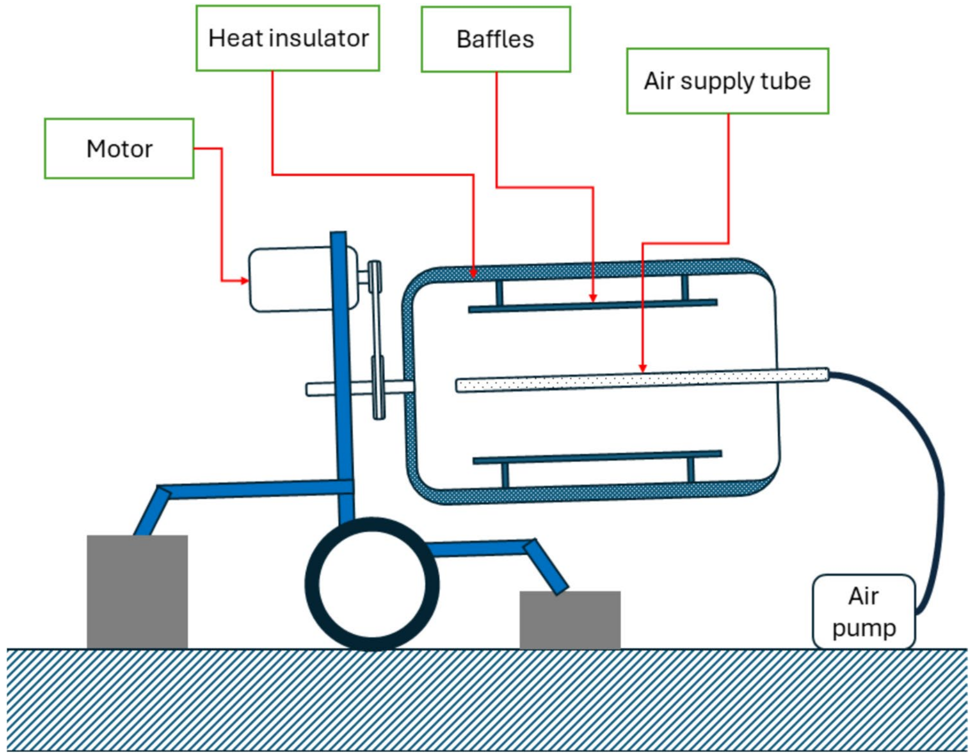

Fig. 1 Schematic diagram of in-vessel composting reactor positioned horizontally; A motor was installed to spin the reactor during pile turning

$$G(\%) = \frac{(M_1 x Q_1) + (M_2 x Q_2)}{(Q_1 + Q_2)} \quad (2)$$

where G = The ideal moisture content for composting, M_n = Moisture content of material n, Q_n = Mass of material n in wet weight (kg)

Sample collection

About 200 g of sample was taken from the mixture after turning. Sub-samples were taken from different locations of the pile, combined, mixed and divided into two portions. The first portion of the sample was kept at 4 °C before subjecting it to pH, electrical conductivity (EC) and moisture content measurements. Second portion was air-dried and kept at room temperature before subjecting it to carbon and nitrogen contents determination. The initial mixture and final biocompost were characterised by pH, EC, germination index (GI), proximate and elemental compositions as well as trace element and heavy metal concentrations. All analyses were conducted in triplicates.

Physicochemical parameters and gaseous emissions determination

Physicochemical parameters including temperature, oxygen level, pH, moisture, EC, carbon content, nitrogen content, and gases emitted including carbon dioxide and methane gas (CH_4) were monitored throughout the process to ensure an efficient composting could be maintained. Temperature of composting pile was measured by using digital thermometer (TM902C, Beizuu, China), whereas oxygen, carbon dioxide and CH_4 levels were measured by using gas analyser (S360, Portable Pump Suction Multi Gas Analyser, Henan Zhongan Electronic Detection Technology Co., Ltd, China). The temperature, oxygen content, carbon dioxide and CH_4 concentrations of the pile were measured before turning it, at six different points of the pile and at a certain depth (around 15–30 cm), to obtain the data of the inner parts of the pile. All six readings were recorded, and an average value was determined. The pH and EC of samples were determined based on method described in AOAC 973.04 and BS EN 13038 (AOAC 1990) with slight modification. Fresh sample was mixed with distilled water at the ratio of 1:20 (w:v, on dry weight basis) and shaken at 180 rpm for an hour at ambient temperature. After centrifuging at 3000 rpm for 15 min, pH and EC were measured with electrometric pH and EC meter probe in the collected supernatant while swirling. Carbon and nitrogen contents of sample were determined using elemental analyser.

Proximate composition determination

The moisture, ash and organic matter contents of sample were measured according to AOAC Official Method 950.01, 967.04, 967.05 (AOAC 1990) with slight modification. About 2.0 g of fresh sample was loaded in pre-weighed crucible (W_1) and dried in oven at 105 °C for 24 h to a constant weight. The dried sample was weighed with its crucible (W_3) and then subjected to ash content analysis by incinerating at 550 °C for 6 h in furnace (Vulcan A-130, NeyTech, USA). After that, the weight of ash (W_4) was recorded after the sample was completely cooled in desiccator. The moisture content (%), ash content (%) and organic matter content (%) of the sample were calculated as in Eqs. 3, 4 and 5:

$$\text{Moisture content (\%)} = \frac{W_2 - W_3}{W_2 - W_1} \times 100\% \tag{3}$$

$$\text{Ash content (\%)} = \frac{W_4 - W_1}{W_2 - W_1(g)} \times 100\% \tag{4}$$

$$\text{Organic matter (\%)} = \frac{W_3 - W_4}{W_2 - W_1} \times 100\% \tag{5}$$

where W_1 = Weight of crucible (g), W_2 = Weight of crucible + fresh sample (g), W_3 = Weight of crucible + dried sample (g), W_4 = Weight of crucible + ash (g).

Elemental composition determination

Carbon, hydrogen, nitrogen and sulphur (CHNS) contents were determined by CHNS/O elemental analyser (Vario El Cube, Elementar, Germany). A 5.0 mg of sample was crimped in an aluminium capsule and placed in the autosampler of analyser. While running the analysis without sample was served as blank, sulfanilamide was used as standard sample. The percentage of each element was obtained at the end of the analysis. The phosphorus, potassium, sodium, calcium and magnesium contents were determined by ion chromatography according to EPA official method 300.0 for phosphorus (anion) (U.S. EPA 1993) and Dionex AN141 for potassium, sodium, calcium and magnesium (cations) (Thomas and Rohrer 2015). A 3.0 g of sample was mixed with 30 mL of filtered deionised water and stirred at 180 rpm for an hour at ambient temperature. The sample was then filtered using 0.45 µm syringe filter and the collected filtrate was analysed using ion chromatograph (Dionex Aquion, Thermo Fisher Scientific, United States).

