An innovative solution for rural food waste treatment: From waste to organic grains

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Abstract

Food waste (FW) in a whole country contains a large amount of nitrogen which could be used to replace chemical fertilizers to produce organic grains, thus mitigating environmental pollution from the source. A two-year field experiment was carried out using rural FW to grow organic grains in Shandong Province, China. Different proportions of FW and cattle manure were designed as followings, FM0, 100% cattle manure compost (CMC); FM1, 75% CMC + 25% FW; FM2, 50% CMC + 50% FW; FM3, 25% CMC + 75% FW; FM4, 100% FW; CF, 100% chemical fertilizer; CK, without any fertilizers. Compared with CK and FM0, the application of FW significantly increased the total nitrogen, total phosphorus and total potassium content of the soil. FW did not cause increase of heavy metals such as cuprum, zinc and chromium in the soils, nor did it increase the heavy metals in the grains. Using FW to replace all cattle manure, the total organic yield of grains reached to an average of 18163 kg ha^{-1}. We found that 1 kg dry FW could produce 1.64 kg organic grains under organic conditions, with the average net income being 5.42 times that of chemical mode. Our findings may provide an innovative solution for treating rural food wastes, ensuring food safety, and conservating the agriculture ecosystem.

1. Introduction

Modern agriculture relies on chemicals to increase food production, with its quality being ignored for a long time. It causes not only serious environmental pollutions (Joseph et al. 2019; Jankowski et al. 2018), but also frequent occurrences of diseases and pests (Nocente et al. 2019), as well as biodiversity loss (Doring et al. 2019) and greenhouse gas emissions (Santillano-Cazares et al. 2018). Unfortunately, because of lower quality and price, a great deal of human food turned into household garbage on the table (Aschemann-Witzel et al. 2019). Such a phenomenon occurs in not only developed but also developing countries. In the United States, the largest developed country in the world, 6.3×10^7 t of food become garbage every year (Dusoruth and Peterson 2020). In China, the largest developing country, about 6.0×10^7 t of food waste is generated every year, which can feed 2×10^8 people (Bi et al. 2019; Cheng et al. 2012). When food becomes garbage, it will not only waste food itself, but also cause environmental pollution and waste of a large number of valuable natural resources and labor. Urban and rural biodegradable household garbage, especially food waste, however, can be used to develop ecological agriculture through cycling of elements, thus solving the environmental and social problems from the source.

The amount of wasted food accounts for about one-third of the global annual food production (Corrado et al. 2019; Guo and Yang 2019). The exponential growth of food waste is imposing a serious threat to our society, such as polluting the environment, harming human health, and occupying land (Paritosh et al. 2017). At present, the disposal of food waste has attracted worldwide attentions (Paritosh et al. 2017; Cerda et al. 2018; Rao and Rathod 2019). Although the resource utilization capacity and level of food waste utilization have been significantly developed, there are still problems existing in the treatments such as insufficient concern to source reduction and obvious gaps in processing capacity. As the amount of food waste is increasing, a huge of energy and bio-resource in the wasted food have been wasted (Guo and Yang 2019). In terms of circular economy, innovative or revolutionary technologies are urgently needed to realize the resource utilization of food waste in the world.

Food waste includes carbohydrate polymers (starch, cellulose, hemicellulose), lignin, proteins, lipids, organic acids and smaller inorganic parts, *etc*. The organic matters can be decomposed into reducing sugars, free amino acids, phosphates and nitrates which are needed by plants in arable soils (Xing et al. 2019). It can be widely collected from the food processing industries, households and hospitality sectors (Paritosh et al. 2017). The food waste might be one of the most promising renewable resources (Cecchi and Cavinato 2019). For instance, it is suitable to be processed into a stable and nutrient-rich biological fertilizer (Haddad and Batarseh 2019; Waqas et al. 2019). Studies have demonstrated that food waste could be fermented to prepare soil conditioners, which might decrease carbon emission and improve land use efficiency (Hou et al. 2017). Some found that long-term application of food waste could increase total organic carbon content in orchard soils and improve soil fertility (Jia et al. 2019). However, the entire process of preparing this kind of bio-compost needs large area and long time. It might be prone to produce peculiar smell and secondary pollutants, which have a negative impact on the environment (Ma and Liu 2019). Using land to directly treat food wastes by using them as organic fertilizers could avoid the above-mentioned defects, reduce the demand for synthetic fertilizers, and greatly reduce the cost of treatment. Someone applied household food waste directly to potting soil and found that it promoted the growth of *Chlorophytum comosum* leaves and increased the effective nutrient content of the soil (Song et al. 2014).

Organic agriculture is considered to be more environmentally friend than conventional one. It could improve soil quality (Joseph et al. 2019), restrict harmful agricultural chemicals, reduce nutrient emissions, enhance biodiversity (Doring et al. 2019), and increase soil organic carbon (Lotter et al. 2003). Previous investigations have confirmed that when agriculture system received higher quantities of nitrogen under organic conditions (Seufert et al. 2012; Muller et al. 2017). Organic agriculture could be beneficial to higher nitrogen import, whereas the conventional one could not benefit from more nitrogen otherwise tend to pollute the environment. Some also found that, if apply more nutrients before crops were planted, the yield would be directly increased under organic conditions (Bergstrand et al. 2020). However, the shortage and higher price of organic fertilizer application has become a bottleneck to restrict the development of organic agriculture. Therefore it is necessary to explore new sources of organic fertilizers (Nayak et al. 2019).

The total output of rural household waste has been increasing due to the lack of proper infrastructure and solid waste management, which has caused environmental pollution and impacts on human health (Hiramatsu et al. 2009; Tian et al. 2018). Biodegradable waste accounts for the largest proportion of rural domestic waste. If it can be effectively separated and returned to farmland, resource waste can be avoided from the source (Han 2015; Li et al. 2019). This on-site treatment method also helps to reduce transportation costs (Zeng et al. 2015). All photosynthesis products on the earth and their biodegradable derivatives can be used as a source of organic fertilizer. Our previous study had revealed that China produced $1.47×10^8$ $t·a^{-1}$ of biodegradable household garbage (dry weight), containing $4.70×10^5$ $t·a^{-1}$ of pure nitrogen (Cui et al. 2021). Rural food waste accounts for a large proportion of biodegradable household garbage which is one of the most produced bio-wastes around the world (Gallipoli et al. 2020). However, our here question that whether or not the biodegradable household garbage can be directly processed through farmland to achieve the purpose of reducing the amount of garbage at the source, increase soil nutrients, and produce organic staple food. Such a kind of research has been seldom reported before.

