Closing the food waste loop: Analysis of the agronomic performance and potential of food waste disposal products

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Abstract: The recycling of urban food waste (FW) is of great importance to the sustainable and low-carbon urban development. Focusing on the solid residues of FW aerobic composting and anaerobic digestion, this study selects three FW disposal products (FWDPs) and compares their nutrient compositions with the main traditional organic fertilizers in China through a literature review; carries out a seven-season field experiment with 30% of the nitrogen in FWDPs substituted for equal chemical nitrogen to explore the impacts on vegetable yields; and uses a field questionnaire to investigate farmers' awareness of FWDPs. FW aerobic compost and FW digestate solid residue can significantly increase seven-season total yields by 21.5% and 17.2% respectively compared with conventional chemical fertilizer alone, and maintain the same yield level with conventional combined application of chicken manure and chemical fertilizer, proved to be effective on crop yield as organic fertilizers. The case study of Xiamen indicates that FWDPs have great potential to produce organic fertilizers and reduce the application amount of pure chemical fertilizers by 5.6% under current conditions, where around one-third of restaurant FW is disposed of using anaerobic digestion technologies. Measures like formulating supportive regulations, expanding government propaganda, and producing qualified and cost-effective commercial organic fertilizers with FWDPs will improve farmers' knowledge and acceptance of FWDPs.

Keywords: Food waste digestate; Digestate biochar; Nutrient composition; Fertilization effect; Nutrient recovery.

1. Introduction

With the rapid development of the social economy, urbanization, and the continuous growth of the urban population, the production of municipal solid waste (MSW) and food waste (FW) is increasingly mounting (Trimmer and Guest, 2018). Waste disposal and resource scarcity have become two serious challenges to the sustainable development of humankind (Wang et al., 2021). Sustainable FW disposal aiming to recover energy and nutrients has been one of the key indicators for urban sustainable development (Gao et al., 2019; Redlingshöfer et al., 2020). China, the largest FW producer in the world, produces over 100 million tonnes of FW every year (Jin et al., 2021). Under the strict practice of China's MSW classification policy, increasing FW is separated out and needs to be treated appropriately (Lv et al., 2021). Therefore, harmless, sustainable, and large-scale treatment technologies to dispose of and manage FW are urgently needed in China.

Many different countries around the globe are committed to searching for appropriate FW treatment techniques. Relatively complete and mature industrial chains of FW recycling and utilization have been formed in Europe, the USA, Japan, South Korea, etc., where have developed into FW treatment technologies based mainly on animal feeding, aerobic composting (AC), and anaerobic digestion (AD) (Cecchi and Cavinato, 2019; Newman, 2018). In developing countries, FW is mainly treated by landfill and incineration together with domestic waste, as the disposal methods are low-cost and involve relatively simple processes (Li et al., 2019). These approaches, however, have drawbacks: they not only lead to several secondary pollution problems such as land occupation, leachate discharge, smelly odors and dioxins emissions, and other environmental issues such as greenhouse gases (GHG) emissions, but also lose the opportunities to recover energy and nutrients from FW (Clark and Tilman, 2017).

In China, FW treatment and management is still in the exploratory phase. The seminal event was the Chinese government's 2010 launch of a pilot project on FW resource utilization and harmless treatment, which selected more than 100 cities or districts as FW treatment pilots and invested 10.9 billion RMB in the construction of FW disposal facilities during the 12th Five-Year Plan period (Bi et al., 2016). Subsequently, China formulated a series of regulations, technical standards, and planning programs for

FW disposal, such as the Technical Code for Food Waste Treatment (CJJ 184-2012, issued in December 2012), the 12th and 13th Five-year Plans for National MSW Treatment Facilities Construction (issued in December 2012 and December 2016 respectively), the Implementation Scheme for MSW classification system (issued in March 2017), the Construction Plan for "Zero-waste Pilot Cities" (issued in December 2018), and the 14th Five-year Plan for MSW Classification and Treatment Facilities Construction (issued in May 2021). In the pilot cities, AD took up 74.3% of the FW disposal facilities, while AC and animal feeding accounted for 12.2% and 13.5% respectively (Yan et al., 2017). AD disposal occupies a dominant position, mainly owing to its advantages of low GHG emissions, low secondary pollution, and suitability for large-scale centralized processing of FW (Li et al., 2019). Some scholars compared different FW disposal approaches with life cycle assessments, and indicated that AD had less environmental effects than other methods like landfill and incineration (Huang et al., 2022; Oldfield et al., 2016). Nevertheless, AD treatment plants require relatively high fixed investment and operational costs. In contrast to AD, AC is a relatively mature technology and is suitable for using at a small, regional scale, as it combines less land occupation and economic input. Through aerobic fermentation, organic wastes are transformed into stable humic acid and usable nutrients, which are ideal bio-organic fertilizers with high oxidized organic matter and high activity. There has been a lot of research on the agricultural application of organic-waste AC products (Hou et al., 2017; Man et al., 2021; Zhu et al., 2020).

Digestate, including FW digestate, is listed as a qualifying raw material for the production of organic fertilizer in the EU Fertilizer Product Regulation (Lu and Xu, 2021). The by-products of AD include biogas and digestate. Biogas is used as energy to generate electricity or fuel, after purification, which could replace fossil fuels and thus reduce carbon emissions (Yasin et al., 2013). Digestate contains organic matter, humic acid, nitrogen (N), phosphorus (P), potassium (K), and other nutrients that are necessary for plant growth (Cheong et al., 2020). Some researchers have studied the agronomic performance of digestate from crop straw, livestock and poultry manures, etc., as organic fertilizers; they proposed that the utilization of digestate by fertilization was an effective method of resource recycling, and could replace chemical fertilizers for agricultural use, so as to reduce carbon emissions and environmental impacts (Ingrao et al., 2018), and to improve soil quality and crop output (Koszel and Lorencowicz, 2015; Riva et al., 2016; Xiao et al., 2017). However, some research that proposed FWDPs could be used as bio-fertilizers usually regarded all nutrient contents as usable nutrients and could replace chemical fertilizers at an equivalent rate, which didn't consider the nutrient losses generated during treatment processes (Cui et al., 2013). This oversight could introduce a large uncertain impact on the nutrient amounts of FWDP input to cropland.

However, with the rapidly rising application of AD in FW disposal, the ever-increasing FW digestate has encountered dilemmas in treatment and recycling in China. The existing landfill and incineration approaches for digestate have resulted in a large amount of resource waste. In addition, FWDPs, including AC and AD products, are difficult to promote as feedstock for commercial organic fertilizers due to the lack of supportive regulations. There are three main causes for this absence of agricultural policy permissions and treatment technologies: first, in contrast to the widely used traditional organic fertilizers (TOFs), the nutrient status and basic characteristics of the FWDPs are not well understood; second, policymakers in China are unsure about FWDPs' effectiveness as organic fertilizers; and third, as the end users of fertilizers, farmers are unaware of the possibilities of using FWDPs, and may be hesitant to accept them. A major influence on the positive side, though, is China's new organic fertilizer standard, issued in 2021, permits FWDPs from sorted and aged FW to be used as the raw materials to produce organic fertilizers. This action opens up a legitimate entrance for the agricultural use of FWDPs and provides official support for further research on the comprehensive impacts of FWDPs on the plant, animal, environmental emissions, etc. before it can be widely applied on cropland.

This study, therefore, aims: (*i*) to understand the fertilizer potential of FWDPs, by comparing the physicochemical and nutritional compositions of three focused FWDPs—FW aerobic compost (FWAC), FW digestate residue (FWDR), and FW digestate biochar (FWDB)—with the major TOFs in China through literature review; (*ii*) to explore the feasibility of substituting partial chemical N fertilizer with N in FWDPs, by constructing a continuous seven-season leafy-vegetable field experiment; (*iii*) to evaluate the agronomic potential and recovery rates of nutrients (N, P, K) from the three FWDPs; and (*iv*) to investigate farmers' awareness and acceptance of FWDPs in Xiamen, southeast China. If FWDPs could work well in farmland as bio-fertilizers or soil amendments, they will connect the path for FW nutrients to return to the soil and close the loop of resource recycling—from soil to soil, which is of great significance to FW management, the food-energy-resource cycle, and the sustainable development of our society.

2. Materials and Methods

2.1. Origin of materials

2.1.1. Description of three FW disposal products

As a FW resource utilization and harmless treatment pilot city, Xiamen, in Fujian Province, southeast China, has established an independent and complete system of FW collection, transportation, treatment, and supervision. This study focuses on the solid residues of FW after AD and AC disposal, to explore their feasibility for agricultural use as organic fertilizer or soil improver. FW digestate is collected from the reCulture Renewable Energy Co., Ltd., in Xiamen city, with a single-phase anaerobic digestion process. The digestate solid fraction is an incompletely decomposed and unstable substance, with unfavorable features such as high moisture content and high viscosity and is difficult to be dehydrated with ordinary mechanical dehydration methods; what's more, it contains biodegradable organic residues and other contaminants that could create phytotoxic risks (Teglia et al., 2011). Thus, post-treatment of digestate is necessary before further utilization. We exploit two post-treatment methods for digestate: (*i*) aerobic composting. Digestate is spread in the open air for about 20 days for sun-drying and composting. After this treatment, the dry matter content of the solid residue reaches 86.2%, compared to 18.9% in the raw stock; (*ii*) pyrolysis. The former aerobic composted digestate residue is pyrolyzed in a rotary furnace under oxygen-limited conditions at 500 ℃ for one hour to produce biochar, whose specific surface area is 38.4 m^2/g. Biochar is a solid pyrolysis product of organic biomass by thermal carbonization at 300-900 ℃, which has abundant refractory organic carbon and well-developed porous structures (Huang et al., 2018). Because of its distinct features, biochar's application in agriculture and effect on the environment has sparked scholars' increasing attention in recent decades.