Trace element and heavy metal concentration determination

The concentration of trace elements and heavy metals were determined using inductively coupled plasma mass spectrometry (ICP-MS) according to EPA Official Method 200.8 (U.S. EPA 1994) using argon gas (10–15 L/min). Sample was prepared according to a modification of EPA Official Method 3050 B (U.S. EPA 1996). A 2.5 g of sample was first suspended in 75 mL of distilled water, followed by the addition of 10.0 mL concentrated hydrochloric acid and 5.0 mL concentrated nitric acid (2:1 ratio). After mixing, the mixture was heated to 95 °C± 5 °C and refluxed for 10–15 min under fume hood. When the digested sample was cooled to room temperature, it was transferred to a 500 mL volumetric flask and marked up with distilled water until it reached calibration mark. After stirring, the sample was filtered through 0.45 µm syringe filter and the collected filtrate was analysed using ICP-MS (Nexion 2000, Perkin Elmer, United States).

Germination index (GI) determination

GI of sample was determined based on the method described by Luo et al. (2023) with slight modifications. Fresh sample was mixed with distilled water at the ratio of 1:20 (w:v, on dry weight basis) and shaken at 180 rpm for an hour at ambient temperature. The compost extract was collected by centrifuging at 3000 rpm for 15 min using a Benchtop centrifuge (Model 2010, Kubota, Japan). A 5 mL of extract was then added to a piece of Whatman No. 1 filter paper placed on a petri dish. Then, ten mung bean (*Vigna radiata* L.) were placed on it and incubated at 25 ± 2 °C in the dark for 48 h. The mung beans were first soaked in distilled water for 30 min before using it in the analysis. Distilled water was served as control and same number of seeds was placed on its filter paper. The analysis was performed in triplicate for each sample. A seed was considered as a germinated seed when its seed coat ruptured and its radicle emerged, solely expansion of seed without rupturing of seed coat was not counted as germinated seed in this context. GI (%) of sample was calculated as in Eq. 6:

$$GI(\%) = \frac{G_E}{G_C} \times \frac{L_E}{L_C} \times 100\% \tag{6}$$

where G_E = Number of germinated seed in extract, G_C = Number of germinated seed in control, L_E = Mean of total root length of germinated seed in extract (cm), L_C = Mean of total root length of germinated seed in control (cm).

Statistical analysis

Mean and standard deviation of each parameter were determined using Microsoft Excel, version 2208 for data description. Pearson correlation between each physicochemical parameter and the significance level of correlation coefficient (*p*-value) were analysed using *rcorr* function under *Hmisc* package in R environment, version 4.3.3. The two-sided *p*-value of < 0.05 was applied and considered to be statistically significant.

Results and discussion

Characteristics of raw materials

According to Table 1, GTSW was found having C/N ratio of 20:1–23:1 and moisture content of more than 75%. On the other hand, rice husk contained C/N ratio of 47:1–49:1 and an average of 12% moisture content. GTSW was also appeared to have amorphous structure, whereas rice husk had a rigid structure (Fig. 2). The concentrations of arsenic, chromium, copper, lead, nickel and mercury found in GTSW were higher than rice husk. Fortunately, these heavy metal concentrations found in GTSW were below the maximum permissible limits of U.S. EPA, TAS 9503-2005 and SIRIM biocompost standards, showing that it was safe to be used as composting feedstock. Although the heavy metal concentrations found in GTSW were within their respective safe ranges, the C/N ratio and moisture content of GTSW were not ideal to initiate composting alone. According to literature, composting mixture was required to be prepared at an optimal initial C/N ratio of 25:1–35:1, and a moisture content of 45–65% (v/w) to begin composting (Gurusamy et al. 2021; Azis et al. 2023). This is because composting is a process that relied on the activity of microorganisms, and these composting parameters would affect the microbial activity, ultimately influencing the composting performance and final biocompost quality. As GTSW had C/N ratio of $< 25:1$, composting it solely could lead to nitrogen loss via ammonia volatilisation during composting, reducing the available nitrogen present in composting mixture while releasing odorous ammonia gas (El-mrini et al. 2022). Having high moisture content or amorphous structure would also decrease the porosity of composting pile whereby high moisture filled pore space with water instead of air and amorphous structure limited void space present in the material due to the lack of structural support. These prevented efficient aeration and inhibited microbial growth, leading to unstable and incomplete composting (Mohammed et al. 2017; Guidoni et al. 2018; Tang et al. 2023). Given that rice husk had higher C/N ratio than GTSW, adding it into GTSW could increase the carbon content and C/N ratio of composting mixture. Co-composting them at a ratio for C/N ratio of 30:1 could also balance the overall mixture's moisture content and increase the porosity of composting pile as contributed by the low moisture content and rigid structure of rice husk. Therefore, in this context, GTSW was served as a nitrogen source, and rice husk was served as a carbon source and bulking agent. According to current GTSW management practice in Malaysia carried out by sewage treatment plant after receiving the waste from grease trap desludging contractors, packing GTSW in perforated bag for landfill disposal after separating it from GTW would have reduced the moisture content of GTSW through evaporation and leaking. Hence, when it was being used in composting, the moisture content of composting mixture could be adjusted and maintained by the addition of water. In addition, when GTSW's characteristics determined in this study were compared with previous studies where GTW's FOG was mixed with GTSW as a feedstock, it was found that the inclusion of FOG made the mixture