Heavy metal is currently one of the major issues affecting the safety of biofertilizers. The use of biofertilizers with higher heavy metal content may lead to pollution of arable land (Du et al. 2018). Secondly, the quality of crops might be degraded if the soils are contaminated by heavy metals. It is still not clear whether food waste can be directly used in organic agricultural production, and whether its components pollute the cultivated soil. Therefore, it is necessary to conduct field crop planting experiments and analyze heavy metals in both soils and grains.

The scientific hypothesis of this paper is that rural food waste contains a large of nutrient resources, especially nitrogen, which can be used to replace chemical fertilizers in producing organic grains. Through direct soil treatment under organic condition, the rural food waste could improve the soil structure, promote plant growth, and maintain the yield as equivalent as chemical agriculture mode or higher. The purpose of this study was to reveal: 1) Whether or not rural food waste could be directly used as organic fertilizer to produce organic grains, if yes how big potential it had; 2) How did the rural food waste affected the soil nitrogen elements? 3) Would heavy metals in the food waste affect the soil and food quality when used as organic fertilizer? This research might provide an innovative solution for the on-site bio-resource management and utilization of rural household garbage.

2. Material And Methods

2.1 Study area

The experiment was conducted over two years in Jiang Jiazhuang Village, Shandong Province, Eastern China (35°26'34' 'N, 117°49'13"E). It is characteristics with typically continental monsoon climate, with the average annual temperature being 12.3°C. In the field, chemical fertilizers, pesticides and herbicides have been completely stopped since 2012. Winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) were planted according to organic production methods. Five tons cattle manure (water content 50%-60%) compost was applied each year, with pests and diseases being controlled by insect traps and biogas slurry. Weeds were controlled using mechanical and artificial methods. The characteristics of cultivated soil (0–20 cm) are shown in Table 1.

Table 1
Properties of the experimental soil and the organic fertilizers applied in growing organic grains.

	Cattle Manure	Food Waste	Soil
Water content (%)	75.57 ± 3.03	75.23 ± 2.92	-
pH	8.95 ± 0.04	5.05 ± 0.66	7.28 ± 0.10
TN($g\ kg^{-1}$)	18.0 ± 0.33	21.30 ± 0.22	1.36 ± 0.15
NO_3-N($mg\ kg^{-1}$)	244.67 ± 88.25	523.59 ± 293.76	6.90 ± 0.85
TP($g\ kg^{-1}$)	5.20 ± 0.02	8.44 ± 0.41	1.05 ± 0.19
TK($g\ kg^{-1}$)	16.79 ± 1.73	35.88 ± 6.25	18.53 ± 0.43
Cu($mg\ kg^{-1}$)	21.66 ± 1.66	2.17 ± 0.48	22.22 ± 0.83
Zn($mg\ kg^{-1}$)	102.30 ± 8.03	27.06 ± 5.19	64.09 ± 3.21
Cr($mg\ kg^{-1}$)	73.57 ± 3.64	66.17 ± 8.91	86.35 ± 5.33

Note: Data were means ± standard error (n = 3). TN, total nitrogen; NO_3-N, nitrate nitrogen; TP, total phosphorus; TK, total potassium. Screening value of soil pollution risk of agricultural land in China: Cu 200 mg kg^{-1}; Zn 250 mg kg^{-1}; Cr 200 mg kg^{-1} (Agricultural Land Soil Pollution Risk Control Standard of China, GB 15618 – 2018).

2.2 Organic fertilizers

Cattle manure compost was collected from Hongyi Organic Farm based in the village. Rural FW was mixed with homes and restaurants locally, 35% of which being taken from the farmer families and 65% from local restaurants. After collection, FW was placed in a sealed plastic barrel for later use. The organic fertilizers characteristics for the experiment were summarized in Table 1. The chemical compound fertilizer used in the experiment was purchased locally.

2.3 Experimental design

Seven treatments (based on nitrogen contents) were set as: (1) FM0, 100% cattle manure compost (CMC); (2) FM1, 75% CMC + 25% FW; (3) FM2, 50% CMC + 50% FW; (4) FM3, 25% CMC + 75% FW; (5) FM4, 100% FW; (6) CF, chemical fertilizers; (7) CK, blank control. The total nitrogen (TN) application for each treatment was 236.25 kg ha^{-1}, all of which were applied as a base fertilizer only once before wheat sowing in the winter wheat-summer maize rotation system. The winter wheat cultivar was “Linmai 9”, and summer maize “Woyu 3”. Each treatment had three replicates, all of which had an area of 12 m^2 (3 m × 4 m).

The winter wheat was sown for two continue years, especially on October 30, 2019 and October 19, 2020, with distance between rows being 0.3 m. After harvest of wheat, the summer maize was planted on June 20, 2020 and June 10, 2021, with the distance being 0.6 and 0.3 m respectively between rows and individuals.

2.4 Sampling and measurement

2.4.1 Soil

During the maize harvest period, soil sampled were taken using a soil auger on five random sampling points in the 0–20 cm layer in September 2020 and September 2021, respectively. The collected samples were removed from debris, air-dried naturally and crushed. To determine pH, the soil samples were passed a 10-mesh sieve. A digital pH meter (PB-10, Sartorius, Germany) was used to measure soil pH under 1:2.5 soil: water ratio condition. For other nutrient indexes the samples were passed a 100-mesh sieve. TN was measured using the Kjeldahl method. Nitrate nitrogen (NO_3-N) was leached with 1mol/L potassium chloride and determined by automatic continuous flow analyzer method. The total phosphorus (TP), total potassium (TK), cuprum (Cu), zinc (Zn) and chromium (Cr) elements were measured by the Panalytical AXIOS mAX instrument by X-ray fluorescence method (Bao 2005).

2.4.2 Yield

Three 1 m^2 wheats were randomly harvested in each plot on June 8, 2020 and June 6, 2021, then air-dried after threshing to calculate winter wheat yield. Three replicates of 10 consecutive summer maize plants in the middle row were harvested on September 21, 2020 and September 16, 2021, then air-dried after threshing to determine maize yield.