The AC product comes from the Fujian Technology Create Beautiful Sky Co., Ltd., which uses several kinds of mesophilic bacteria to decompose input FW in a specific microbial processing apparatus. The apparatus's decomposition rate of FW can reach 99% in 24 hours, and the liquid generated during decomposition is treated with a high-temperature deodorization technology, to form water vapor, CO_2, and NH_3, which can be discharged directly into the air. The remaining solid residue consists of fine particles with a low moisture rate and is rich in organic matter and nutrients. The processing apparatus is small in size, occupying very little space, and can be moved to any suitable location for on-site disposal of organic waste.

The compositions of the aforesaid three FWDPs are measured. Chicken manure, a type of organic fertilizer widely used in Xiamen, is also collected and measured for comparison. Their physical and chemical properties are shown in Table 1.

Table 1

Composition contents of three FWDPs and chicken manure in Xiamen.

Organic material	Water content[1] (%)	pH[2]	TOC[2] (%)	TN[2] (%)	C/N[2] (%)	TP[2] (%)	TK[2] (%)
FW aerobic compost	7.6±3.1	6.6±1.0	40.8±9.1	3.5±0.9	12.1±3.4	1.0±0.6	1.4±0.9
FW digestate residue	13.8±4.7	8.2±0.4	24.9±9.9	3.4±1.7	7.6±0.9	2.4±0.4	0.7±0.04
FW digestate biochar	0.9±0.2	12.2±0.2	25.9±0.9	1.6±0.6	20.4±10.3	4.7±1.8	1.7±1.0
Chicken manure	11.9±1.5	7.6±0.6	28.7±6.2	3.0±1.5	11.0±5.3	1.3±0.2	2.0±1.4

Notes: [1] Measured in wet matter. [2] Measured in dry matter.

2.1.2. Literature review on composition contents of major traditional organic fertilizers in China

Organic fertilizer is a critical component in agricultural production, for increasing crop yield as well as improving soil quality. There are many kinds of organic fertilizers in China. Investigating the composition of organic fertilizers is a significant prerequisite to pinpointing their suitability for downstream application, and a basis for determining the proper fertilization amount. We compare the aforesaid FWDPs with TOFs in the Chinese market, with three kinds of indicators, to analyze their availabilities as organic fertilizers: (*i*) total organic matter (TOM) and carbon-nitrogen ratio (C/N); (*ii*) nutrient contents, including contents of total nitrogen (TN), total phosphorus (TP), total potassium (TK), and the sum of the three; (*iii*) basic physicochemical properties, including pH value and soluble salt content. The parameters of TOFs come from copious literatures, books, and research reports about different organic fertilizers in China, which are collected from the Web of Science, the China National Knowledge Internet, and the E-government portals. We collect the detailed composition values of about 20 TOFs in five categories from 1999 to the present: (*i*) human and livestock manures, (*ii*) composting manures, (*iii*) crop straws, (*iv*) cake fertilizers, and (*v*) green manures. The original data, research location, and reference for each fertilizer are listed in Tables S1-S2. Based on these data, the average values and standard deviations of each kind of TOF's indicators are calculated as presented in Table S3.

2.2. Field questionnaire

In order to understand the crop planting habits and awareness about FWDPs of local farmers, we conducted a field questionnaire on fertilizer application types/amounts, farmers' knowledge about FWDPs as organic fertilizers, and farmers' willingness to use FWDPs in Xiamen city, during September and December 2020. The survey was carried out by four of our trained teachers and students through face-to-face interviews with farmers, who were selected at random from a database covering the main farming areas of the city. Altogether, 338 questionnaires are obtained, and 314 of them are eligible, with completed answers, giving an effective rate of 92.9%. The Kaiser Meyer Olkin (KMO) test and Bartlestt's sphericity test of questionnaire data are carried out in SPSS 25.0 to check the questionnaire's validity (Ferguson and Cox, 1993; Wu, 2021). The KMO test coefficient is 0.53 (> 0.5) and the Bartlett sphericity test is significant ($p = 0.00 < 0.05$), indicating good validity of the questionnaire.

Three questions in the questionnaire are designed to discover each farmer's awareness of and acceptance for applying FWDPs as organic fertilizers:

Question 1: Do you know about the disposal products of food waste? (A. Know nothing; B. Know a little C; Know a lot)

Question 2: If there were food waste disposal products on the market, would you be willing to use them as fertilizers? (A. No; B. Not sure; C. Yes)

Question 3: What factors do you care about when choosing food waste disposal products? (open-ended question)

2.3. Field experiment

2.3.1. Experimental site and design

The field experiment is set up at a vegetable field in a suburban area of Houxi Town, Xiamen city, at the geographical coordinate of 118°02'01.31"E, 24°38'16.93"N. A suburban area is a transition zone between an urban district and a rural district, and it is a crucial location for absorbing organic waste generated by city dwellers' production and daily activities. Xiamen belongs to the subtropical maritime monsoon climate area, with a mild and rainy climate. The annual average temperature is about 20.8 °C, the annual average sunshine time is 2233.6 hours per year, the annual average sunshine rate is 51%, and the average annual rainfall is about 1200 mm. Due to the warm climate, sufficient sunshine, and abundant rainfall, Xiamen is suitable for agricultural production all year round, and vegetables and rice are the two main crops. Crops are usually cultivated throughout the year with many cycles, high planting intensity, and great demand for fertilizers. The soil at the experimental site is a brown sandy loam type, and the basic physical and chemical properties of the topsoil (0-20 cm) before our cultivation experiment are presented in Table 2.

Table 2

Soil physical and chemical properties prior to cultivation.

Soil grain diameter (%)	<=0.02 mm	11.3	**Soluble salt (%)**		0.1
	0.02-0.075 mm	18.6	**Constituent mass**	**Soil organic matter ($g\cdot kg^{-1}$)**	1.4
	0.075-0.25 mm	33.1		**TN ($g\cdot kg^{-1}$)**	1.0
	0.25-1 mm	33.8		**NH_4^+-N ($mg\cdot kg^{-1}$)**	11.1
	>=1 mm	3.2		**NO_3^--N ($mg\cdot kg^{-1}$)**	45.5
Soil type		Sandy loam		**TP ($g\cdot kg^{-1}$)**	1.5
Soil bulk density ($g\cdot cm^{-3}$)		1.4		**TK ($g\cdot kg^{-1}$)**	1.8
Total porosity (%)		46.0		**Available phosphorus ($mg\cdot kg^{-1}$)**	110.2
pH		4.6		**Available potassium ($mg\cdot kg^{-1}$)**	287.5

Considering the advantages and disadvantages of organic fertilizers and chemical fertilizers, balanced application of the two has become an effective fertilization approach, which can not only increase crop yield and nutrient uptake efficiency, but also increase soil organic matter, optimize the soil microbial community structure, and maintain protracted soil productivity (Ning et al., 2017). Previous research reveals that intermediate substitution (20%-40%) of chemical fertilizer N by organic fertilizer N could significantly improve nitrogen use efficiency and crop yield (Zhang et al., 2020). Therefore, this study selects the aforesaid three FWDPs as organic fertilizers to carry out the field experiment, replacing 30% of N contained in local conventional chemical fertilizer, for detecting their effects on crop yield. Two local conventional fertilizing modes are set as control treatments: fertilizing (*i*) with chemical fertilizer alone and (*ii*) with chemical fertilizer combined with chicken manure. Five fertilizer treatments are set up in a completely random block design: (1) conventional chemical fertilizer N (Treatment A); (2) conventional 30% chicken manure N and 70% chemical fertilizer N (Treatment B); (3) 30% FW aerobic compost N and 70% chemical fertilizer N (Treatment C); (4) 30% FW digestate N and 70% chemical fertilizer N (Treatment D); (5) 30% FW digestate biochar N and 70% chemical fertilizer N (Treatment E). There are three replicates for each fertilizer treatment. Each experimental plot size is 2.5 m × 8 m (20 m^2), containing a planting size of 1.7 m × 8 m (13.6 m^2) and a ridge of 0.5-m width. In order to avoid the interaction of water and fertilizers among different treatments, each plot is separated from adjacent ones by a 0.8-mm thick and 0.5-m deep plastic film buried in the soil.

2.3.2. Field fertilization and management

As leafy vegetables are widely grown crops in Xiamen, we choose two kinds of leafy vegetables (pakchoi and swamp cabbage) as our cultivating objects. In a total of 13 months from April 2021 to May 2022, we conducted seven seasons' field cultivating experiments, including (1) pakchoi (April 9 to May 8, 2021), (2) swamp cabbage (June 15 to August 30, 2021), (3) pakchoi (September 2 to September 28, 2021), (4) pakchoi (October 13 to November 10, 2021), (5) pakchoi (December 2, 2021 to January 11, 2022), (6) pakchoi (January 29 to March 14, 2022), and (7) pakchoi (April 10 to May 8, 2022).

The total N, P, and K contents used in all treatments are the same. Based on the field questionnaire, we obtained local conventional fertilization quantities of N, P and K used on leafy vegetables, and applied the fertilization values as our experiment's specified fertilization dosages for each treatment, which are 375 kg N ha^{-1}, 98 kg P ha^{-1} and 218 kg K ha^{-1}, respectively. The growth period of pakchoi is short, about 28 days in the warm months from March to November, and 40 days in the winter, from December to February of the following year. Swamp cabbage has a long growth period of about 75-80 days. The seed quantity of pakchoi is 42 g per plot in the first season, and then is adjusted to 33 g per plot. Pakchoi seeds are scattered evenly into every plot by a skilled farmer and then ploughed into the topsoil. Swamp cabbages are transplanted with seedlings from surrounding farmer's fields, with a density of 12 plants/m^2.