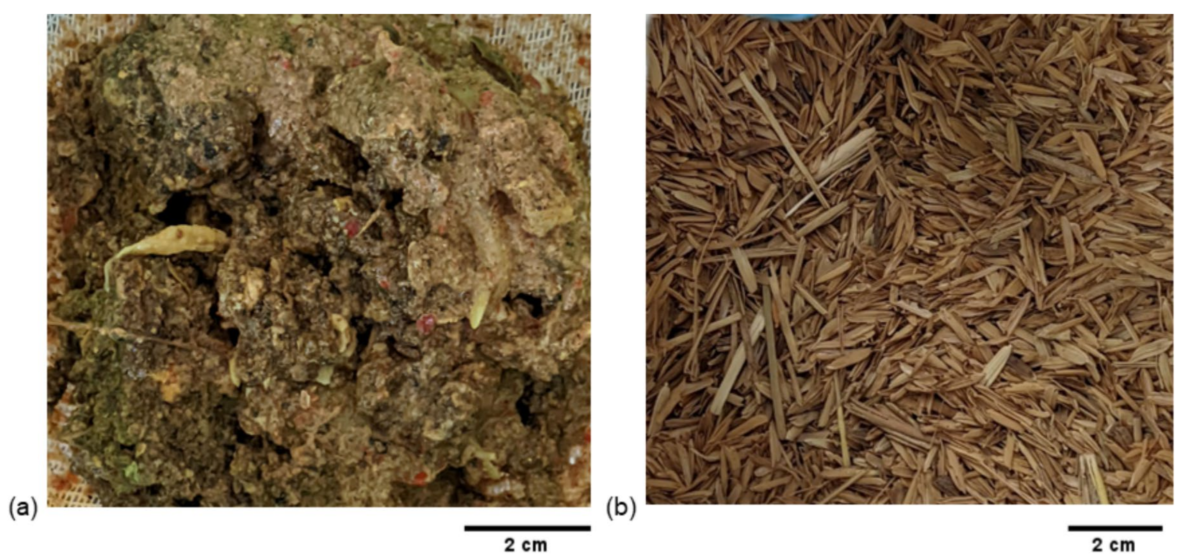

Fig. 2 Feedstock used in this composting study; **a** GTSW and **b** rice husk

contained significantly higher carbon content (99.14%), lower moisture content (40.76%) and greater volatile solid concentration (98.86%) than GTSW alone (Chitthaluri and Venkateswara Rao 2023). Thus, this suggested that proper separation of FOG from GTSW was essential to ensure GTSW could serve as a nitrogen source effectively during its co-composting with rice husk.

Changes of physicochemical parameters and gaseous emissions

The co-composting of GTSW and rice husk was conducted twice in this study. In both runs, the composting process reached maturity in 70 days. Figure 3 demonstrates the physicochemical properties changes, whereas Fig. 4 shows

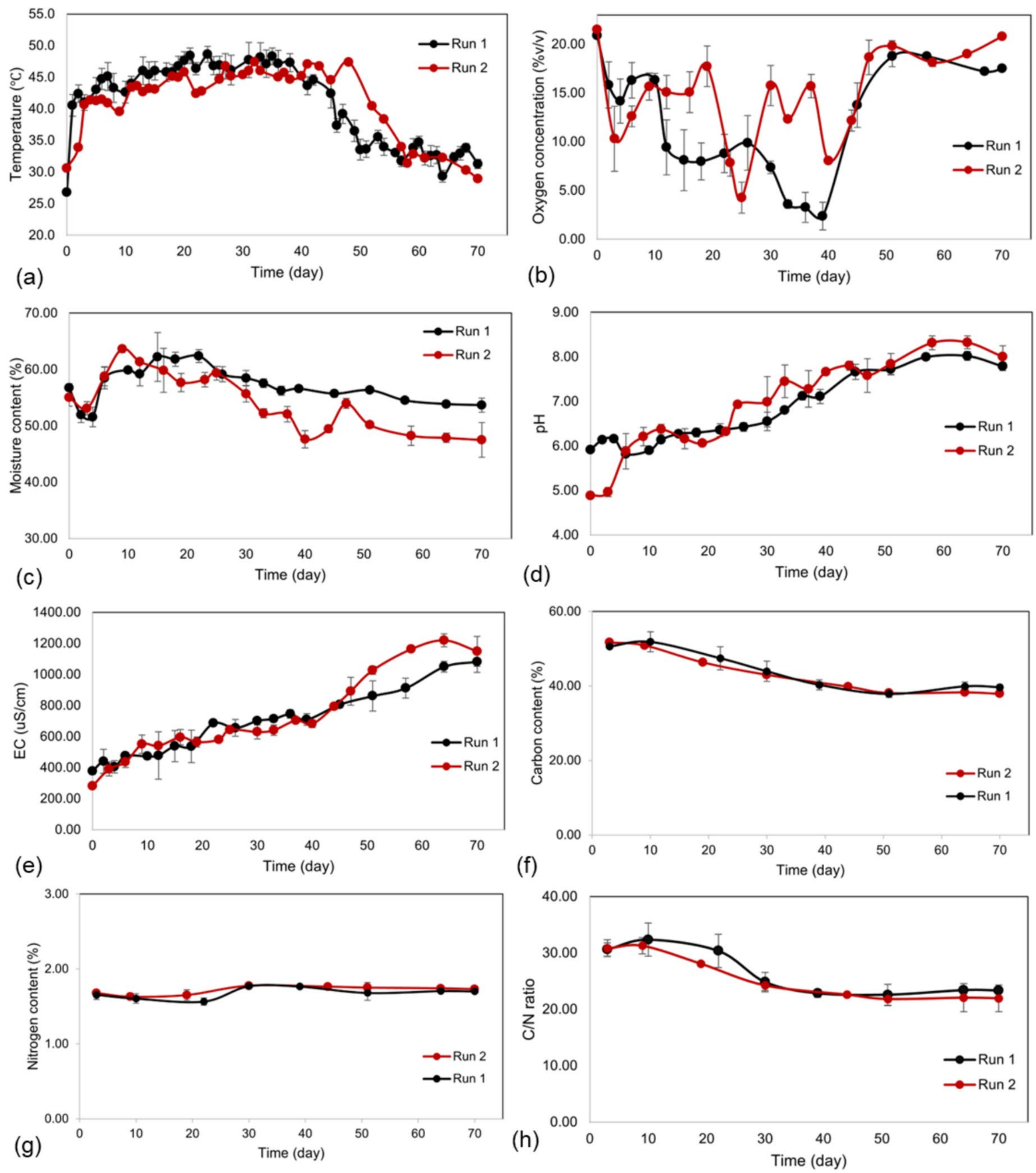

Fig. 3 Variations of **a** temperature, **b** available oxygen level detected, **c** moisture content, **d** pH, **e** EC, **f** carbon content, **g** nitrogen content and **h** C/N ratio during co-composting of GTSW and rice husk

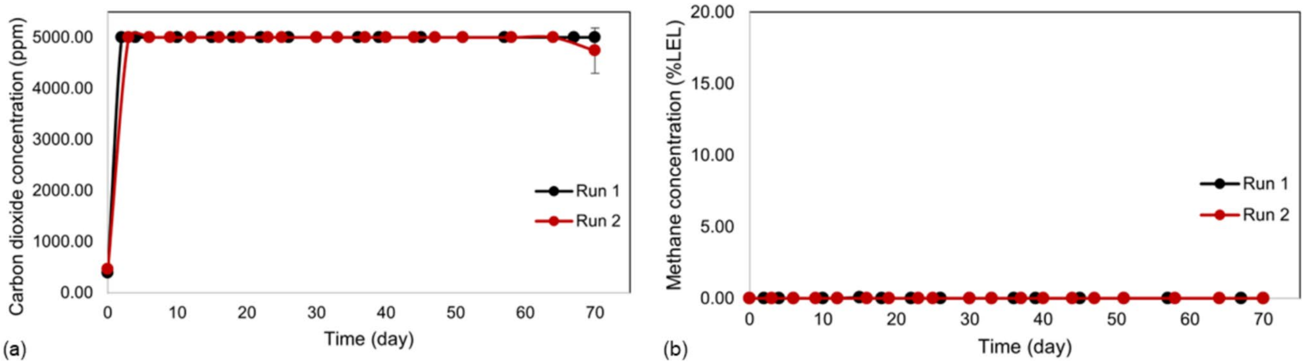

Fig. 4 Variations of **a** carbon dioxide concentration, **b** methane concentration emitted during co-composting of GTSW with rice husk

changes of gases emitted during the co-composting of GTSW and rice husk.