2.4.3 Economic benefits

The total inputs and outputs of the seven treatments was recorded in detail. The organic grains were sold in the Taobao E-communitial Plantform at prices of $ 0.91/kg and $ 1.22/kg, respectively for wheat and maize. According to the market prices, chemical fertilizer-treated wheat and maize were sold at the prices of $ 0.33/kg (wheat) and $ 0.38/kg (maize) in 2020; and $ 0.33/kg (wheat) and $ 0.41/kg (maize) in 2021, respectively. Finally, we used the annual average net income to assess the economic benefits.

2.4.4 Organic grains production potential

The potential of food waste in producing organic grains was estimated by dividing the yields of wheat and maize grains by the total amount of food waste (dry weight) application.

2.5 Statistical analysis

Microsoft Excel 2007 was applied to process the data. SPSS 20.0 (SPSS Inc, Chicago, IL, USA) single factor analysis of variance and Duncan’s multiple comparison method were applied to test the differences among treatments. Figures were generated using SigmaPlot 12.5 (Systat Software Inc., San Jose, CA, USA).

3. Results

3.1 Heavy metal contents in soil and grains

Since the heavy metal contents from food waste were much lower than the soil background value (Table 1), all the heavy metals in this experiment did not exceed the national standards of China (Agricultural Land Soil Pollution Risk Control Standard of China, GB 15618 – 2018). The effects of different treatments on the contents of soil heavy metals are displayed in Fig. 1. In 2020, FM3 had the highest Cu content, 24.08 mg kg^{-1}, however, there was no significant difference between FM4 and CF, both having significantly higher Cu than FM0 (Fig. 1A, $P < 0.05$). Among FM0, FM1, FM2 and CK, there were also no significant differences. In 2021, FM2 had the highest Cu content, which was significantly higher than CK and FM0 ($P < 0.05$), again there was no significant difference among FM1, FM3, FM4 and CF treatments. Compared with 2020, the soil Cu content from CK, FM3, FM4 and CF decreased significantly in 2021 ($P < 0.05$). Among all the treatments, CK had the highest Cu content in winter wheat grains (Table 2). Nevertheless, there was no significant difference in the Cu contents of summer maize grains among all treatments. The application of organic and chemical fertilizers had no impact on Cu contents of crop grains.

In 2020, FM2 had the highest soil Zn content, 70.39 mg kg^{-1}, however there were no significant differences among FM1, FM3, FM4 and CF (Fig. 1B) ($P < 0.05$). There were also no significant differences among FM0, FM1 and CK. In 2021, FM2 was found to have the highest Zn, but not significantly different from CF, both having higher Zn than other treatments ($P < 0.05$). Compared with 2020, FM0 remarkably declined its soil Zn in 2021($P < 0.01$). For the Zn contents of winter wheat grains with different treatments, CK had the highest value (Table 2). Against 2020, FM2 and FM4 treatments increased remarkably in 2021 ($P < 0.01$), with CF treatments being significantly increased ($P < 0.05$). For the Zn content in grains of summer maize, FM0 and FM2 had the highest value, respectively in 2020 and 2021. Compared with CK, the application of organic and chemical fertilizers did not increase the Zn content of crop grains (Table 2).

FM2 had the highest Cr content, 104.86 mg kg^{-1}, which was significantly higher than other treatments ($P < 0.05$). FM0, FM3 and FM4 had significantly higher soil Cr than CF ($P < 0.05$). However, there was no significant difference between CK and CF. Among FM0, CF and CK, there were also no significant difference in soil Cr. Compared with 2020, the soil Cr content from CK and FM0 decreased significantly in 2021 ($P < 0.05$). For the Cr content of winter wheat grains with different treatments, FM0 had the highest value during the two experimental years (Table 2). At summer maize grains, there were also no significant difference in soil Zn contents among all the treatments in both 2020 and 2021, indicating soil Zn was not affected by application of food waste. The application of cattle manure increased the Cr content of winter wheat grains, while the application of chemical fertilizers increased the Cr content of summer maize grains. Even thorough, the contents of Cr were within the limitation of National standards.

Table 2 Heavy metals content in grains of winter wheat and summer maize in different treatments.

years	treatment	Winter wheat			Summer maize		
		Cu	Zn	Cr	Cu	Zn	Cr
2020	CK	3.47 ± 0.17a	32.98 ± 1.78a	0.86 ± 0.18bc	0.30 ± 0.12a	17.31 ± 0.25a	0.38 ± 0.16a
	FM0	2.40 ± 0.06bc**	26.27 ± 1.41b	1.45 ± 0.10a	0.09 ± 0.13a	17.82 ± 0.35a	0.45 ± 0.07a
	FM1	2.06 ± 0.03c**	20.91 ± 0.69c	0.86 ± 0.03bc	0.24 ± 0.18a	14.67 ± 0.52b*	0.53 ± 0.07a
	FM2	1.75 ± 0.06c**	20.95 ± 1.09c**	0.81 ± 0.03bc	0.34 ± 0.17a	17.43 ± 0.39a	0.40 ± 0.01a
	FM3	2.17 ± 0.17bc**	22.09 ± 0.96c	0.66 ± 0.12c	0.02 ± 0.13a	15.67 ± 0.20b*	0.48 ± 0.11a
	FM4	2.75 ± 0.44b	20.34 ± 0.73c**	1.14 ± 0.18ab	0.14 ± 0.17a	14.69 ± 0.14b*	0.45 ± 0.14a
	CF	2.25 ± 0.13bc*	19.65 ± 1.02c*	0.77 ± 0.22bc	0.23 ± 0.09a	15.10 ± 0.30b	0.47 ± 0.11a
2021	CK	3.80 ± 0.11A	29.85 ± 0.05A	0.83 ± 0.10ABC	0.17 ± 0.01A	16.86 ± 0.05C	0.49 ± 0.13ABC
	FM0	3.66 ± 0.16AB	26.17 ± 0.40BC	1.07 ± 0.02A	0.14 ± 0.02A	17.17 ± 0.04C	0.67 ± 0.09AB
	FM1	3.44 ± 0.05BCD	26.74 ± 0.11B	0.70 ± 0.05BC	0.13 ± 0.03A	17.45 ± 0.04BC	0.31 ± 0.10C
	FM2	3.61 ± 0.11ABC	28.89 ± 0.53A	0.73 ± 0.20BC	0.33 ± 0.07A	18.75 ± 0.23A	0.51 ± 0.15ABC
	FM3	3.46 ± 0.04BCD	25.90 ± 0.23BC	0.69 ± 0.06BC	0.14 ± 0.05A	18.10 ± 0.41AB	0.48 ± 0.08ABC
	FM4	3.35 ± 0.07CD	29.34 ± 0.68A	0.96 ± 0.05AB	0.25 ± 0.13A	17.36 ± 0.47BC	0.38 ± 0.07BC
	CF	3.28 ± 0.04D	25.35 ± 0.05C	0.60 ± 0.04C	0.17 ± 0.03A	15.17 ± 0.17D	0.76 ± 0.06A

Note: The China National Food Safety Standard: Limits of pollutants in foods: Cu 10 mg kg^{-1}; Zn 50 mg kg^{-1}; Cr 1.0 mg kg^{-1} (GB 2762 – 2017). The data were means ± standard error (n = 3). Different lower letters indicated significant differences between different treatments in 2020 (P< 0.05). Different capital letters indicated significant differences between different treatments in 2021 (P< 0.05). *: Indicating significant differences between different years at P< 0.05 level; **: Indicating significant differences between different years at P< 0.01 level.