The ratio of basal dressing to top dressing is 6:4 for N. The specific application amount of different organic materials is calculated based on 30% of the N application amount (namely 112.5 kg N ha^{-1}) and the corresponding TN content is exhibited in Table 1. The chemical fertilizers used are urea (N 46%), superphosphate (P_2O_5 12%), and potassium sulfate (K_2O 50%). If the P or K content in organic fertilizer is insufficient to 98 kg P ha^{-1} or 218 kg K ha^{-1}, additional single superphosphate or potassium sulfate will be added in to reach the specified P/K dosage. The P and K fertilizers are completely applied as basal fertilizer before planting.

Cultivating management practices like irrigation, pest and disease control, and weed control are carried out in accordance with local conventional measures and keep the same among different treatments. Vertical rotating sprinkler irrigation equipment is used for irrigation, and the irrigation amount of each treatment is the same. Irrigate once a day during the rain-free period when the soil surface looks dry, according to farmers' experience; irrigate once after topdressing the soil surface with urea. Pesticides are normally used 2 times during the vegetables' growing period.

The biomasses of the plants' aboveground portion of a 1 m × 1 m (1 m^2) area from each plot (avoiding the marginal area) are collected and weighed after each season's harvest. Crop yield is defined as the fresh weight of the aboveground biomass. Because of the long growth period of swamp cabbage, the aboveground stems and leaves are harvested three times, on July 18, August 2, and August 30, 2021; and the yield of swamp cabbage is taken as the sum of the three harvests.

2.4. Statistical analysis

SPSS 25.0 statistical software (IBM, Armonk, NY, USA) is adopted for data analysis, and Duncan's Multiple Range test in One-Way ANOVA test is executed to assess the significant differences of indicators among different organic fertilizers and crop yields of different treatments at the 5 % level ($p < 0.05$). SigmaPlot 14.0 software (Inpixon, Palo Alto, CA) is used to draw relevant statistical analysis charts.

3. Results and Discussion

3.1. Composition comparison of food waste disposal products and traditional organic fertilizers

3.1.1. Total organic matter and C/N

Organic matter is a pivotal component of soil and an important source of nitrogen, carbon, and other nutrients in soil. Soil organic matter (SOM) is generally regarded as a key index to reflect soil fertility (Schroth and Sinclair, 2003). SOM has a colloidal characteristic that enables it to adsorb a large number of cations, so that soil has preservation capacity and buffer action of water and fertility (Triberti et al., 2008). Besides, SOM plays an important role in loosening soil and improving soil physical properties, and it also provides essential energy and a carbon source for soil microbes (Adekiya et al., 2020; Iqbal et al., 2020). The application of organic fertilizer is a major way of supplementing SOM (Gao et al., 2018). The higher the content of TOM in fertilizer, the more it can be used by crops and microorganisms. As shown in Fig. 1(1), the TOMs of all three FWDPs are above the minimum level (30.0%, in DW) set in China's new organic fertilizer standard (NY/T 525-2021), in the order FWAC (70.4%) > FWDB (44.6%) > FWDR (42.9%). Crop straws, crop cakes, and green manures have higher TOM than most other kinds of TOFs at a range of 59.7%-79.3%. FWAC is within this range, with no significant differences. Human and livestock manures' TOM contents are distributed at 42.3%-74.6%. RaM (74.6%), HuM (72.5%), and PiM (64.6%) occupy the top three slots of this category's fertilizers. After an anaerobic fermentation process, organic matter in food is decomposed by anaerobes into small molecular compounds, producing CH_4, CO_2, water, etc. (Zhang et al., 2019). In consequence, the mean TOM content of FWDR is relatively low, reaching only about 60.9% that of FWAC; while it is close to the TOM contents of ChM, DuM, and FaM. Accordingly, the three FWDPs have rich TOM contents, comparable to those of many animal manures, and FWAC, especially, is a high TOM-containing organic substance.

C/N is a vital index for measuring compost maturity and organic fertilizer's nutrient balance (Bernal et al., 2009). Furthermore, it plays an important role in the metabolism of microorganisms (Forster-Carneiro et al., 2008). If the C/N of an organic fertilizer is too low, the energy required for microbial growth and reproduction will be limited; inversely, when an organic fertilizer's C/N is too high, it is easy to cause soil nitrogen deficiency, thus affecting the growth and development of crops. Decomposed organic fertilizer with C/N less than 20 can be applied to farmland directly (Lin, 2008). Except for crop straws, which have rather high C/N values (50.5-65.3), other categories of fertilizers are concentrated in the range of 4.9-20.4, showing no significant differences (Fig. 1(2)). The average C/N values of FWAC, FWDR, and FWDB are 12.1, 7.6, and 20.4 respectively. FWDR has a relatively low C/N, mainly because its feedstock experiences unbalanced degradation velocities of carbohydrates and proteins, and loses more carbon than N during the anaerobic digestion process (De Gisi et al., 2018). FWDB has a higher C/N, as its TN is much lower than both FWAC and FWDR (Table 1). Hence, the three by-products generated from FW are good organic fertilizers from the C/N perspective.

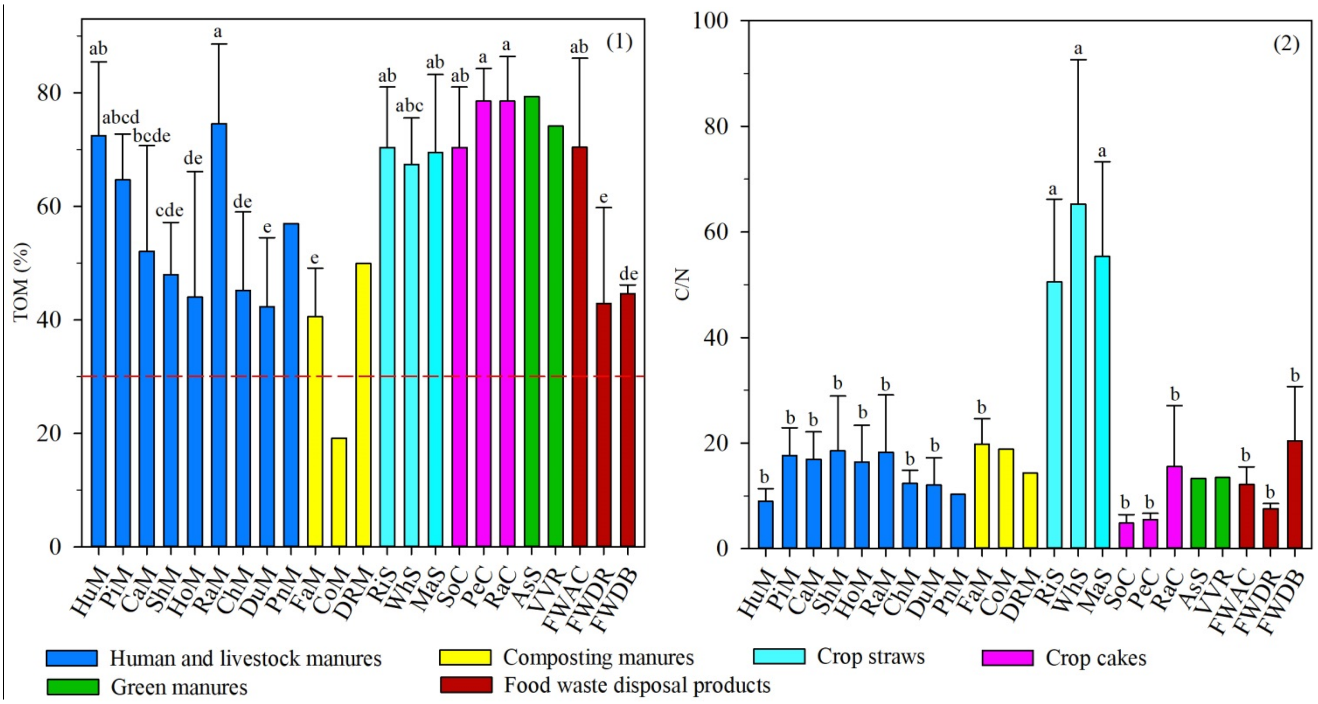

Fig. 1. (1) TOM and (2) C/N contents of different organic fertilizers.

Notes: The red dotted line represents the minimum level of OM proposed in China's new organic fertilizer standard (NY/T 525-2021). The black error bars indicate the standard deviations. The average values' significant differences are analyzed by Duncan's Multiple Range test in One-Way ANOVA test. Identical letters above the error bars indicate no statistically significant differences among different organic fertilizers, while different letters indicate significant differences ($p < 0.05$. The same as below). Multiple labeled letters like 'ab' represent the statistically insignificant differences between a and ab, b and ab. Average value without an error bar (such as CoM) indicates only one value is collected and does not take part in the significance analysis.

3.1.2. Nutrient compositions

N, P, and K are crucial indicators for determining organic matter's agronomic function, as they quantify essential nutrients for crop growth (Teglia et al., 2011). N is one of the most active nutrient elements in soil, and a large amount of this nutriment is required by crop growth. As seen from Fig. 2(1), SoC and PeC in the crop cakes category contain the highest TN proportions, reaching 7.2% and 7.0%, significantly exceeding other matters, followed by HuM and RaC at 5.4% and 4.8% respectively. The TN contents of livestock manures range from 1.6% to 4.0%, situated in the middle level of all fertilizers.