Temperature

According to Fig. 3a, the temperature of composting pile began to increase when composting started. The temperature was then maintained between 40 and 50 °C for weeks until it entered the 7th week of composting. After that, the temperature reduced gradually and eventually achieved ambient temperature at the end of composting. The rise of temperature during composting was due to the heat generated from microbial activity. The degradation of organic matter by microorganisms would release heat energy. As the heat generated was trapped within composting pile, the temperature of the pile increased. As composting progressed, organic matter present in compositing mixture depleted. The exhaustion of organic matter would lead to a decrease in microbial activity, reducing the heat energy generated, and therefore decreasing temperature of the pile (Aydin Temel 2023).

The temperature changes during composting reflected composting stages and conditions, monitoring the changes was crucial for maintaining compost quality and stability. Composting has four important phases occurred throughout the process, which were (1) initial mesophilic phase, in which feedstocks were mixed and composting was initiated, (2) thermophilic phase, whereby the temperature of composting pile increased and maintained above 40 °C, (3) cooling phase, in which the temperature decreased after staying at high temperature for a period of time, and lastly (4) maturing phase, in which the temperature reached ambient temperature and began curing until the composting pile was matured (Partanen et al. 2010). Figure 3a temperature profile demonstrated that these four phases happened distinctly in the co-composting of GTSW and rice husk, in which thermophilic phase began on Day 1 and lasted till 47th–48th day, cooling phase took place for about ten days (57th–58th days), then entered maturing phase and matured on 70th day. The temperature changes throughout the process followed a typical composting temperature pattern. The temperature was also stable and not fluctuating drastically throughout composting, indicating that the composting conditions were suitable and well-maintained for the growth of microorganisms. Having a stable temperature of more than 40 °C for several weeks at thermophilic phase also suggested that potential pathogens found in composting mixture could be removed as it only required the pile temperature to be remained at 40 °C for a minimum of five days to eliminate pathogens (U.S. EPA 1985).

Given that temperature could provide an understanding of composting conditions, it was commonly the main physicochemical parameter being investigated and discussed in composting study. Compared with previous studies (Table 2), co-composting GTSW with rice husk had a significantly longer thermophilic phase (46–47 days). The duration of cooling and maturing phases of GTSW-rice husk composting (22–23 days) was similar to Belyaeva and Haynes (2010) study, but it was shorter than Chitthaluri and Venkatewara Rao (2023) and Lemus et al. (2004) studies. Thermophilic phase duration was longer than cooling and maturing phases duration in GTSW-rice husk composting, however, thermophilic phase was found being shorter than cooling and maturing phases duration in other GTSW co-composting studies. This opposite duration length for both phases could be due to the inclusion of FOG in composting process. The presence of FOG in excessive amount reduced the porosity of composting mixture, obstructing air flow and then inhibiting microbial activity. Additionally, FOG being more easily degradable than carbohydrate- and protein-rich organic materials limited the microbial activity involving in those materials' degradation (Du et al. 2024). Having low microbial activity would eventually lead to lower degradation rate of organic matter during composting, resulting in generating lesser amount of heat. Therefore, this shorten the thermophilic phase of GTSW co-composting process when FOG of GTW was added. Belyaeva and Haynes (2010) and

Table 2 Comparison of GTSW-rice husk co-composting (this study) to other GTSW co-composting

Raw materials[1]	Composting period (days)	Initial C/N ratio	Duration of Initial phase (days)	Thermophilic phase		Duration of Cooling and Maturing phases (days)	Biocompost quality			References
				Duration (days)	Highest temperature (°C)		Final C/N ratio	pH	EC (µS/cm)	
GTSW + FOG + saw dust pellet	53	35.1	n.r.[3]	n.r.	n.r.	n.r.	n.r.	n.r.	n.r.	Rojas-Vargas et al. (2022)
GTSW + FOG + yard trimming (10% lipid)[2]	119	26.2	2	2	60–65	115	17.9	6.0	n.r.	Lemus et al. (2004)
GTSW + FOG + yard trimming (5% lipid)	119	26.0	2	5	65–70	112	15.6	6.6	n.r.	
GTSW + FOG + synthetic food waste (10% lipid)	119	27.9	2	5	55–60	112	10.9	6.2	n.r.	
GTSW + FOG + synthetic food waste (5% lipid)	119	24.9	4	3	50–55	112	9.3	6.5	n.r.	
GTSW + FOG + green waste	42	n.r.	3	18	78	21	12.0–15.0	7.7	28	Belyaeva and Haynes (2010)
4%(GTSW + FOG) + grass clipping waste + vegetable waste	55	22.1	2	6	49.1	47	n.r.	8.8	6800	Chitthaluri and Venkatewara Rao (2023)
8%(GTSW + FOG) + grass clipping waste + vegetable waste	55	24.9	2	6	49.6	47	n.r.	8.8	5520	
12%(GTSW + FOG) + grass clipping waste + vegetable waste	55	29.4	2	13	49.7	40	n.r.	8.8	6970	
16%(GTSW + FOG) + grass clipping waste + vegetable waste	55	29.7	2	13	47.8	40	n.r.	8.7	5050	
GTSW + rice husk	70	30.0	1	46–47	50.4	22–23	21.9–23.8	7.0–8.0	1012–1245	This study

[1]FOG included in GTSW co-composting was the FOG of GTW. It was mixed with GTSW and used as a single feedstock

[2]The percentage of lipid content was adjusted by the amount of GTSW + FOG added into mixture

[3]n.r.—not reported

Lemus et al. (2004) also found that the reduction in porosity of mixture contributed by FOG caused a delay of 2–4 days in reaching thermophilic phase in their GTSW co-composting process. Having no delay in temperature rising during co-composting GTSW with rice husk suggested that mixing GTSW with rice husk without including FOG improved porosity of the mixture.

