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Effect of fertilizer and food waste compost on soil carbon, nitrogen use efficiency, and yield of Chinese cabbage (*Brassica Rapa* L.)

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Abstract

Food waste contributes significantly to environmental challenges, such as greenhouse gas (GHG) emissions and soil and water contamination through conventional disposal methods. Converting food waste into food waste compost (FWC) offers an alternative that reduces GHG emissions and enriches soil carbon stocks, supporting sustainable agriculture. However, the high sodium (Na) levels in FWC can adversely impact soil health and crop growth. Therefore, the objective was to thoroughly investigate the effect of different amounts of FWC on soil chemical properties, soil carbon stock (SOC), nitrogen use efficiency (NUE), growth, and yield of Chinese cabbage over three crop seasons. The treatments included: i) No fertilization (NF), ii) inorganic fertilization (NPK, control), iii) NPK + FWC-1 time (FWC1, optimal amount of food waste compost), iv) NPK + FWC-2 times (FWC2), and v) NPK + FWC-3 times (FWC3). The results showed that excessive FWC application decreased NUE (27.1%) and negatively affected cabbage yield. The FWC3 treatment during second and third crop seasons (CS) increased soil electrical conductivity (EC), Na content, and exchangeable sodium percentage (ESP). Initial FWC applications enhanced SOC stocks by 8.2%; however, continuous use declined SOC stocks. The FWC2 of the second CS increased the NUE and yield of Chinese cabbage, while growth improved in the FWC2 of the first CS. This study provides valuable insights into the balanced use of FWC to improve soil properties, crop growth, and soil carbon sequestration and promote sustainable agriculture.

Keywords Crop yield, Food waste, Nitrogen use efficiency, Organic amendments, Soil carbon

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Introduction

Food waste increases with a growing population and industrial expansion, contributing to GHG emissions. Conventional food waste disposal methods, such as landfills and incineration, contribute to environmental pollution and GHG emissions, with food waste accounting for about 20% of global emissions, and the agri-food system increased global CO₂ emissions by 1.6 GT in 2020 [1–3]. Therefore, scientists have focused on finding sustainable ways to utilize food waste rather than relying on environmentally harmful disposal methods. Recycling food waste is environmentally friendly, as it reduces its detrimental environmental impact. O'Connor et al. [2] explored food waste recycling methods in agriculture, including compost, dehydration, digestate, biochar, and hydrolysis. These methods can improve soil quality by increasing the availability of essential nutrients, such as C, N, P, and K. Sung et al. [4] reported that food waste-derived amendments contain higher nitrogen levels, stimulating NUE in crops and enhancing crop growth.

In South Korea, over 5 million tons of food waste are generated annually. Approximately 94% of waste is recycled, with 40% being recycled as compost because of its low heavy metal content, favorable C/N ratio, and high organic matter [5–7]. The remaining waste is recycled as livestock feed and energy [5]. The compost produced from food waste contains about 4% nitrogen (N), 2% phosphorus (P₂O₅), and 1% potassium (K₂O) [8]. Applying this FWC in agricultural lands, such as paddy, upland, and orchard, can improve soil carbon storage. Zhao et al. [9] reported that soil carbon stock significantly enhanced in topsoil when applied with organic amendments, including FWC, compared to chemical fertilizer. Similarly, Maillard and Angers [10] also found that the organic amendments resulted in a cumulative increase in SOC by $1.26 \pm 0.14\%$.

The SOC is an important carbon sink that increases carbon sequestration and mitigates GHG emissions [11, 12]. However, in anaerobic conditions, such as paddy soil, labile organic carbon from organic matter can stimulate methanogen activity, eventually increasing CH₄ emissions [13]. In aerobic conditions, like upland and orchard soil, high levels of mineral nitrogen (N) (NH₄⁺ and NO₃⁻) released from synthetic fertilizers and available carbon (C) compounds contribute to N₂O emissions [14, 15]. Lee et al. [6] demonstrated that FWC applications, especially at 1.5 time recommended dose, significantly increased soil microbial population and enzyme activity compared to control (no fertilizer), mineral fertilizer, and commercial compost. These increased microbial populations and enzyme activity can further increase GHG emissions, making their reduction more challenging. Therefore, stabilizing and optimizing organic amendments such as

organic fertilizer, livestock compost, FWC, and biochar can help mitigate GHG emissions [12, 16].