3.2 Total nitrogen and nitrate nitrogen

At maize harvest stage in 2020, CF treatment displayed the highest soil TN content, 1.39 g kg^{-1}, however there were no significant differences among CK, FM3 and FM4 (Table 3). In 2021, TN content from FM3 treatment showed the highest TN (1.44 g kg^{-1}), but there was no significant difference from FM4, both being significantly higher than others (P< 0.05). Compared with 2020, TN content in CK decreased significantly (P< 0.05) in 2021, with FM0 decreasing remarkably (P< 0.01). Again, there was no significant difference in the other treatments during the two experimental years. Along with the application ratio, the application of food waste significantly increased TN content of the soil.

During the maize harvest period of 2020, FM4 had the highest NO_3-N content (12.35 mg kg^{-1}), however there was no significant difference between FM3 and CF. In 2021, NO_3-N content from FM3 was noted to be the highest, however there was no significant difference between FM0 and FM4 (Table 3). Against 2020, NO_3-N content from FM3, FM4 and CF in 2021 were decreased remarkably ($P< 0.01$). The more the amount of food waste was applied, the higher NO_3-N content in the soil. Food waste was more likely to increase soil NO_3-N content than the cattle manure. Nevertheless, with the extension of application time, soil NO_3-N contents in the food waste treatments had been declined significantly.

Table 3
The soil total nitrogen and nitrate nitrogen in different treatments.

Treatment	TN (g kg^{-1})		NO_3-N (mg kg^{-1})	
	2020.9	2021.9	2020.9	2021.9
CK	1.30 ± 0.05ab*	1.12 ± 0.01C	5.56 ± 1.34bc	3.05 ± 0.08B
FM0	1.18 ± 0.01bc**	0.94 ± 0.02D	4.49 ± 0.34c	4.98 ± 0.16A
FM1	1.14 ± 0.06c	1.19 ± 0.02C	7.97 ± 1.11b*	2.80 ± 0.27B
FM2	1.24 ± 0.04bc	1.26 ± 0.05B	6.82 ± 0.80bc*	2.89 ± 0.55B
FM3	1.29 ± 0.06ab	1.44 ± 0.01A	11.80 ± 0.54a**	5.00 ± 0.23A
FM4	1.30 ± 0.04ab	1.39 ± 0.00A	12.35 ± 0.56a**	4.21 ± 0.90AB
CF	1.39 ± 0.03a	1.31 ± 0.01B	11.42 ± 1.23a**	3.28 ± 0.08B

Note: The data were means ± standard error (n = 3). Different lower letters indicated significant differences between different treatments in 2020 ($P< 0.05$). Different capital letters indicated significant differences between different treatments in 2021 ($P< 0.05$). *: Indicating significant differences between different years at $P< 0.05$ level; **: Indicating significant differences between different years at $P< 0.01$ level.

3.3 Total phosphorus and potassium

In 2020, the highest TP content, was found in CF treatment (1.17 g kg^{-1}) in 2020. However, among FM1, FM2, FM3 and FM4, there were no significant difference. All the mentioned above treatments had significantly higher TP than CK and FM0 ($P< 0.05$). In 2021, FM3 had the highest TP content, but it had no significant difference with CF treatment, both having significantly higher TP than others ($P< 0.05$). Compared with 2020, TP content from FM0 and FM2 increased significantly ($P< 0.01$), while FM4 increased extremely ($P< 0.05$). The application of food waste remarkably increased the TP of the soil, with the content being elevated with the increase of the application ratio.

In 2020, FM2 had the highest TK content (19.52 g kg^{-1}). However, there was no significant difference between FM3 and FM4. FM2 and FM4 had significantly higher TK than other treatments ($P< 0.05$) (Fig. 2B). In 2021, FM2 had the highest TK, which was significantly higher than others ($P< 0.05$). The application of food waste and chemical fertilizer significantly increased TP ($P< 0.05$), with FM0 being the lowest. Compared with 2020, FM1, FM3 and FM4 treatments remarkably increased soil TK in the year of 2021 ($P< 0.01$).

3.4 Crop yield

In 2020, the winter wheat yields from CK, FM0, FM1, FM2, FM3, FM4 and CF were 3505, 5385, 6403, 7956, 7634, 9758 and 8719 kg ha^{-1}, respectively (Fig. 3). Among them, FM4 had the highest yield, however, there were no significant differences among FM2, FM3 and CF, which had significantly higher yields than FM0 and FM1 ($P< 0.05$). There was also no significant difference between FM0 and FM1. The changes of grain yields in 2021 and 2020 was in a better consistent trend. The application of food waste treatment had significantly higher effect than that of CK (P< 0.05), with FM4 being 2.57 and 1.90 times that of CK and FM0, respectively. Although the grain yield of FM2 treatment in 2021 decreased a little bit compared with 2020, other treatments were not found to be significantly different in the two experimental years.

The summer maize yields from CK, FM0, FM1, FM2, FM3, FM4 and CF in 2021 were 4220, 6375, 6616, 7327, 8672, 8470 and 8722 kg ha^{-1}, respectively. Among them, CF had the highest yield. However, there was no significant difference between FM3 and FM4, both having significantly higher grain yields than others except CF (P< 0.05). The changes of 2021 and 2020 was in a consistent trend. The application of food waste treatment has significantly increased the grain yields compared with CK (P< 0.05).