Oxygen and methane concentrations

The available oxygen concentration detected in composting pile during co-composting of GTSW and rice husk was beyond lower than atmospheric oxygen concentration (20–21%v/v). However, when composting entered the 7th week, the available oxygen concentration detected in composting pile increased gradually, reaching between 15 and 19%v/v of oxygen concentration (Fig. 3b). This oxygen concentration changes occurred because composting is an aerobic process, microorganisms utilised oxygen to break down organic matter into simple molecules and water. The oxygen level detected was low before entering the 7th week of composting as more oxygen was consumed during active composting (thermophilic phase) to facilitate the high decomposition rate. When the process entered cooling phase, less oxygen was needed as the decomposition rate reduced with the depletion of organic matter (Liu et al. 2022). Aeration was provided through pile turning and forced aeration. Monitoring oxygen level throughout composting process could ensure composting pile was aerated adequately and prevent composting process from entering anaerobic conditions, promoting anaerobic microbial activity. Not only greenhouse gas such as methane could be generated when composting took place under anaerobic conditions, but also undesirable odour could also be released from composting pile. Moreover, temperature of the pile would also be reduced as anaerobic degradation was less exergonic than aerobic decomposition and anaerobic conditions inhibited the aerobic microorganisms' growth and activity, therefore resulting in less heat energy released (Jiang et al. 2015; Leng et al. 2018). This could prolong the composting process, preventing an effective pathogen removal from composting mixture and reducing the final biocompost quality.

To maintain an aerobic composting, the oxygen level detected within the pile should be prevented reaching zero as this value implied insufficient air supply to support the activity of aerobic microorganisms (Zeng et al. 2018). Based on Fig. 3b, the oxygen level detected within the pile for both runs was maintained above zero. Apart from that, the methane concentration released during co-composting of GTSW and rice husk was also found below the detection limit (Fig. 4b). Notably, every gas measurement was performed before turning the composting pile in this study. Based on the temperature, oxygen level and methane concentration profiles (Figs. 3a, b and 4b), they suggested that the pile turning frequency and forced aeration rate practised in this study were sufficient to aerate the pile without interfering heat trapping while maintaining an aerobic condition within the pile. This also demonstrated that rice husk improved the porosity of its mixture with GTSW, facilitating efficient aeration and maintaining stable thermophilic temperatures throughout composting. Although the generation of methane was unfavourable to the environment, studies showed that it was unavoidable to have certain regions within composting pile became anaerobic zone when the size of composting pile increased, especially during thermophilic phase. This is because the active decomposition of organic matter in thermophilic phase would increase the oxygen consumption rate, reducing the available oxygen present in the pile quickly. Nevertheless, larger composting pile could have hindered the rapid oxygen diffusion into the core of pile to meet the oxygen demand and supply adequately, increasing the possibility of developing anaerobic areas within the pile and generate methane. Optimising turning frequency and forced aeration rate according to composting stages should be considered during upscaling as they were found able to minimise the development of anaerobic zone in larger composting pile (Nguyen et al. 2023; Nordahl et al. 2023).

Moisture

The moisture content of composting mixture was found reducing during co-composting of GTSW and rice husk (Fig. 3c). This is because the moisture was evaporated from the mixture as the heat generated through microbial activity dissipated during pile turning (Lai et al. 2024). The moisture content of composting mixture first reduced by 10% at the beginning of composting. It increased shortly to 60–63% after that and then decreased gradually 47–53% as composting progressed. This occurred because when composting started, the microbial population was relatively small. Although water was one of the by-products generated during the microbial degradation of organic matter, the amount of water produced was inadequate to compensate the water lost through evaporation. Hence, the moisture content decreased. As the microbial population increased, the amount of water produced overtook the amount of water evaporated, thus increasing the moisture content of composting mixture. Nevertheless, the amount of heat generated was also increasing along with the increase of microbial activity. When heat dissipated at a greater rate than the amount of water produced by microorganisms, the moisture content of composting mixture would be reduced (Raza et al. 2023).

Higher degree of aeration and higher temperature of pile could increase moisture evaporation rate as more heat dissipated (Shen et al. 2015), leading to a greater reduction in moisture content throughout composting process. Moisture content of composting mixture could affect microbial activity as not only it played a role in material transformation and nutrient transportation for the growth and metabolic activity of microorganisms, but also it could affect microorganisms' access to oxygen as moisture level influenced air diffusion and dissolution efficiency (Godlewska et al. 2017). Maintaining the moisture content during active composting stage was necessary to ensure the microbial activity was sustained. With the stable temperature changes shown in Fig. 3a, the changes in moisture content suggested that it was desirable to support microbial activity without being too moist that interrupted the air flow within the pile nor being too dry that prevented the nutrient uptake and growth of microorganisms.

Carbon dioxide concentration

The carbon dioxide concentration increased from about 480–5000 ppm when composting began, however, its concentration remained as 5000 ppm until the composting ended (Fig. 3a). The carbon dioxide concentration increased when composting started because carbon dioxide was released as by-product during microbial decomposition of organic matter. It increased to 5000 ppm and remained constant until composting ended because the limit of carbon dioxide concentration that could be detected by gas analyser used in this study was 5000 ppm. Figure 4a also shows no decrease in carbon dioxide concentration even though the composting process entered cooling and maturing phase. Nevertheless, studies showed that the carbon dioxide released during active composting should have been more than the concentration detected in other composting phases due to its higher decomposition rate of organic matter. When the organic matter decomposition rate reduced, the temperature and carbon dioxide concentration generated would be reduced and eventually reached atmospheric conditions (Li et al. 2023). However, in this study, the carbon dioxide concentration detected remained high instead of lowering to atmospheric carbon dioxide concentration when temperature reduced and reached ambient temperature. This is because the moisture content of composting mixture in cooling and maturing phases was more than 40%, in which it could still support the microorganisms to respirate and release carbon dioxide as by-product (Cruz-Paredes et al. 2021). Thus, carbon dioxide was still detected in cooling and maturing phases even though microorganisms were not decomposing organic matter as implied by the reduction in temperature (Fig. 3a).