The three FWDPs' TN contents are 3.5% (FWAC), 3.4% (FWDR), and 1.6% (FWDB), falling in the TN range of livestock manures. FWDB's TN content is about 0.5 of FWDR's, indicating that N volatilization occurs during FWDR's pyrolysis process to transform into FWDB. The TN contents of composting manures vary in the range of 0.7%-2.0%, and crop straws distribute at 0.8%-0.9%, lower than most other kinds of fertilizers.

The TP contents of the organic fertilizers vary from 0.3% (VVR) to 4.8% (FWDB) (Fig. 2(2)). The TP contents of PiM (2.3%) and ChM (2.1%) occupy the top two slots, and HoM (0.6%) is at the bottom, in the human and livestock manures category. Crop cakes' TP contents are 1.1% (PeC) to 1.7% (RaC). Composting manures, crop straws, and green manures remain at a comparatively lower TP content level, ranging from 0.3% (VVR) to 0.8% (DRM). The TP contents of FWDPs are in the order of FWDB (4.7%) > FWDR (2.4%) > FWAC (1.0%). FWDB's TP content is twice that of its precursor FWDR, manifesting a large degree of P accumulation during FWDR's pyrolysis process.

The TK contents of the organic fertilizers are distributed in the range of 0.6%-2.4% (Fig. 2(3)), with VVR and AsS having the highest TK values while FWDR has the lowest. The TK contents of human and livestock manures are concentrated among 0.9%-2.1%, and ChM (2.1%), PnM (2.0%), and HuM (1.8%) are the top three among them. TK contents vary at 0.9%-1.4% for composting manures, at 1.2%-2.1% for crop straws, and at 1.1%-1.8% for crop cakes. FWDPs' TK contents are in the order of FWDB (1.8%) > FWAC (1.4%) > FWDR (0.7%). Similar to the correlation of FWDB's and FWDR's TP contents, FWDB's TK content is 2.8 times that of FWDR's, which shows a cumulative trend of K during FWDR's pyrolysis process.

We add the TN, TP, and TK of every fertilizer together to get its total nutrient content, as displayed in Fig. 2(4). The new organic fertilizer standard (NY/T 525-2021) reduces the requirement of organic fertilizer's total nutrient content from no less than 5% (in DM) in the previous edition (NY 525-2012) to 4%, lowering the nutrient access threshold of organic fertilizer production. This change also sends the signal that the Chinese government encourages organic waste to be reused for farming as organic fertilizer. The total nutrient contents of FWDPs are in the order of FWDB (8.0%) > FWDR (6.4%) > FWAC (5.1%), all of them are above the minimum total nutrient content requirement for organic fertilizer. Crop cakes have rather higher total nutrient content, distributed as SoC (10.3%) > PeC (9.6%) > RaC (7.6%). Combined with their high TOM content, crop cakes are imbued with organic matter and nutrient elements, especially N. In light of the national organic fertilizer quality grading standard, crop cakes belong to the first grade of organic fertilizers (NATESC, 1999). HuM is also rich in total nutrient content (9.4%), higher than any livestock manure. Human manure has always been used as a good organic fertilizer during traditional agricultural cultivation in China because of its complete nutrients, zero cost, and rapid fertilization effect (NATESC, 1999; Yang et al., 2021), as well as being a benign soil regulator and humus supplement (Cofie et al., 2009). While with the advent of rural toilet renovation projects and the adoption of flush toilets, the inevitable result is a large quantity of feces slurry with high water content and low reuse efficiency. PnM, ChM, and PiM follow HuM in the total nutrient content, at 7.2%, 6.8%, and 6.4%, respectively. FWDB's total nutrient content is a little higher than PnM's or ChM's. FWDR's total nutrient content is slightly higher than PiM's. FWAC's total nutrient content is close to DuM's. Green manures possess a moderate level of total nutrient content amongst the TOFs, at about 6%. Crop straws have relatively less total nutrient content, distributed as RiS (3.4%) > WhS (2.5%) > MaS (2.1%), all below the suggested minimum limit of total nutrient content in the organic fertilizer standard, while they have advantages in terms of TOM and the C/N. The three FWDPs have higher nutrient contents than composting manures. Composting manures also have low total nutrient content, at 2.0%-3.7%, as their crude materials are usually complex and contain a large proportion of low-nutrient materials, such as hay, soil, leaves, etc. (NATESC, 1999).

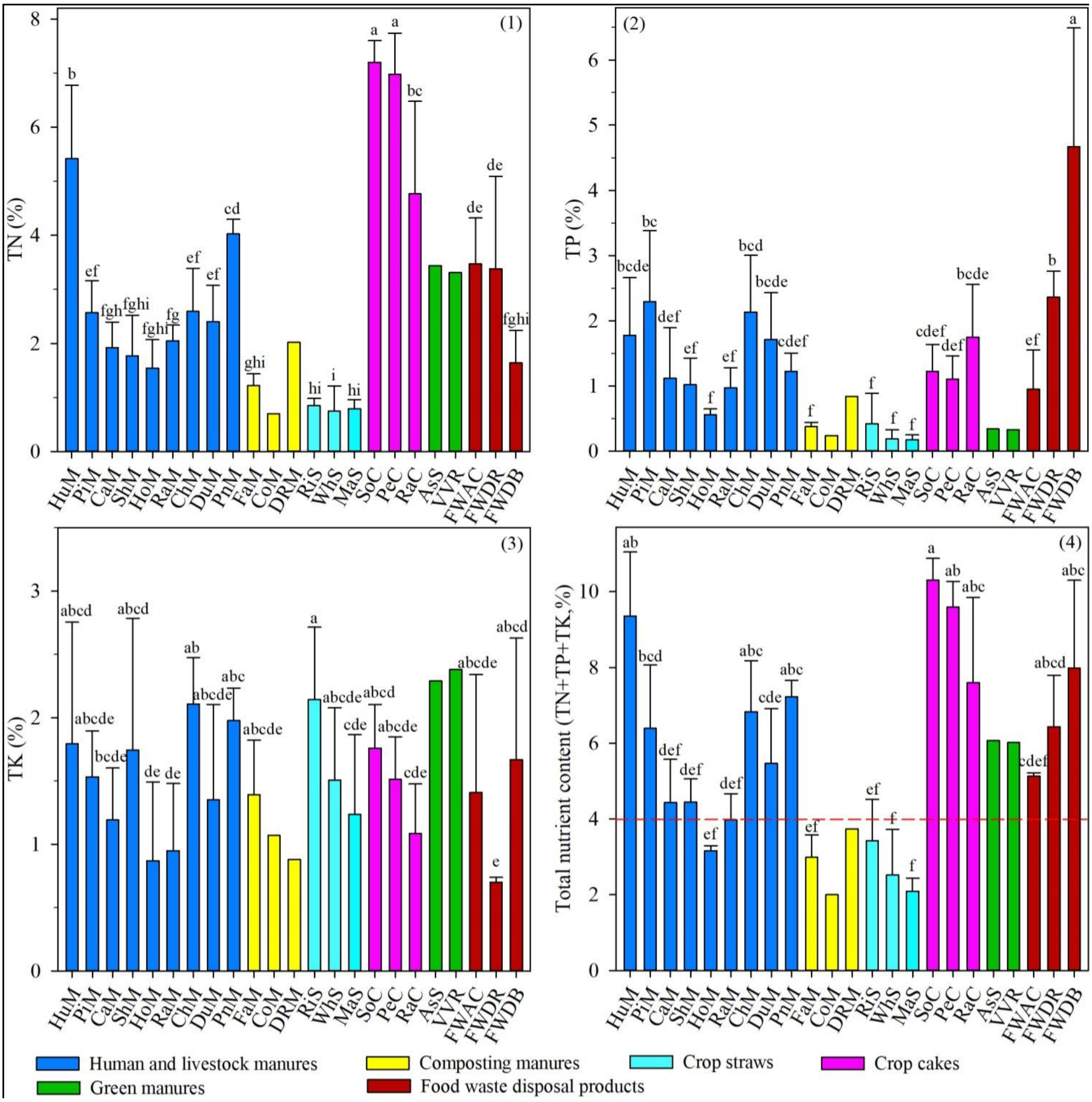

Fig. 2. Nutrient compositions of different organic fertilizers: (1) TN, (2) TP, (3) TK, and (4) the sum of the three. Notes: The red dotted line represents the minimum level of total nutrient content proposed in China's new organic fertilizer standard (NY/T 525-2021).

3.1.3. pH and salt content

pH is an important factor affecting microbial growth and reproduction. According to the provision on organic fertilizer standard, the pH value of organic fertilizers is suitable at 5.5-8.5. We collected the pH values of 15 types of TOFs in three categories and compared them with the FWDPs, as displayed in Fig

3(1). The pH values of human and livestock manures are neutral or slightly alkaline, within 7.0-8.2. Composting manures are slightly alkaline (pH 7.6-8.2), and crop straws are neutral or slightly alkaline (pH 6.8-8.1). These TOFs all fulfill the organic fertilizer standard in terms of pH range. The pH values of FWAC and FWDR are 6.6 (neutral) and 8.2 (slightly alkaline), which also meet the suitable pH range for organic fertilizers. During the anaerobic digestion process of FW, aliphatic acids are degraded and calcium ions are released from the degradation of organic matter, contributing to the rise of FWDR's pH (Weiland, 2010). The pH value generally varies at 6.7-8.4 (neutral and slightly alkaline) during the anaerobic digestion process (Chuka-ogwude et al., 2020), and in this environment the microbes are active and biogas production is high in the digester. However, FWDB has the highest pH value of 12.2, being strongly alkaline and significantly higher than other organic fertilizers. FWDB's pH value is 1.5 times that of its precursor FWDR, revealing that salts of alkali and alkaline earth elements are gathered and acidic elements are removed during carbonization. Correspondingly, the high pH value of FWDB might not support its direct use on agricultural soil, at least not in large amounts.