In 2020, FM4 had the highest annual yield (wheat + maize), which was significantly higher than other treatments (P< 0.05). Nevertheless, there was no significant difference between FM3 and CF. FM2 was noted to be significantly higher annul yield than CK, FM0 and FM1 (P< 0.05) (Fig. 3C). The changes of 2021 and 2020 were in a consistent trend. Food waste treatments had better effect than those of CK and FM0 (P< 0.05), as there was no significant difference with CF, indicating food waste could replace chemical fertilizer without yield losses. Compared with 2020, the annual yield of FM1 increased significantly in 2021 (P< 0.05), nevertheless there was no significant difference in other treatments during the two years. The use of food waste as organic fertilizer was more conducive to increasing the annual yield of winter wheat and summer maize than cattle manure.

3.5 Economic benefits

CF treatment had the highest inputs, FM4 and CK the lowest, with others being somewhere in between (Table 4). For the outputs of different treatments, FM4 had the highest value, \$19219.6 ha^{-1}, in 2020, while FM3 had the highest in 2021, \$20045.9 ha^{-1}. CF was found to have the lowest output. Above all, the outputs of organic fertilizer treatments were much higher than CF treatment (Table 4). FM3 and FM4 had the highest net outputs among all the treatments. CF had the lowest net outputs, which were 3074.6 and \$3367.4 ha^{-1} in 2020 and 2021, respectively. The net outputs of organic fertilizer and CK were higher than that of CF treatment.

Table 4 Comprehensive economic benefits under different fertilizer treatments. Unit: \$ ha^{-1}

		Details	CK	FM0	FM1	FM2	FM3	FM4	CF
Input	Materials	Fertilizer	0.0	490.5	367.9	245.2	122.6	0.0	1441.6
		Seed	206.3	206.3	206.3	206.3	206.3	206.3	206.3
	Equipment	Ploughing	182.6	182.6	182.6	182.6	182.6	182.6	182.6
		Seeding	136.9	136.9	136.9	136.9	136.9	136.9	136.9
		Harvesting	365.2	365.2	365.2	365.2	365.2	365.2	365.2
	Labor	transportation	0.0	245.2	235.0	224.7	214.5	204.2	0.0
		Fertilization	0.0	91.3	91.3	91.3	91.3	91.3	7.6
		Irrigation	273.9	273.9	273.9	273.9	273.9	273.9	273.9
		Weed control	547.8	547.8	547.8	547.8	547.8	547.8	547.8
Annual average input			1712.7	2539.8	2406.9	2274.0	2141.1	2008.2	3161.9
Output		2020	8337.5	12677.2	13899.4	16183.0	17525.4	19219.6	6236.5
		2021	9975.2	15061.4	16240.1	17897.9	20045.9	19560.7	6529.4
Annual average net income		2020	6624.7	10137.4	11492.5	13909.0	15384.3	17211.3	3074.6
		2021	8262.5	12521.6	13833.2	15623.9	17904.7	17552.4	3367.4

Note: $1.0 = 6.5719 Chinese Yuan. The organic fertilizer treatment of wheat and maize were calculated according to the organic price, which were sold online for $ 0.91/kg and $ 1.22/kg, respectively. According to market prices, the output values of chemical fertilizer-treated wheat and maize were respectively $ 0.33/kg and $ 0.38/kg in 2020; were $ 0.33/kg and $ 0.41/kg in 2021.

4. Discussion

4.1 The effect of food waste on soil heavy metals

Long-term utilization of chemical fertilizers had caused serious environmental pollutions. More and more people, who believe that organic agriculture is much healthier, are concerning about the relationship between modern agriculture and quality of the environment (Lopez-Yerena et al. 2019). For organic agriculture, chemical fertilizers are totally prohibited, with organic fertilizers being used instead. However, organic fertilizers are usually insufficient which limit the development of organic agriculture, so alternative sources of nutrients need to be urgently explored (Nayak et al. 2019). As a source of the biomass nitrogen, rural food waste could be ideally treated by farmland and combined with agricultural production, thus improving soil quality and reducing the load on landfills.

People are usually worrying about heavy metal pollutions when food waste is applied as organic fertilizer. Heavy metals can inhibit plant photosynthesis (Kupper et al. 1996), change the abundance and structure of microbial communities (Huang et al. 2020), inhibit microbial activities (Sun et al. 2021). The before mentioned activities further interfere with the absorption of potassium, phosphorus, calcium, iron and other elements, and affect transportation of elements from the root to the top, thereby reducing the elements necessary for plant growth and hindering the effective use of elements (Du et al. 2018). A decrease in elements' concentration will damage plant health and reduce yield (Hajihashemi et al. 2020). Heavy metals in the soil may enter the human body through the food chain, which will endanger human health (Sun et al. 2021). Common heavy metals in food waste include Cr, Cu, Zn *etc.*, which may casuse various degrees of pollution hazards and further incerase treatment costs (Chu et al. 2019). However, this pollution does not necessarily exist. Some found food waste processing undergone appropriate separation usually contained low contents of heavy metals (Govasmark et al. 2011; Vanroosmalen et al. 1987). Some others further stated that when food waste was used as organic fertilizer, heavy metals pollution can be avoided to a certain extent (Xiong 2015; Du et al. 2018). When the organic part of municipal solid waste was used to replace part of the inorganic fertilizer to grow tomatoes, there was no soil pollution by heavy metals such as Cu, Zn, and Cr (Brunetti et al. 2019). In our experiment, the heavy metal contents of food waste were much lower than the soil background values (Table 1). All the heavy metals did not exceed the national standards.

At the end of the two-year experiment, compared with CK, the application of organic fertilizer and chemical fertilizer increased soil Cu (Fig. 1A) and Zn (Fig. 1B). Compared with CK and CF, the application of food waste increased soil Cr content (Fig. 1C). However, the content of heavy metals was much lower than the national agricultural land soil pollution risk. Food waste with lower heavy metal contents may have limited impact on soil heavy metal contents which are higher than the former. For the organic grains especially, the application of food waste did not increase the heavy metal contents of winter wheat and summer maize, though cattle manure increased Cr a little bit in winter wheat (Table 2).