pH, EC, Carbon and Nitrogen

The pH and EC of composting mixture increased steadily from pH 4.9–5.9 to pH 7.8–8.0 and 292–400 μS/cm to 1050–1240 μS/cm as composting process progressed (Fig. 3d, e). This was due to the mineralisation of organic matter and the release of inorganic ions during decomposition of organic matter. When carbon containing compounds were being decomposed, it was first being broken down into organic acids, then further degraded into carbon dioxide and water. The carbon dioxide produced could have reacted with water and produced carbonic acid which would then further dissociated into bicarbonate ions. Small organic acids such as acetic acid or propionic acid could also be further volatilised. As for nitrogen organic matters, its breakdown released ammonium ions, which could be converted to nitrite and nitrate ions via nitrification. The rapid decomposition of organic acids followed by these inorganic ions production led to an increase in pH and EC (Sun et al. 2021; Gao et al. 2024; Zhang et al. 2024). Additionally, the degradation of organic matter led to a reduction in carbon content (Fig. 3f). Carbon content decreased steadily from 50.6–51.7% to 37.8–38.1% during thermophilic phase as it was consumed by microorganisms and released as carbon dioxide. It then remained relatively constant between 37–39% when it entered cooling phase until the end of composting due to the exhaustion of readily degradable carbon and the formation of stable organic compounds through humification (Sun et al. 2024). On the other hand, the nitrogen concentration increased slightly from 1.66–1.68% to 1.70–1.73% during composting (Fig. 3g). This is because of the concentrating effect due to the weight loss contributed by the mineralisation of organic matter (Sánchez-Monedero et al. 2001; Zhang et al. 2019). Despite the nitrogen organic matter could be broken down into ammonium, nitrite and nitrate ions, the total nitrogen content remained showing a slight increment because elemental analyser measured only organic nitrogen, inorganic nitrogen such as those ions were not included. The decrease of carbon content and increase of nitrogen content eventually reduced C/N ratio of mixture during composting (Fig. 3h).

A minor fluctuation of pH and EC were observed in some days of composting according to Fig. 3d, e, mainly during active composting phase. For pH, this could have attributed to the generation and degradation rates of organic acids. When organic acids released at a greater rate than its further degradation, the presence of large number of organic acids reduced the pH, nevertheless, its rapid decomposition followed that would raise back the pH. Apart from that, the changes of pH and EC could have also owned to the formation and uptake rate of inorganic ions. Inorganic ions could be consumed by microorganisms to support their cell multiplication and metabolic processes. When inorganic ions released at a slower rate than the uptake rate by microorganisms, pH and EC would be reduced. Similarly, higher formation rate of inorganic ions offsetting the microbial consumption rate could raise pH and EC. Therefore, these led to the minor fluctuation in pH and EC profiles throughout composting. Many studies reported that the increment of pH and EC could have been affected by the moisture content of composting mixture as the decrease of moisture content would have elevated the ion concentration, increasing pH and EC values (Ge et al. 2022). However, in this context, the pH and EC were determined in dry matter basis, therefore moisture content was eliminated from being a factor in influencing the changes of pH and EC.

Correlation between physicochemical properties

Figure 5 shows the association between each physicochemical property investigated in this study determined via Pearson correlation test. The results showed that a statistically significant positive association ($p < 0.01$) was found between moisture and carbon, moisture and C/N ratio, pH and EC, carbon and C/N ratio. On the other hand, a statistically significant negative association was found between moisture and pH, EC and C/N ratio, nitrogen and C/N ratio at $p < 0.05$, and pH and carbon, pH and C/N ratio, EC and carbon at $p < 0.01$. There was no significant correlation between temperature and any investigating physicochemical parameters, as well as oxygen and any investigating physicochemical parameters. This could be due to their distinct composting dynamics, resulting in constrained temperature development and oxygen depletion compared to the consistent changes observed in other physicochemical parameters. Identifying the correlation intensity and its significance level between each physicochemical parameter provided the foundation for developing predictive models for efficient process monitoring and control in GTSW-rice husk co-composting (Shi et al. 2025).

Characteristics of final biocompost

The co-composting of GTSW and rice husk ended when composting mixture was matured. GI was employed as maturity indicator in this study, in which composting mixture with GI greater than 80% indicated that it was matured (Zhang et al. 2018). On 70th day of composting, the mixture displayed GI more than 80%. Thus, it was matured and could be harvested for further use. Table 3 and Fig. 6 demonstrated the physical and physicochemical characteristics of initial composting mixture and final biocompost for both runs of composting. The characteristics of final biocompost were different from the characteristics of initial feedstock mixture due to the microbial decomposition of organic matter that took place during composting. The matured compost became darker in colour than the initial composting mixture due to the humus formation during decomposition (Meng et al. 2024). Furthermore, further microbial degradation of organic acids, which were produced as intermediate product during organic matter degradation, not only increased pH, but also removed undesirable odorous smell from final biocompost, allowing it to release a favourable earthy smell instead of a rotten sour smell like the initial composting mixture (Sundberg et al. 2013). The increase of EC, ash, nitrogen, phosphorus, potassium, sodium, calcium, zinc, manganese and copper contents were attributed to mineralisation of organic matter, whereas the decrease of carbon and hydrogen were contributed by microbial consumption and product formation (Tibu et al. 2019; Xie et al. 2023). In addition, a minimal concentration of arsenic, chromium, lead, nickel and mercury were detected in final biocompost. These heavy metal concentrations found in final biocompost were similar to the concentrations of initial feedstock mixture, which were mainly contributed by GTSW (Table 1).

Biocompost was commonly used as organic fertiliser or soil amendment to improve soil quality and maintain soil fertility. It should possess nutrients that could fertilise the land and support plant growth without introducing hazardous substances into soil that might enter the food chain and compromise food safety through biomagnification. To ensure its effectiveness and safety as organic fertiliser or soil amendment, the composition of biocompost should comply to the established standards (Du et al. 2024). Various standards were established by different countries to regulate their countries' biocompost application. As for Malaysia, the biocompost composition standard was developed by SIRIM Berhad, a research organisation owned by the Ministry of Investment, Trade and Industry. Comparing the biocompost composition to multiple standards not only could facilitate

Fig. 5 Pearson correlation heatmap of composting physicochemical parameters; *significant at $p < 0.05$, ** significant at $p < 0.01$

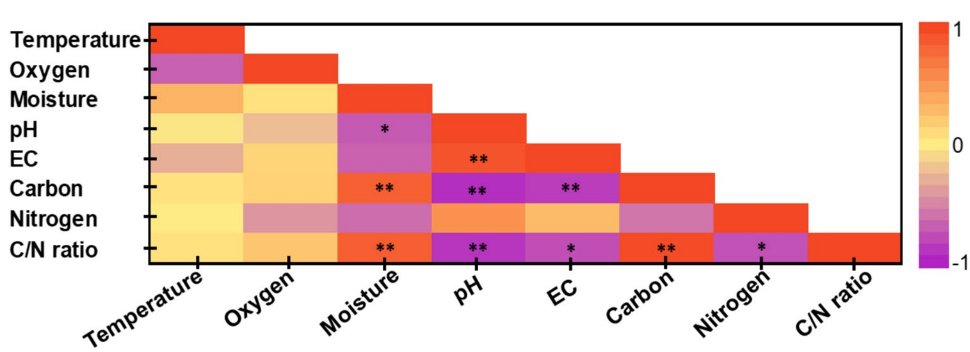

Table 3 Physicochemical characteristics of initial composting mixture (Day 0) and final biocompost (Day 70) from Run 1 and Run 2