FWC contains relatively higher sodium (Na) and chloride (Cl⁻) concentrations than most organic amendments, which may adversely affect soil health and crop yield if applied excessively [2, 17]. However, FWC has a favorable C/N ratio, high organic matter, and also releases nutrients quickly, which can induce crop growth [2, 17]. These unique features of FWC necessitate evaluating not only the short-term benefits on soil fertility and carbon stock, but also the potential risks of salinity build-up and crop yield reduction under continuous application [8, 18]. For instance, Sanoubar et al. [19] found that 100 mmol L⁻¹ concentration of NaCl reduced white cabbage yield by 62%, while 200 mmol L⁻¹ concentration reduced yield by 70%. Similarly, red pepper and rice growth and yield decreased in salinity accumulated in the soil due to excessively applied FWC [8]. Salinity induces osmotic and ionic stress in crops, leading to a decline in growth [20]. In addition to crop impacts, salinity also deteriorates soil properties, including soil porosity, aggregate stability, and soil carbon content [21].

However, the relationship between the applied amount of FWC, SOC levels, and their effects on crops remains to be determined. More experiments are needed to explore how sodium (Na) content of FWC affects crops and soil. However, several studies have examined their effects on crops and soil individually; more information is needed on the impact of different FWC applications on crop growth, soil properties, and soil carbon stocks. Furthermore, many studies have examined FWC effects in a single growing season. The present study addresses this gap by systematically assessing the multi-seasonal effects of different FWC application rates on soil chemical properties, SOC stock, nitrogen use efficiency, and Chinese cabbage growth. The Chinese cabbage (*Brassica rapa* L.) is a nutritious vegetable, widely consumed in East Asia [22]. Therefore, the present study focuses on Chinese cabbage to investigate the effects of FWC on i) soil chemical properties, ii) soil carbon stock, iii) Chinese cabbage growth and yield index, iv) NUE of Chinese cabbage cultivated under different amounts of FWC over three-years.

Materials and methods

Field experiment

The experiment was conducted in 2020 at Rural Development Administration (RDA) experimental upland field in Wanju, Jeollabuk-do, Republic of Korea (35°49'45"N, 127°02'28"E). The soil properties (0–15 cm) of the study sites are presented in Table 1.

During the experiment, the mean annual temperature and precipitation were 14.2 °C and 1,450 mm, respectively. The experimental design consisted of five

Table 1 Soil properties of the experiment field (0–15 cm)

Parameters	Value
pH (1:5 H ₂ O)	6.3 (0.0)
EC (dS m ⁻¹)	0.42 (0.0)
SOC ^a (g kg ⁻¹)	8.6 (0.5)
Total N (%)	0.10 (0.0)
Available P (mg P ₂ O ₅ kg ⁻¹)	65.8 (0.8)
K (cmol _c kg ⁻¹)	0.71 (0.0)
Ca (cmol _c kg ⁻¹)	7.5 (0.1)
Mg (cmol _c kg ⁻¹)	2.1 (0.0)
Na (cmol _c kg ⁻¹)	0.06 (0.0)
ESP (%)	0.57 (0.0)

^aSOC: Soil Organic Carbon; ESP-exchangeable sodium percentage. Values are expressed as means (n=3) with standard deviation

Table 2 The characteristics of food waste compost (FWC) used in field experiments