The effect of organic fertilizer on the heavy metals in edible parts of crops is closely related to the organic fertilizer type and amount, soil type and pH, and crop type (Wang and Li 2014). In a short-term experiment, it was found that food heavy metal contents using organic fertilizer was not increased compared to the control. On the contrary, the application of chemical fertilizer under certain conditions would enhance the absorption of heavy metals by crops (Zhang et al. 2020). The quality of organic fertilizer is dependent of many sources of variation including the feedstock source, composting facility design, and proportions applied. In addition, there are further variabilities in plants responding for the differences among fertilizer composts if applied in different types of field soils (Hargreaves et al. 2008). Food waste included not only food residues such as rice and vegetables, but also some materials related to food consumption, such as waste tableware, paper towels, plastics, *etc*. The former is the residue of edible parts and generally do not contain heavy metals (Table 1), while the latter may contain small amounts of heavy metals (Manfredi et al. 2010). For example, paper and cardboard contain 25% Cu, 23% Zn and so on (Huerta-Pujol et al. 2010; Vanroosmalen et al. 1987). Although we did not detect those risks in the grains (Table 2), to avoid the detriment of heave metals, sorting of the rural domestic garbage at the source is necessary which can greatly avoid heavy metals pollution.

4.2 The effect of food waste on soil nutrients

Nitrogen deficiency is one of most important constraining factors that limited the quantity and quality of agricultural products (Shao et al. 2020). N is also the key element restricting the development of organic agriculture (Seufert et al. 2012). P and K are also essential nutrients (Zhou et al. 2018), together with N affecting plant growth and development (Cai et al. 2018; Li et al. 2018). Organic cultivation can enhance some of the soil properties, such as N, P, and K (Roussos et al. 2019). Food waste is rich in organic substances such as starch, protein, fat, cellulose *etc.*, which are easily decomposed into reducing sugars, free amino acids, phosphates and nitrates under the hydrolysis of microorganisms (Awasthi et al. 2018; Wang and Zeng 2018). In addition, food waste also contains inorganic minerals, such as N, P, K and others (Zhu et al. 2017). The recycling of elements from food waste when used as organic fertilizers could help to improve nutrient utilization efficiency and reduced pollutions caused by inorganic fertilizers (Chew et al. 2018). Some found that the application of municipal solid waste compost promoted the growth of ryegrass (*Lolium perenne* L.) throughout the growing season, and increased plant height and shoot biomass (Zhao et al. 2020). Adding municipal solid waste compost during tomato planting could increase N and K contents in the growth medium, promoted leaf growth and increased yield (Tzortzakis et al. 2020). Directly applied food waste to potted *Chlorophytum comosum* had increased the content of available soil nutrients such as N, P and K (Song et al. 2014). The findings from this experiment are in agreement with the previous investigations (Table 3; Fig. 2). Along with the food waste application ratio increased, N content elevated considerably (Table 3). During the maize harvest in 2020, FM4 treatment had the highest NO_3-N, however, there was no significant difference from FM3 and CF. In 2021, although FM3 treatment had the highest NO_3-N, there was no significant difference between FM0 and FM4 treatments. Against CK and FM0, the application of food waste significantly increased soil TP (Fig. 2A) and TK content (Fig. 2B). Soil NO_3-N and TK content have also been increased by food waste when compared with chemical fertilizer, indicating that the elements contained in food waste were more conducive to the growth of grains. Nitrate, as the main form of nitrogen absorbed and used by most crops in cultivated soils, is the most abundant source of nitrogen that plants in cultivated soils can be absorbed (Andrews et al. 2013). Nitrate is reduced to ammonia, and incorporated into amino acids and nucleotides (Rehman et al. 2020). The ammonia N produced by the fermentation of food waste during storage was dissolved in water and converted into nitrate nitrogen under the action of microorganisms (Xue 2018), which is beneficial to plant growth.

4.3 Food waste promotes organic grains production

Organic agriculture is believed to be a promising approach to achieving sustainable food systems, however its yield is also contested (Muller et al. 2017). Some reported that in organic farming, the yield had been declined by an average of 20% compared with chemical agriculture (Buchi et al. 2019). Nevertheless, some augured that the yields of particular crops with good management practices in an organic agriculture system could almost match the yields or higher than that of the conventional agriculture system (Seufert et al. 2012). Our previous eight-consecutive-years experiment showed that organic yields not only increased steadily year by year, but also achieved 9.6 times net income of before (Liu et al. 2016). Here we found that, when food waste was used as organic fertilizer, the crop grain yields had been increased significantly with the increase in the proportion of food waste, indicating that food waste was conducive to the growth of crops. Therefore, food waste could be applied as an effective supplementary source of organic fertilizer for crop production. The winter wheat yields were 9758 and 8115 kg ha^{-1}, and summer maize yields were 8470 and 9983 kg ha^{-1}, respectively in 2020 and 2021(Fig. 3). Even only food waste was applied, both exceeded the local yields of wheat (6379 kg ha^{-1}) and maize (6594 kg ha^{-1}) (China Statistical Yearbook 2021). The total amount of organic grains produced in 2020 and 2021 were 18228 and 18098 kg ha^{-1}, respectively. For the grain yields, there was no significant difference with chemical fertilizer, indicating that the application of food waste would not decline crop yield. On average, we finally found that 1 kg food waste could produce 1.64 kg organic grains without using any chemical fertilizers, pesticides and herbicides.

4.4 Economic benefits of food waste converting organic grains

Crop yield is not the only factor that farmers care, economic benefits are even more important than yields. Compared with conventional farming, organic agriculture is more profitable and environmentally friend, and deliver equally or more nutritious foods which contain little or none pesticide residues (Reganold and Wachter 2016). When the soil quality has been improved, much higher environmental effects could be obtained (Boone et al. 2019). Turning the food waste into organic fertilizer not only gives play the function of grain production of the land but also solve the ecological problems in waste disposal, as well as makes up for the lack of organic fertilizer in developing organic agriculture. For the grain yields, there was no significant difference between food waste and chemical fertilizer (Fig. 3). However, as the price of organic food is much higher, \$0.91/kg and \$1.22/kg, respectively for wheat and maize, farmers could be benefited by the innovative agriculture. The input cost of 100% food waste was \$2008.2 ha^{-1}, the net output value was \$17211.3 and \$17552.4 ha^{-1} in 2020 and 2021, which were 5.60 and 5.21 times that of conventional agriculture (Table 4). If the degraded bio-matters in the domestic garbage (more than 40%) in the country were used at the source, the management cost and transportation cost would have been greatly reduced. Thus realizes the unity of the recycling of domestic garbage and the sustainable development of agriculture. Based on the amount of food waste produced in China, we calculated that food waste had the of 51.60×10^6 t a^{-1} organic grains production potential, eventually generating a market value of \$55.1 billion. Therefore, we here suggest to continue to promote the classification and utilization of garbage at the source. Especially, the rural food waste could be directly returned to farmland after simple stacking, which would greatly reduce the amount of domestic garbage generated while increasing grain production and economic income.