Parameter[1]	Run 1		Run 2		U.S. EPA[2]	TAS 9503–2005	SIRIM (2012)
	Day 0	Day 70	Day 0	Day 70			
pH	5.91–5.92	7.69–7.88	4.88–4.89	6.99–8.04	5.0–8.5	5.5–8.5	n.s.[3]
Electrical conductivity, EC (uS/cm)	356.55–400.11	1011.93–1153.27	292.10–312.10	1052.69–1244.91	n.s	< 3500	n.s
Moisture (%)	55.95–57.47	52.38–54.93	53.49–56.57	44.42–50.58	30.00–60.00	< 35.00	< 30.00
Ash (%)	5.71–9.16	11.35–12.20	5.95–7.71	14.84–21.64	n.s	n.s	n.s
Organic matter (%)	35.26–38.72	32.99–36.15	37.48–38.80	31.91–36.61	30.00–65.00	> 35.00	n.s
Carbon, C (%)	50.59–50.66	38.94–40.37	50.16–53.18	35.66–40.16	n.s	n.s	n.s
Nitrogen, N (%)	1.59–1.72	1.75–1.80	1.65–1.71	1.69–1.77	n.s	> 1.0	> 1.5
Phosphorus, P (%)	0.04–0.05	0.46–0.55	0.04–0.08	0.39–0.52	n.s	> 0.5	n.s
Potassium, K (%)	0.00[4]	0.15–0.17	0.00	0.14–0.17	n.s	> 0.5	n.s
Hydrogen, H (%)	7.21–7.91	5.84–5.91	7.73–7.96	5.74–5.82	n.s	n.s	n.s
Sulphur, S (%)	0.05–0.06	0.07–0.11	0.08–0.09	0.14–0.17	n.s	n.s	n.s
C/N ratio	30.61–31.81	22.91–23.75	30.82–32.30	21.94–23.62	n.s	< 20:1	< 25:1
Sodium, Na (%)	0.00	0.02–0.03	0.00	0.03–0.04	n.s	n.s	n.s
Magnesium, Mg (%)	0.00	0.00	0.00	0.00	n.s	n.s	n.s
Calcium, Ca (%)	0.00	0.03–0.04	0.00	0.03–0.05	n.s	n.s	n.s
Zinc, Zn (mg/kg)	9.36–9.83	14.89–15.04	9.28–9.75	14.01–14.16	2800	n.s	n.s
Manganese, Mn (mg/kg)	6.07–7.06	18.18–19.48	5.09–5.37	11.86–15.02	n.s	n.s	n.s
Germination index, GI (%)	50.62–76.53	155.85–202.97	66.25–84.45	106.78–133.68	n.s	> 80	n.s
Arsenic, As (mg/kg)	0.20–0.26	0.39–0.40	0.18–0.20	0.38–0.40	41	< 50	50
Cadmium, Cd (mg/kg)	0.00	0.00	0.00	0.00	39	< 5	5
Chromium, Cr (mg/kg)	1.13–2.39	1.19–1.65	1.59–2.52	2.10–2.29	n.s	< 300	200
Copper, Cu (mg/kg)	1.60–1.99	2.58–4.55	3.58–3.91	2.24–4.21	1500	< 500	n.s
Lead, Pd (mg/kg)	0.60–0.70	0.60–0.80	0.60–0.70	0.56–0.77	300	< 500	300
Nickel, Ni (mg/kg)	0.90–1.19	1.14–1.19	1.15–1.19	1.15–1.20	420	n.s	150
Mercury, Hg (mg/kg)	0.20–0.30	0.20–0.48	0.25–0.44	0.20–0.40	17	< 2	n.s

[1]All percentages, concentrations, pH and EC are determined by dry weight basis, except moisture, ash and organic matter were measured using fresh sample

[2]In U.S. EPA compost standard, the moisture was measured in wet weight basis, the organic matter was measured in dry weight basis, and the limits of heavy metal concentrations was based on U.S. EPA Class A standard, 40 CFR 503.13

[3]n.s.: not stated

[4]A value of zero was recorded when the concentration was below the detection limit

market identification, but also could use one as guideline for the unstated components in another standard, ensuring the biocompost product to be well-prepared for agricultural use.

According to the composition of biocompost produced in this study, its pH, EC, organic matter, nitrogen, C/N ratio, GI, trace element and heavy metal concentrations complied with the standards. Having optimum pH and organic matter content could maintain the physical properties of soil and enhance the availability of nutrients to plants. Under overly acidic conditions (pH < 5), cementing agents that function as soil structure stabiliser might be damaged. Under excessively alkaline conditions (pH > 8.5), deflocculation of soil might be stimulated, causing soil particles to disperse and clogging pore space. Both extreme pH conditions would decrease soil stability and disrupt soil structure, impeding efficient water infiltration, aeration, and nutrient movement from soil to plants, and microbial activity for nutrient cycling. Additionally, when the soil was too acidic, it inhibited the release of calcium and magnesium but escalated the release of aluminium and manganese. When the soil was too alkaline, it hindered the release of iron, copper, zinc and phosphorus (Xia et al. 2024). As for organic matter, its presence in biocompost could increase the porosity and water holding capacity of soil, eventually improving soil structure. Moreover, organic matter could also provide essential nutrients for plants by undergoing decomposition and mineralisation after applying biocompost to soil, releasing inorganic ions and elevating the nutrient availability in soil (Kim and

Fig. 6 Appearance of **a** initial composting mixture (Day 0) and **b** final biocompost (Day 70)

Park 2024). The release of inorganic ions during mineralisation of organic matter would also increase EC of soil. EC reflected the salt concentration of the medium and could also influence the nutrient accessibility to plants. When EC was more than 3.5 dS/m, it could create salinity stress, increasing the surrounding osmotic pressure and restricting water and nutrient uptake by plants (Ding et al. 2018). Having EC lower than 3.5 dS/m in biocompost could ensure nutrients and water being readily accessible to the plants, protecting plants from experiencing salinity stress and wilted upon stress exposure. Apart from heavy metals, excessive concentration of salt and trace elements could toxify the plants. GI was not only a maturity indicator, but also reflected phytotoxicity of compost. Having GI more than 80% indicated that the biocompost was non-phytotoxic, indirectly implying that the salt, heavy metals and trace elements concentrations were at a safe level for plant health (Qadir et al. 2013). Having heavy metal concentrations below the maximum permissible limits of standards also indicated that the biocompost could be applied safely and the plant crops grown on it were safe for human and animal consumption. However, intensive biocompost application on the same agricultural land might lead to heavy metal accumulation in soil (Zhen et al. 2020). Thus, further studies should be done on evaluating the environmental impact of the application of GTSW-rice husk based biocompost and establishing a safe application rate.