Chinese dietary habits dictate that a substantial dose of salt is added into food when cooking. FW often contains a lot of salt, with the salt content ranging from 1.3% to 2.6% (Lü et al., 2017). In order to increase animal productivity, mineral salts are routinely added to animal feed in livestock and poultry farms, leading to livestock manures containing a substantial amount of salt. Application of organic fertilizers with high salinity tends to cause salt accumulation in soil, inhibiting crop seed germination as well as crop growth. The soluble salt contents of FWDPs are in the order of FWDB (7.6%) > FWAC (3.2%) > FWDR (1.3%) (Fig 3(2)). FWDB's soluble salt content is about 5.8 times that of its feedstock FWDR, testifying to a large aggregation of soluble salt during the pyrolysis process of FWDR. FWAC's soluble salt is between that of PnM (4.5%) and ChM (2.4%). FWDR's soluble salt is close to PiM's (1.7%), significantly lower than FWAC, mainly because partially soluble salt is carried away by water during the anaerobic digestion process, and only a small amount of residual soluble salt remains in the digestate. A field experiment done by Yao et al. (2007) showed that the soil total soluble salts increased when successively high rates of chicken and pigeon manures were applied in Guangzhou, a region with abundant rainfall in south China, which brought potential risk for secondary soil salinization. Another study forecasted that soil would reach a moderate salinization level when livestock manures were applied in salinized soil at medium or high fertilizing rates after 2-3 years of accumulation, while soil salinity would not increase significantly when livestock manures were applied at low fertilizing rates

(Wang et al., 2008). Hence, in terms of soluble salt indicator, FWDB might be unfit to apply directly to soil as an organic fertilizer in large amounts; and FWAC and FWDR have the potential risk of causing soil salinization. Determining the specific effect of salt on soil and crops, however, requires further field experiments.

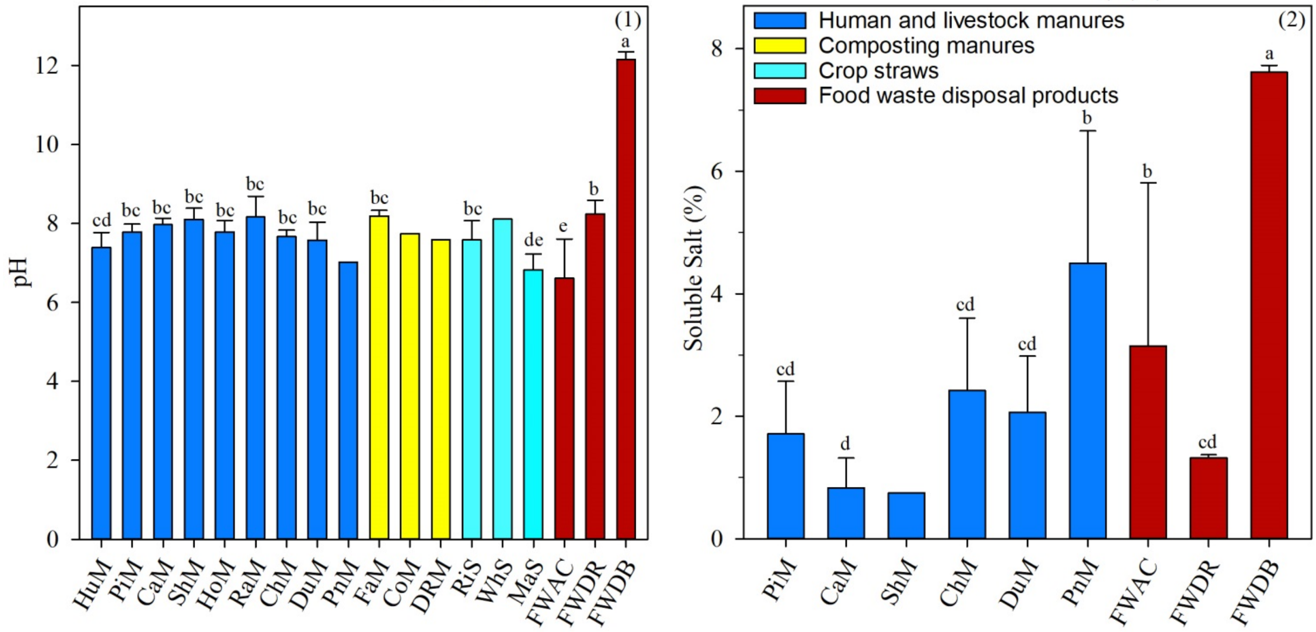

Fig. 3. (1) pH and (2) soluble salt values of different organic fertilizers.

3.2. Effects of food waste disposal products on leafy vegetable yields

As seen from Fig. 4, in the first season of pakchoi (S1), yields follow the rank of Treatment C (41.2 $t\ ha^{-1}$) > Treatment A (40.3 $t\ ha^{-1}$) ≈ Treatment B (40.2 $t\ ha^{-1}$) > Treatment D (37.2 $t\ ha^{-1}$) > Treatment E (33.6 $t\ ha^{-1}$). Compared with conventional Treatments A and B, the yield of Treatment D reduces by 7.6% and 7.4% respectively, and Treatment E reduces by 16.6% and 16.3% respectively. No significant differences occur among different treatments, indicating the yields of the five treatments lie on the same level. The yields of swamp cabbage in the second season (S2) follow the rank Treatment B (55.3 $t\ ha^{-1}$) > Treatment A (53.6 $t\ ha^{-1}$) > Treatment C (50.9 $t\ ha^{-1}$) > Treatment E (49.9 $t\ ha^{-1}$) > Treatment D (44.6 $t\ ha^{-1}$). Treatments C and E show no obvious differences from Treatment A or B. Treatment D is 19.3% (significantly) lower than Treatment B and 16.8% (insignificantly) lower than Treatment A. From the third season (S3) to the seventh season (S7) of pakchoi, with the accumulation of cultivating times, the yields of Treatments B, C, and D show increasing trends, while the yields of Treatment A remain almost constant. In the S3's pakchoi, both yields of Treatments C (31.4 t/ha) and D (29.9 t/ha) are higher than Treatments A (24.7 t/ha) and B (24.9 t/ha), which increase 27.2% and 21.1% respectively compared with Treatment A. Treatment E's yield (21.3 t/ha) is slightly lower than Treatments A, B. No significant differences occur among the five treatments. Compared with Treatment A from S4 to S6, the yields of Treatment C significantly increase by 35.6%, 63.9%, and 29.4% respectively, and the yields of Treatment D significantly rise by 36.7%, 65.3%, and 23.9% respectively. In S7, the yields of Treatments C and D are 28.9% and 42.9% higher than that of Treatment A, while no significant differences occur. Traditional organic fertilizers have positive effects on arable soil and crops, and have been widely recognized and applied by Chinese farmers. The yields of Treatments C and D also surpass those of Treatment B during S3-S7. Compared with Treatment B from S3 to S7, the yields of Treatment C increase from by 26.4% to by 8.0%, and the yields of Treatment D increase from by 20.4% to by 19.7% respectively, but have not yet reached significant increases. It shows that the agronomic performance of FWAC and FWDB as organic fertilizers can be comparable to conventional chicken manure.

In terms of the total yields of the seven seasons' vegetables, Treatment C achieves the largest yield (266.3 t ha^{-1}), 21.5% and 8.0% higher than those of Treatment A (219.3 t ha^{-1}) and Treatment B (246.5 t ha^{-1}) respectively, showing a significant difference with Treatment A and an insignificant difference with Treatment B. The yield of Treatment D (256.9 t ha^{-1}) comes second, significantly 17.2% higher and insignificantly 4.2% higher than the yields of Treatment A and Treatment B respectively. The yield of Treatment E (225.5 t ha^{-1}) is close to that of Treatment A and 8.5% lower than that of Treatment B, showing insignificant differences with Treatments A and B. Many studies have proved that a sustained and stabilized release of nutrients from organic fertilizers' organic matter improves the physio-chemical properties of soil and is beneficial to the absorption of N, P, and K in leaf tissues, as compared to chemical fertilizer alone (Adekiya et al., 2020; Geng et al., 2019). Our results also demonstrate that FWAC and FWDR could be viable alternatives for chemical fertilizer and reach better agricultural effects than conventional chicken manure, when 30% of the chemical N fertilizer is substituted with FWAC, FWDR, and conventional chicken manure.

FWDB has lower TN, higher TP and TK, and higher pH and soluble salt content than FWAC or FWDR. At the same substitution level of 30% organic N instead of total chemical fertilizer N, the application quantities of ChM, FWAC, FWDR, and FWDB are 4256.5 kg ha^{-1}, 3478.7 kg ha^{-1}, 3838.5 kg ha^{-1}, and 7095.1 kg ha^{-1}, respectively. Applying FWDB in large quantities brings more alkaline and saline inputs to the soil, which might be phytotoxic to plants and inhibit seed germination and even change soil pH, having a negative effect on crop growth. As the yields of Treatment E are slightly lower than those of Treatment A from S1 to S4, it is considered that FWDB restrains the vegetables' growth at the current application amount of 30% FWDB N substituted for an equal amount of chemical N fertilizer. Therefore, FWDB is not suitable to be used as organic fertilizer at high application rates. Starting from S5, we adjusted the fertilizer amount of Treatment E to 10% FWDB N and 90% chemical fertilizer N. The yields of Treatment E increase by 16.3% in S5 to 23.2% in S7 relative to Treatment A, manifesting FWDB applied as a soil amendment in low application rates (2365.0 kg ha^{-1}) can improve soil quality and consequently promote crop growth. This result is consistent with previous studies on other kinds of biochar in agricultural experiments. Xie et al. (2020) investigated cucumber growth and the uptake of potentially toxic elements in soilless cultivation, with growth substrate amended with different proportions of sewage sludge biochar (0, 5, 10, 15, and 20 wt%); they found that 10 wt% biochar added was optimal for reaping high cucumber biomass with low environmental risk. A lower application rate of N-enriched biochar (4 t ha^{-1}) produced from rice straw and waste wood could maximize rice yield and soil organic carbon accumulation, without increasing soil carbon emissions; while a higher rate of biochar was found to be detrimental to plant nutrition and development (Yin et al., 2021).