5. Conclusion

Using food waste to replace cattle manure in an organic farming system significantly increased the soil TN, TP and TK content. It did not cause soil heavy metal pollutions, nor did it increase the heavy metal contents of grains. The total organic grains yield of wheat and maize reached to 18163 kg ha^{-1}, and 1 kg food waste (dry weight) could be produced 1.64 kg organic grains on average. Rural food waste could be used as ideal organic fertilizers to improve the nutrient level of the soil, mitigate environmental pollution, reduce the demand for synthetic fertilizers, and increase the grain output per unit land area to ensure food security.

Declarations

Ethics approval and consent to participate

This study follows all ethical practices during writing.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Authors contribution

Wang Lan: Conceptualization, Methodology, Investigation, Software, Writing-Review & Editing. Zhou Gaifang: Investigation. Qin Tianyu: Methodolog, Investigation. Guo Liyue: Software. Li Caihong: Investigation. Liu Meizhen: Writing-Review & Editing. Jiang Gaoming: Investigation, Writing-Review & Editing.

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Figures

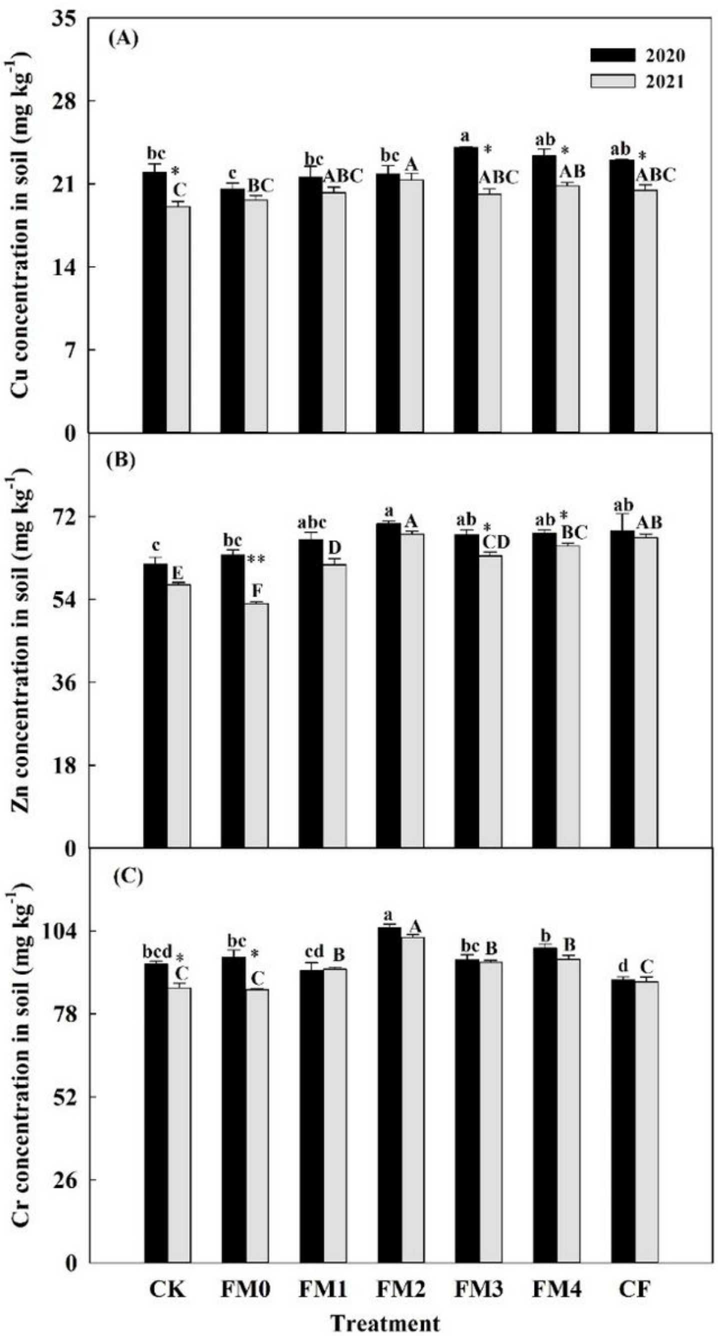

Figure 1

Different treatments of soil Cu (A), Zn (B) and Cr (C) content

Note: The data were means ± standard error (n=3). Different lower letters indicated significant differences between different treatments in 2020 (P<0.05). Different capital letters indicated significant differences between different treatments in 2021 (P<0.05). *: Indicating significant differences between different years at P<0.05 level; **: Indicating significant differences between different years at P<0.01 level.