On the other hand, the moisture content of biocompost (45–54%) was higher than the required moisture stated in Thai Agricultural Standard (TAS 9503-2005) and SIRIM biocompost standard. This was due to the enclosed environment created by reactor where it prevented excessive moisture lost during composting (Jain et al. 2019). The biocompost produced through windrow composting would usually reach a lower moisture content than the biocompost produced via in-vessel composting and it could meet the standard easily as heat could be dissipated freely throughout composting and not just during pile turning (Yang et al. 2024). However, when composting was carried out in reactor, the heat dissipated from composting pile during thermophilic phase was trapped within the reactor, the escaped moisture was then condensed on the wall of reactor and returned to composting pile; moisture was only lost via heat dissipation during pile turning whereby it was performed with the lid of reactor removed, leading to slower moisture reduction. Having lower moisture content could prevent the development of mold in biocompost, lengthening its shelf-life and enhancing its safety for agricultural use. Given that the moisture content of biocompost produced in this study was higher than the standards, it could be reduced by sun-drying. After drying, the organic matter content of biocompost would be increased too since it was measured in wet weight basis. Nevertheless, when this production was upscaled, employing windrow composting method could allow the moisture content of biocompost to be reduced swiftly, omitting the needs of further drying before packaging.

Furthermore, phosphorus content of biocompost was barely achieving the requirement, and potassium content was below the desired concentration of the standards. In fact, the initial phosphorus content found in initial composting mixture was low, and potassium content was also found below the detection limit. While nitrogen was required for chlorophyll synthesis and photosynthesis, phosphorus was used in nucleic acids, phospholipids and adenosine triphosphate formation to support cell division and stimulate root growth and flowering, whereas potassium was used in water and nutrient transport throughout the plant and maintained osmotic homeostasis within the plant (Sardans and Peñuelas 2021; Jiaying et al. 2022; Khalofah et al. 2022). Despite the low concentration found in biocompost, these components could be supplemented by soil amendment rich in phosphorus and potassium during application as utilising multiple fertilisers was a common practice in fertilising agricultural land to overcome nutrient imbalance of a single fertiliser and diversify soil microbial community for improving nutrient cycling, disease suppression and soil structure (Chen et al. 2020; Gonzalez and Aranda 2023). With moisture, phosphorus and potassium contents of biocompost to be adjusted during its application, GTSW-rice husk based biocompost was suitable to be used as organic fertiliser.

Based on Table 2, GTSW-rice husk based biocompost had significantly lower EC than any FOG-GTSW-co-substrates based biocompost reported in previous studies. In fact, the EC of FOG-GTSW-grass clipping waste-vegetable waste based biocompost produced by Chitthaluri and Venkatewara Rao (2023) (5.05–6.97 mS/cm) exceeded the maximum permissible limit of TAS 9503-2005 biocompost standard (< 3.5 mS/cm). While the EC of FOG-GTSW-green waste based biocompost produced by Belyaeva and Haynes (2010) fell within the acceptable range of TAS 9503-2005 biocompost standard, its GI (51–59%) was lower than 80%, indicating that it could inhibit seed germination and seedling growth as a GI lower than 80% was recognised as phytotoxic (Zhang et al. 2018). They further elucidated that the low GI was attributed to the relatively high soluble salt concentration (2.8 mS/cm), extractable phosphorus content (970 mg/dm^3) and ammonium ions accumulation (79.8 mg/dm^3) of biocompost, which were contributed by FOG + GTSW mixture as the final biocompost (GI ≥ 100%) produced from composting green waste alone only contained 1.1 mS/cm soluble salt concentration, 179 mg/dm^3 extractable phosphorus and 3.9 mg/dm^3 ammonium ions. In contrast, the biocompost produced from co-composting GTSW with rice husk in this study achieved GI of 107–202% (≥ 80%) and EC of 1.0–1.2 mS/cm. This discrepancy not only suggested that the presence of FOG was a significant factor contributing to the observed lower GI and higher EC of GTSW-based biocompost in previous studies, but also demonstrated the potential of GTSW as composting feedstock without the inclusion of GTW's FOG in producing biocompost complied with U.S. EPA compost standard and most requirements of TAS 9503-2005 and SIRIM compost standard. Therefore, the findings of this study showed that co-composting GTSW with rice husk was an effective strategy to valorise GTSW.

Conclusion

This is the first study investigating the physicochemical parameters changes, gaseous emission and biocompost quality of co-composting of GTSW and rice husk. GTSW was found able to be composted with rice husk and reached maturity in 70 days. The temperature profile followed a typical composting temperature pattern with thermophilic phase lasted for 46–47 days and cooling phase lasted for ten days before reaching maturity on 70th day. The available oxygen level detected within the pile was low during thermophilic phase, but it started raising back and reached around atmospheric oxygen level when temperature reduced. Carbon dioxide was detected throughout composting, whereas methane was found below the detection limit. The pH, EC and nitrogen content increased, whereas the moisture, carbon contents and C/N ratio decreased during active composting. Among the physicochemical parameters, moisture and carbon content, moisture and C/N ratio, pH and EC, carbon content and C/N ratio, showed a positive correlation, whereas moisture and pH, EC and C/N ratio, nitrogen content and C/N ratio, pH and carbon content, pH and C/N ratio, EC and carbon content, showed a negative correlation ($p < 0.05$). Also, GTSW-rice husk based biocompost achieved GI ≥ 80% and complied with U.S. EPA biocompost standards. However, its phosphorus and potassium contents were not complied with TAS 9503-2005 and SIRIM biocompost standard, and needed enhancement before application. All in all, the findings of this study demonstrated that co-composting GTSW with rice husk was an effective alternative strategy to repurpose GTSW and divert it from landfill disposal.

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Author contribution LXL: conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, visualization. HAH: methodology, validation. PQT: methodology, investigation. NFEMF: Investigation. AMR: conceptualization, methodology, resources, writing—review and editing, supervision, project administration, funding acquisition. HA: conceptualization, methodology, resources, supervision. MZMY: conceptualization, methodology, resources, supervision. NR: conceptualization, methodology, resources, supervision. N-AA-M: conceptualization, resources, supervision.

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Data availability Data will be made available on reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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