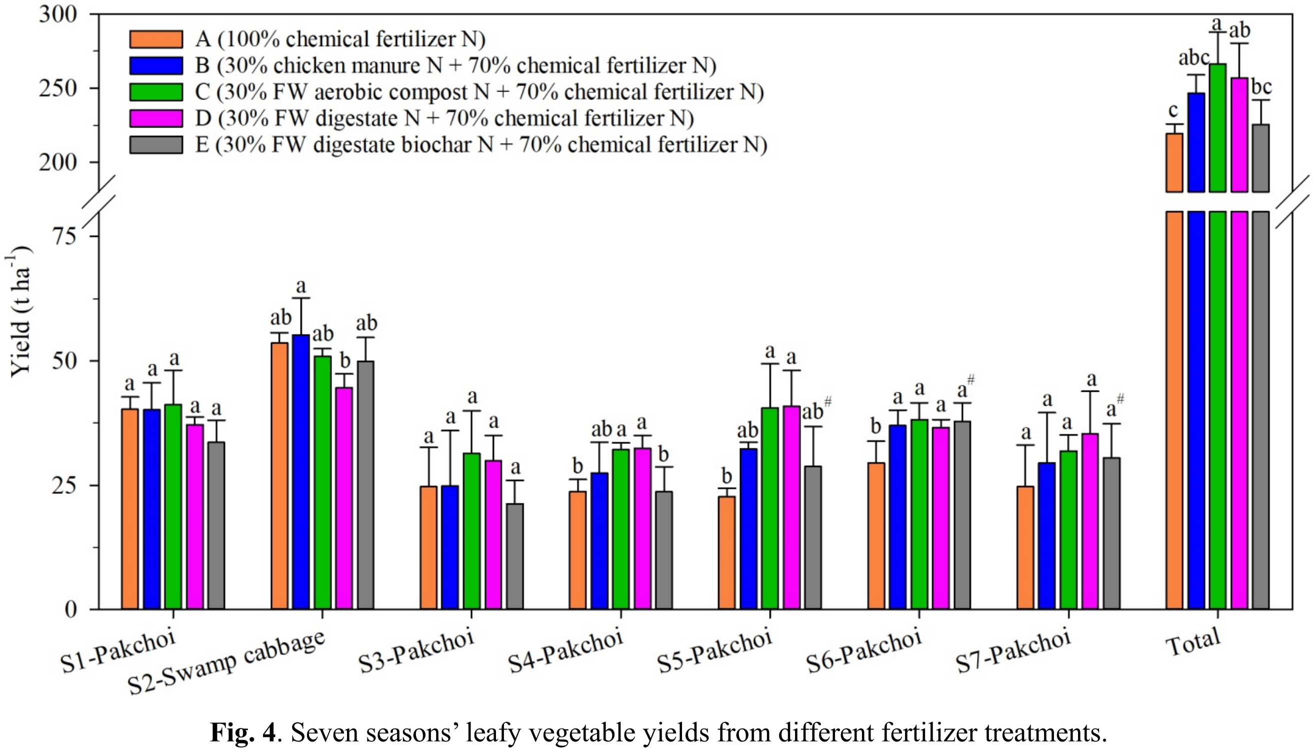

Fig. 4. Seven seasons' leafy vegetable yields from different fertilizer treatments.

Notes: S1-S7 means the first to the seventh cultivating season. # Indicates that we change the fertilizer amount of

Treatment E to 10% FWDB N and 90% chemical fertilizer N during S5-S7. Identical letters above the error bars indicate that no statistically significant difference occurs among different treatments of each crop, while different letters indicate significant differences occur ($p < 0.05$).

3.3. Food waste disposal products' application potential and prospects

3.3.1. Agronomic potential and prospects of food waste disposal products

China has recently been engaged in finding efficient and eco-friendly methods to treat FW. The year 2021 marks the beginning of China's 14th Five-year Plan, and an important turning point in the development of FW disposal. China's new organic fertilizer standard permits FWDPs' access to agricultural use as organic fertilizers. In the meantime, the National Development and Reform Commission, Ministry of Housing and Urban-Rural Development compiled the "14th Five-year Plan for MSW Classification and Treatment Facilities Construction", proposing to choose suitable FW treatment methods to settle the barriers occurring in the application of biogas residue and slurry derived by composting processes to agriculture and forestry production; to proactively promote FW recycling technologies to produce biodiesel, biogas, soil amendments, bio-protein, and other products from FW, befittingly. Our multiple crop seasons field experiment confirms that FWAC has a favorable effect on increasing vegetable yields, in agreement with previous studies (Hou et al., 2017; Man et al., 2021). More importantly, it also indicates that FWDR as organic fertilizer could increase yields when combined with chemical fertilizer, and FWDB with a low substitution amount of chemical fertilizer N could achieve higher yields than using chemical fertilizer alone. The results provide two treatment methods and two derivatives of FW digestate. Although composting of digestate residue consumes more energy and emits more ammonia compared with incineration and landfill, it has the lowest global warming potential (Chen, et al., 2021). Corresponding approaches are needed to valorize digestate and reduce GHG emissions during its post-treatment process. Hence, it is feasible to apply the by-products of urban FW as organic fertilizers to suburban cropland systems, and to close the cycle of food waste resources in the urban-suburban region. Under the favorable conditions of current policies, once meeting the relevant regulatory standards, the different FWDPs—FWAC, FWDR, and FWDB—are viable to be produced as commercial organic fertilizers or soil amendments and applied to farmlands and forests.

According to our surveys on the tested FW microbial aerobic compost plant and AD digestate plant, we analyzed the outputs and main compositions of different FWDPs and calculated the recovery rates of N, P, K from FW to FWDPs (the ratios of TN, TP, TK amounts in the FWDPs to those in the original FW). The nutrient components of local FW are displayed in our published report (Huang et al., 2022). As shown in Fig. 5, treating 1 t FW will produce an average of 100.0 kg aerobic compost in a microbial aerobic decomposition process, which could replace 3.2 kg, 0.9 kg and 1.3 kg of chemical fertilizers N, P, and K amounts simultaneously with respect to FWAC's nutrient contents (Table 1), or could generate 61.5 kg of solid digestate residue with the anaerobic digestion process. Under our aerobic composting and pyrolysis treatments, these residues will produce an average of 13.5 kg FWDR compost or 5.3 kg FWDB. Almost 1,400 t d^{-1} of restaurant FW is generated in Xiamen city in 2020 (Ye, 2019), while only about 452 t d^{-1} of restaurant FW is collected and transported to the AD plant. The rest is sent for incineration together with other household waste. About 27.8 t d^{-1} solid digestate remains after anaerobic digestion and initial dehydration process, and the solid digestate is sent for landfill. Supposing the digestate were recycled to produce bio-fertilizer or soil amendment, about 6,100 kg d^{-1} (equal to 2,227 t yr^{-1}) of FWDR or 3,100 kg d^{-1} (equal to 1,132 t yr^{-1}) of FWDB could be generated. Every 100 kg FWDR would supersede an equivalent of 2.9 kg N, 2.1 kg P, and 0.6 kg K from chemical fertilizers. Thus, about 65.3 t N, 46.1 t P, and 13.4 t K from chemical fertilizers could be reduced per year if 6100 kg d^{-1} FWDR were produced and reused as organic fertilizer. According to the Yearbook of the Xiamen Special Economic Zone (2021), the pure chemical fertilizer amount used in Xiamen in 2020 is 10,694 t, including 2,349 t fertilizer N, 1,186 t fertilizer P_2O_5, 1,945 t fertilizer K_2O, and 5,214 t compound fertilizers. After N, P, and K elements equal conversion calculation, the amount of FWDR could replace 5.6% of chemical fertilizers that contain 1.6% N, 3.6% P, and 0.4% K simultaneously. Ideally, supposing all 1,400 t d^{-1} restaurant FW generated in Xiamen were collected and treated by AD and then all the digestate residue were converted to organic fertilizer, 6,899 t yr^{-1} of FWDR — equivalent to chemical fertilizers of 202.1 t N, 142.7 t P, and 41.6 t K — would be produced every year; accordingly, 31,427 t yr^{-1} semi-liquid digestate residue would be withheld from landfills. The FWDR could result in a total of 17.5% (including 4.9% N, 11.2% P, and 1.4% K) substitution ratio of chemical fertilizers, having great potential for replacing chemical fertilizers. The assumption also indicates it is of great importance to increase the level of FW collection, transportation, and treatment, and to increase the outputs of FW by-products (biogas, biodiesel, and bio-fertilizer). Thereby, AC and AD are two practicable FW disposal methods that can realize resource recovery with agricultural applications of their derivatives.