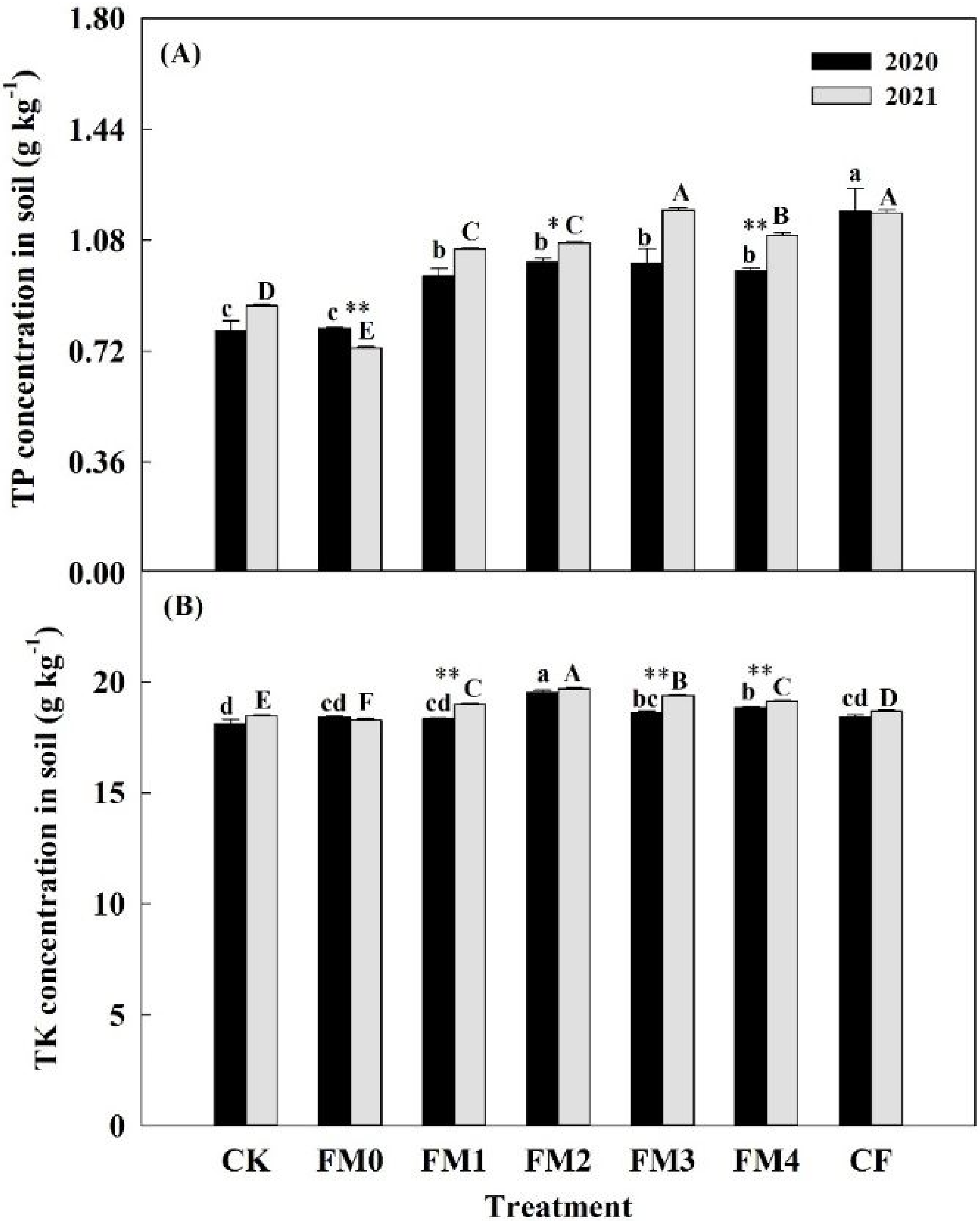

Figure 2

Different treatments of soil total phosphorus (A) and total potassium (B)

Note: The data were means ± standard error (n=3). Different lower letters indicated significant differences between different treatments in 2020 (P<0.05). Different capital letters indicated significant differences between different treatments in 2021 (P<0.05). *: Indicating significant differences between different years at P<0.05 level; **: Indicating significant differences between different years at P<0.01 level.

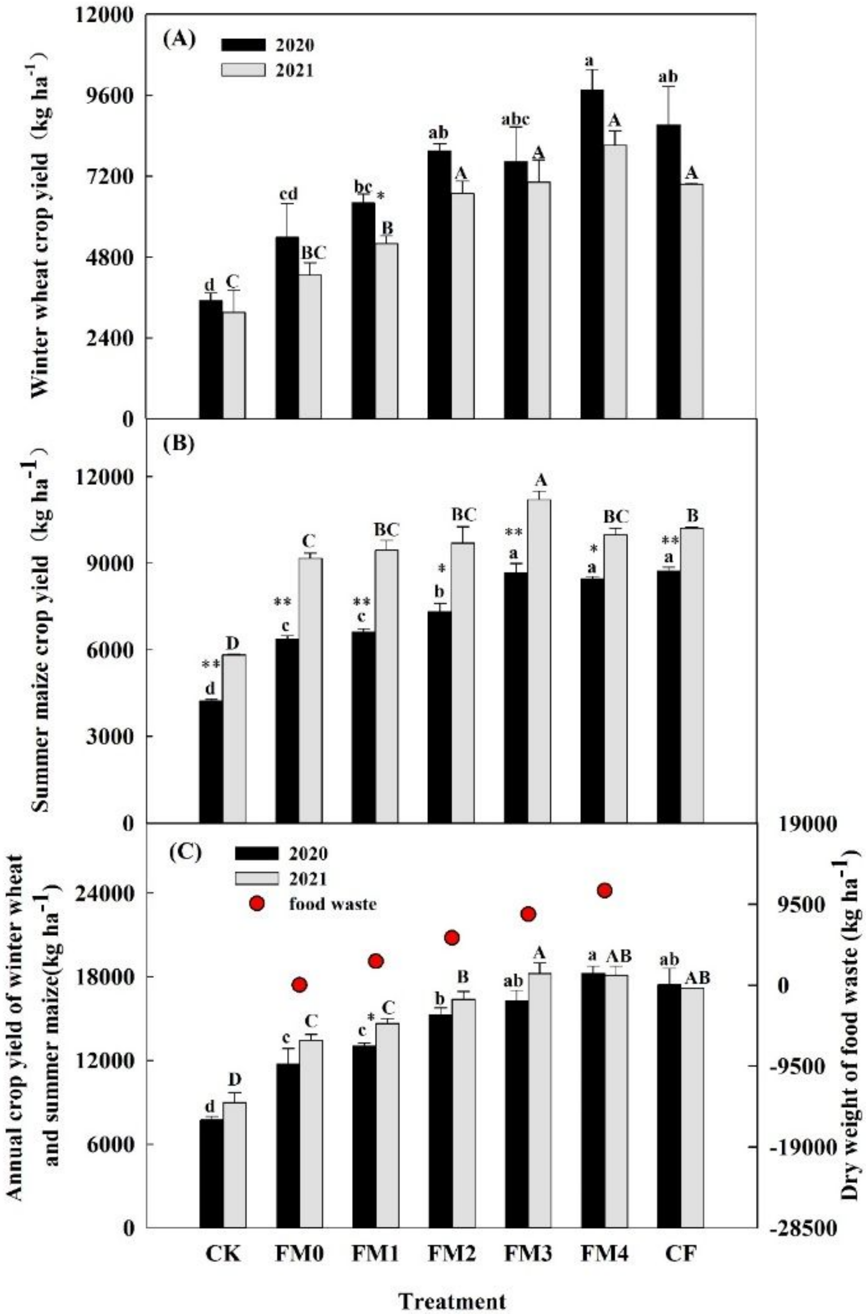

Figure 3

Winter wheat (A) and summer maize yields (B) in different treatments and the applied biomass of food waste (C)

Note: The data were means ± standard error (n=3). Different lower letters indicated significant differences between different treatments in 2020 (P<0.05). Different capital letters indicated significant differences between different treatments in 2021 (P<0.05). *: Indicating significant differences between different years at P<0.05 level; **: Indicating significant differences between different years at P<0.01 level.