Considering the advantages and disadvantages of AC and AD, the AD process will dominate the FW disposal market, and AC can be adopted to treat scattered FW in rural or suburban areas that are remote to urban areas and inconvenient to collect and transport FW, as a complementary process to AD. Reusing the FWDPs as organic fertilizers or soil amendments while discharging them as waste will change the destination of FW from "waste" in landfills to "wealth" on cropland, avoiding land occupation and environmental burdens from FW disposal residue, returning nutrients to the soil, and closing the food circulation loop.

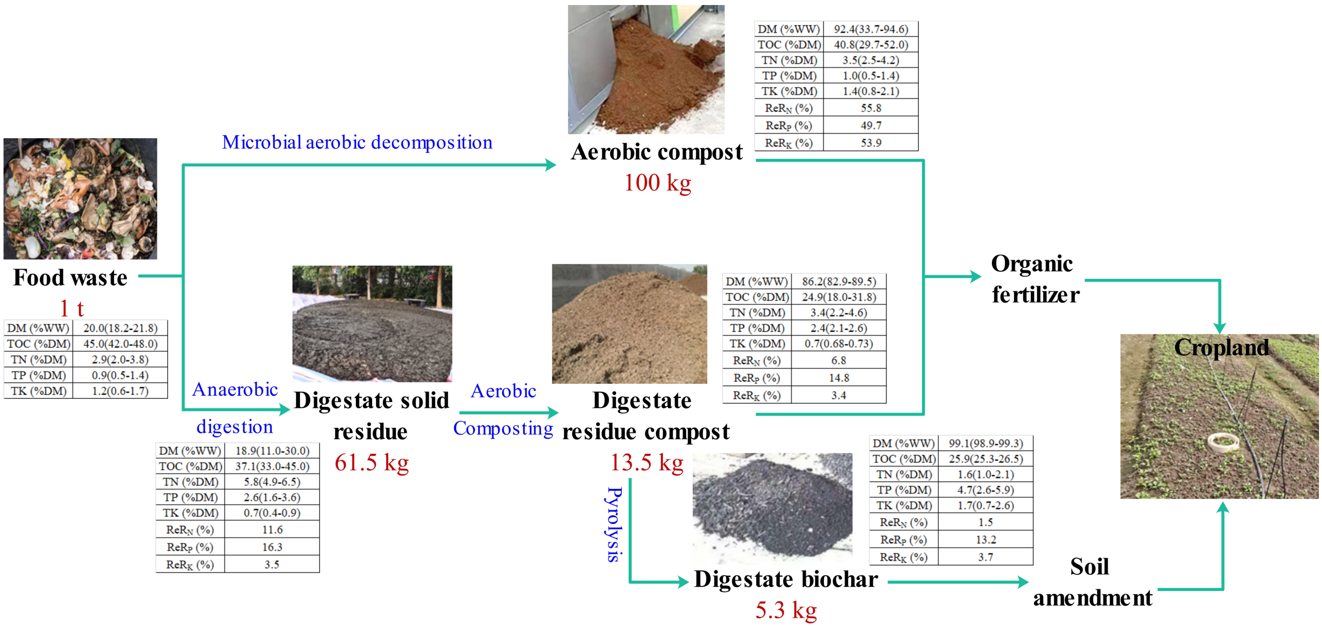

Fig. 5. The outputs, main compositions, and recovery rates of different by-products of 1 t FW through different treatments.

Notes: WW – wet weight; DM – dry matter. ReR_N, ReR_P, and ReR_K refer to the recovery rates of N, P, and K respectively.

As shown in Fig. 5, nutrient elements are generally lost during various disposal processes. FWAC has the highest N, P, and K recovery rates, at 55.8%, 49.7%, and 53.9% respectively, among the three FWDPs. FWDR has a low N recovery rate at only 6.8%, as NH_3 is generated and is volatilized in the organic matter degradation process and the dehydration process of the AD disposal and composting process. Dehydration also takes away portions of P and K elements from digestate residue, leading to limited P and K recovery rates from FWDR. During the pyrolysis process, the N recovery rate of FWDB continues to decrease substantially, while P and K recovery rates of FWDB change very little, indicating that FWDR and FWDB have relatively better recovery efficiencies of P than of N or K. The nutrient recovery rates of different FWDPs will provide parameters for the analysis of material flow in FW circulation.

3.3.2. Agronomic benefits and extended applications of food waste biochar

As analyzed in Section 3.1, we conclude that FW digestate biochar has four high contents: high TOM, high total nutrient content, high pH, and high soluble salt. The variations among seven seasons of leafy vegetables' yields in our plantation experiment illustrate that FWDB is inappropriate to use as an organic fertilizer in large quantities, unlike FWAC and FWDR; whereas it will be a good alternative for the farmland ecosystem as a soil amendment with low application amounts (2365.0 kg ha^{-1} in this study).

Previous research has proved that biochar is a cost-efficient product for increasing soil carbon stocks (Anyaoha et al., 2018), improving soil properties (Dunnigan et al., 2018; Tauqeer et al., 2022), reducing N_2O emissions (Borchard et al., 2019), and enhancing crop growth (Hale et al., 2020). The agronomic function of biochar is mainly determined by its physicochemical properties and soil texture. Research is also active on biochar post-processing for further functionalization improvement (Albanese et al., 2019). When applied to soil, FWDB's strongly alkaline property will be bound to affect the soil pH. Many studies have indicated that the high pH of biochar could increase the pH of acid soils (Hass et al., 2012; Shetty et al., 2021). Acid soils are broadly distributed in tropical and sub-tropical areas and occupy a main portion of the world arable land (Kochian et al., 2004). As excessive and long-term use of chemical fertilizers has exacerbated soil acidification, alkaline digestate biochar will be a benign remediator to modulate soil pH and relieve acidification. Additionally, as FWDB is rich in P and K, it can help renovate phosphorus- or potassium-deficient soil. Further research is needed about FWDB's specific effects on soil organic carbon, nutrient contents, GHG emissions, and heavy metals, with long-term field experiments.

As biochar is a stable carbon-rich organic matter that could be stored in soils for centuries, producing biochar is regarded as a negative-emission technology (Smith, 2016). Biochar's feedstock could rely on many kinds of waste resources, like forest and agricultural residues, food waste, digestate, sewage sludge, etc. (Elkhalifa et al., 2019; Tan et al., 2015; Turan, 2019), which are low-cost and available in tremendous quantities. In addition to applying as a soil amendment, biochar has many other usages that will add its commercial value. It has a strong adsorption ability to remove contaminants such as heavy metals and organic compounds (Wang et al., 2015; Zubair et al., 2021). Producing activated carbon with biochar from waste and their by-products has been a widely focused technique that could integrate carbon sequestration and waste-resource recycling into multiple applications, including sewage disposal, contaminated soil remediation, and CO_2 capture (Ahmed et al., 2016; Tan et al., 2017). Johari et al. (2016) obtained biochar from coconut pith and found that the Hg adsorption capacity of biochar obtained from high pyrolysis temperature exceeded that of a commercial brand of activated carbon. In terms of carbon absorption, some scholars used pyrolytic biochars from different wastes such as sawdust, coffee grounds, rice husks, bagasse, almond shells, etc. to capture CO_2, and evaluated their capture capacity and good cyclic stability as a profitable approach to waste recycling and carbon reduction (Boonpoke et al., 2011; Liu and Huang, 2018). An innovative experiment executed by Lee et al. (2021) added a wood waste-derived biochar to a food-waste anaerobic digestion process to first absorb CO_2 from biogas and then filter out solids from the digestate. The biochar could remove 31% COD, 8% NH_3, and 90% total suspended solids from the digestate wastewater, outperforming a centrifugal dewatering process, and could retain more nutrients in the solid fraction of the digestate for recycling as bio-fertilizer. The above analyses enlighten us that biochar applied to soil can play a dual role in retaining nutrients and adsorbing CO_2 from soil and air synchronously, with critical impacts on agricultural production and carbon reduction.

Most research about the pyrolysis of FW has been focused on a single component or several components of FW, while limited research has been conducted on producing biochar from mixed FW or its digestate (Elkhalifa et al., 2019). As biochar's physicochemical properties are significantly influenced by the composition of its feedstock and processing conditions (Liu et al., 2020), high variability of the composition of mixed FW poses difficulties to further processing of biochar and brings uncertainty to the properties of biochar. Further research is required on the improvement of pyrolysis technology for mixed FW and its digestate, focusing on property optimization and high-value application channels' expansion of FW biochar.

3.4. Farmers' awareness and acceptance of food waste disposal products

As for farmers' awareness of FWDPs (Fig. 6(1)), 262 farmers know nothing about FWDPs, comprising 83.4% of all the farmers in the study. 49 farmers (15.6%) know a little, and only 3 (1.0%) know a lot about FWDPs. When asked about their willingness to use FWDPs as fertilizers (Fig. 6(2)), 205 farmers (65.3%) are willing to try them, while the rest are unwilling (18.8%) or not sure (15.9%), revealing there is a benign acceptability of FWDPs among farmers. We further investigate the factors farmers consider about using FWDPs (a single farmer may have selected more than one factor), as shown in Fig. 6(3). Farmers' top concern is the fertilizer's effect, which included 53.2% of the selections; followed by the price of the compost products, accounting for 31.1% of all responses. A few farmers care about the quality of (7.6%) and government subsidies for (6.0%) FWDPs. Other considerations like sanitary risks, safety problems, environmental effects, etc., are selected by several farmers (2.1%).

The results express that most farmers are interested in adopting FWDPs, although they generally lack knowledge about FWDPs, which might influence their attitudes toward them. Measures are needed to improve people's knowledge of FWDPs and to popularize their use. The government's supportive regulations and propaganda are surely the most extensive and reliable approaches to promote FWDPs. Farmers' main considerations tell us that good fertilizer effect, competitive cost compared to chemical fertilizers or other organic fertilizers, and favorable quality of FWDPs will also encourage farmers to apply FWDPs. Thus, it's important to improve the nutrients and quality of FWDPs and offer them at competitive prices.

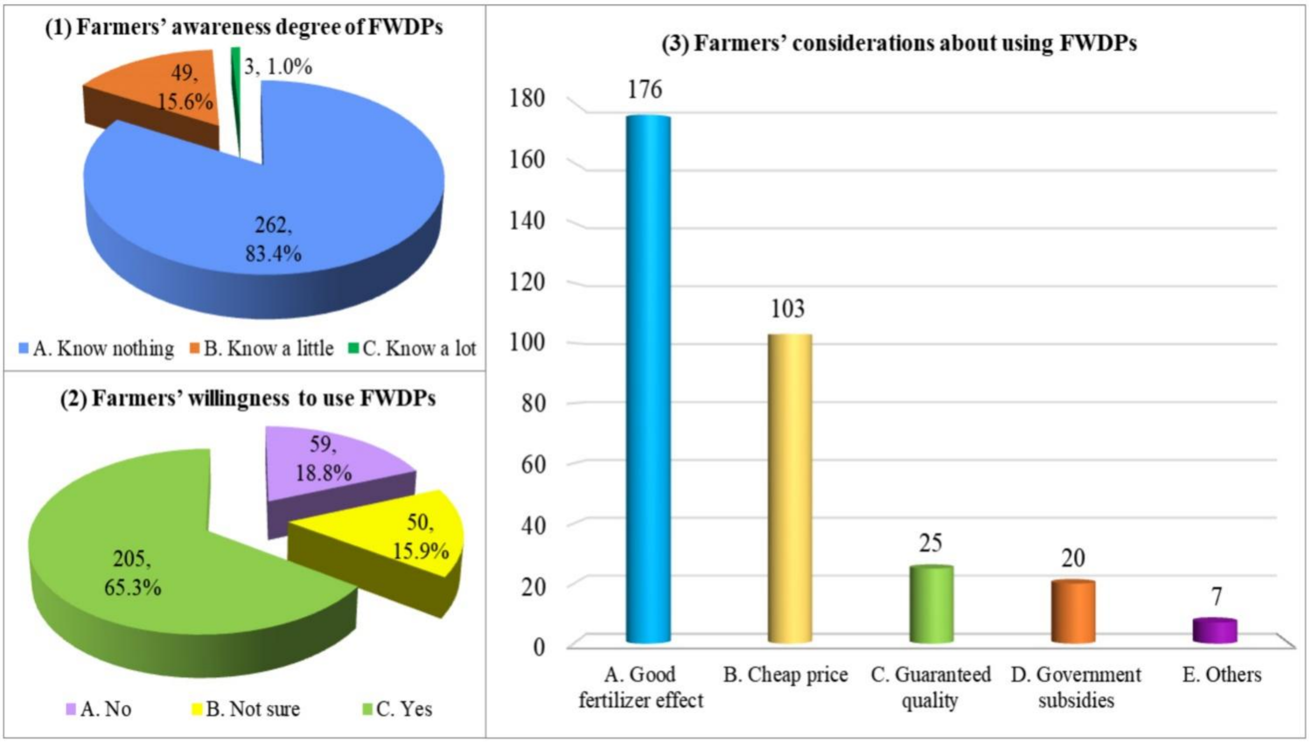

Fig. 6. Farmers' awareness (1), willingness to use (2), and considerations (3) for FWDPs.

4. Limitations and recommendations for recycling food waste disposal products

Three FWDPs are assessed for their potential as organic fertilizers or soil amendments in this study. However, food waste digestate from anaerobic digestion plant is a sticky semi-liquid slurry with high moisture content (70%-89% in Xiamen), which is difficult to separate the solid fraction and liquid fraction with conventional dehydration methods. This makes the digestate difficult and costly to store, transfer, and transport. Post-treatment of digestate is necessary to decrease its moisture and phytotoxicity. Biodrying and thermophilic composting are recommended effective methods to achieve the dewatering and valorization of digestate on account of their lower energy consumption and higher nitrogen fixation (Lu and Xu, 2021). We suggest digestate post-treatment facilities and fertilizer production plants be installed in or next to anaerobic digestion plants, which could allow on-site drying, composting, or pyrolysis processes to produce commercial organic fertilizer or soil amendment, to reduce transportation cost/time and environmental impact. Admittedly, it will be a long way to achieving the integration of FW digestate generation, processing, and fertilizer production.

As the salt content is intrinsically high in Chinese food waste, salt is contained in FWDPs and is difficult to remove effectively. An existing desalting method is to wash with water, which uses up water resources and only transfers salt from the food waste to the water, not only consuming water but also bringing about another sewage pollution burden, which is neither economically feasible nor environmentally viable. As discussed above, FWAC and FWDB have rather high soluble-salt content, which may lead to an additional risk of salinization. In southern China, frequent irrigation will sufficiently leach away some of the salt in the soil, and reduce salt's negative influence on soils and crops. Yet whether long-term fertilization with FWDPs will induce salt accumulation in soil and groundwater needs to be further studied.

Antibiotic resistance genes (ARGs), one kind of emerging contaminant, were detected in an FW treatment plant by He et al. (2019). They found the sulfonamides and quinolones generated during FW treatment and ARGs were resistant to sulfonamides, tetracyclines, and macrolides in FW leachates. This reminds us that many types of food may have suffered antibiotic resistance pollution during manufacturing and processing. The potential risk of ARGs in FW needs to be considered when recycling FW as organic fertilizer. Chen et al. (2021) investigated a laboratory-scale co-composting of FW with sewage sludge and discovered that aerobic composting could effectively remove some antibiotics and

ARGs from FW and sludge. Composting conditions, processing durations, and control methods all influence the removal effect. Future research is suggested, to focus on evaluating the distribution of antibiotics and ARGs on FWDPs and their agronomic risk as well as feasible approaches to avoid/treat antibiotics and ARGs pollution.

5. Conclusions

The TOM, TN, TP, and TK contents of three studied FWDPs are analogous to those of several broadly accepted livestock manures in China. The seven-season vegetables' total yields of treatments with FWAC added and FWDR added increase by 21.5%, 17.2% respectively compared to conventional chemical fertilizer alone treatment, and maintain the same level with conventional chicken manure added treatment. Thus it is proved that FWAC and FWDR have considerable potential for resource reuse on agricultural fields, and have good fertilizer effects, which is farmers' top concern. FWDB used at low application amounts as a soil amendment is also beneficial to crop growth. The current FW collection and treatment capacity in Xiamen could produce 2,227 t yr^{-1} of FWDR, which would reduce the application amount of pure chemical fertilizers by 5.6%. The reduction rate would be raised to 17.5% if all restaurant generated FW were gathered and treated with anaerobic digestion — the ideal situation. As farmers' lack of knowledge on FWDPs hinders their willingness to use them, the whole society's joint endeavors are needed to improve the popularity, efficiency, quality, and competitiveness of FWDPs. Agricultural application of FWDPs will be a multi-win approach that not only eliminates and recycles FW disposal residues but also reduces the consumption rate of limited fossil resources and brings economic benefits to farmers, thus promoting the circular evolution of food-energy-resource. Further research is required to monitor the specific impacts of FWDPs on soil organic carbon, nutrient contents, and GHG emissions, and examine their potential fertilization risks like salt accumulation, antibiotics, and ARGs, with long-term field experiments.

CRediT authorship contribution statement

Xuejuan Fang: Conceptualization, Methodology, Data collection and curation, Software, Writing - original draft. **Bing Gao**: Methodology, Field experiment design, Field survey, Writing - review & editing, Supervision. **Dongliang Zhong**: Data collection, Field survey. **Lihong Wang**: Field survey.

Aiduan Borrion: Data curation, Supervision. **Wei Huang**: Data collection. **Su Xu**: Data curation. **Shenghui Cui**: Conceptualization, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare no competing interests.

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Acronym and nomenclature lists

Acronyms

AC	Aerobic composting
AD	Anaerobic digestion
DM	Dry matter
FW	Food waste
FWAC	Food waste aerobic compost
FWDB	Food waste digestate biochar
FWDP(s)	Food waste disposal product(s)
FWDR	Food waste digestate residue
GHG	Greenhouse gases
KMO	Kaiser Meyer Olkin
MSW	Municipal solid waste
ReR	Recovery rate
SOM	Soil organic matter
TK	Total potassium
TN	Total nitrogen
TP	Total phosphorus
TOC	Total organic carbon
TOF	Traditional organic fertilizer
TOM	Total organic matter
WW	Wet weight

Acronyms of Traditional Organic Fertiliers

HuM	Human manure

PiM	Pig manure
CaM	Cattle manure
ShM	Sheep manure
HoM	Horse manure
RaM	Rabbit manure
ChM	Chicken manure
DuM	Duck manure
PnM	Pigeon manure
FaM	Farmyard manure
CoM	Ordinary aerobic compost manure
DRM	Digestate residue manure
RiS	Rice straw
WhS	Wheat straw
MaS	Maize straw
SoC	Soybean cake
PeC	Peanut cake
RaC	Rapeseed cake
AsS	Astragalus smicus
VVR	Vicia villosa Roth

Nomenclatures

C/N	Carbon-nitrogen ratio
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
K	Potassium
K_2O	Potassium oxide
N	Nitrogen
NH_3	Ammonia
NH_4^+-N	Ammonia nitrogen
N_2O	Dinitrogen monoxide
NO_3^--N	Nitrate nitrogen
P	Phosphorus
P_2O_5	Phosphorus pentoxide

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