Parameters	Value
pH (1:10 H ₂ O)	6.5 (0.0)
EC (dS m ⁻¹)	32.4 (0.8)
OM ^a (%)	68.6 (1.1)
Total N (%)	2.9 (0.0)
OM/N	23.4 (0.2)
Available P (%)	3.3 (0.2)
K (%)	1.2 (0.0)
Ca (%)	8.5 (0.2)
Mg (%)	0.7 (0.3)
Na (%)	1.2 (0.0)
Moisture (%)	10.7 (0.1)

^aOM: Organic matter

Values are expressed as means (n=3) with standard deviation.

treatments, each with three replicates, arranged in randomized blocks for cultivating Chinese cabbage. The treatments were: i) No fertilization (NF), ii) inorganic fertilization (NPK, control), iii) NPK + FWC-1 time (FWC1, optimal amount of food waste compost), iv) NPK + FWC-2 times (FWC2), and v) NPK + FWC-3 times (FWC3). Inorganic fertilizers N-P₂O₅-K₂O at a concentration of 32-7.8-19.8 kg 10a⁻¹ were applied to all treatments except the NF plot [23]. The FWC was applied at a ratio of 720 kg 10a⁻¹ based on FWC1, and each treatment was applied differently according to the usage ratio. Inorganic fertilizer and FWC were applied two weeks before transplanting Chinese cabbage. The characteristics of FWC used in this experiment are shown in Table 2.

Crop cultivation and nitrogen use efficiency

During the experiment, Chinese cabbage was transplanted in plots with a spacing of 100 cm between rows and a width of 40 cm within rows. Cabbage was transplanted every September and harvested in November. At harvest, various growth characteristics of the crops, including height, length, chlorophyll content, and yield

were measured, and yield index was calculated using Eq. 1.

$$\text{Yield index (\%)} = \frac{Y_T}{Y_C} \times 100 (\%) \quad (1)$$

Where, Y_T indicates the yield of each treatment (kg 10a⁻¹), and Y_C denotes the yield of control group (NPK treatment) (kg 10a⁻¹), respectively.

The chlorophyll content was measured with SPAD value (SPAD-502 Plus, Konica Minolta Japan). The harvested crops were dried in oven at 60 °C (DS-80-3, Dasol Scientific Co., Ltd., Hwaseong, Korea). The dried crops were crushed into a fine powder using a mortar and pestle and analyzed for nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) following the soil and plant analysis method of National Institute of Agricultural Science and Technology (NIAST) (2000) [24]. The crop nitrogen content was analyzed by elemental analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Germany). The soil and plant K, Ca, Mg, and Na contents were measured by an inductively coupled plasma optical emission spectrometer (ICP-OES) (AU/CINTRA6, GBC Scientific Equipment Pty Ltd, Malaysia). To assess the impact of applications of FWC on crop growth characteristics and yield, NUE was calculated using Eq. 2, Cheng et al. [25].

$$\text{NUE (\%)} = \frac{N_F - N_0}{F_N} \times 100 (\%) \quad (2)$$

Where, N_F and N₀ are the nitrogen uptake by crops treated with nitrogen treatment (kg 10a⁻¹) and nitrogen uptake without nitrogen treatment, and F_N is the amount of nitrogen applied, respectively.

Soil chemical properties and carbon stock analysis

Soil samples were collected from the surface layer (0–15 cm) after each harvest from different treatment plots using a soil auger. Each sample was thoroughly mixed, air-dried, and sieved (< 2 mm) with a stainless steel sieve and analyzed chemical properties according to the soil and plant analysis method [24]. To measure soil pH and EC, soil sample was mixed with distilled water in a 1:5 ratio, respectively, and determined using a pH meter (Orion 5 star, Thermo Scientific, USA) and EC meter (Orion star A222, Thermo Scientific, USA). The soil available phosphorus (Av. P₂O₅) was measured using the Lancaster method. Total nitrogen (TN) and SOC contents were analyzed using the elemental analyzer (Vario Max CN, Elementar Analysensysteme GmbH, Germany). The soil exchangeable cations were extracted with 1 M ammonium acetate (NH₄OAc) and analyzed by ICP-OES analysis (AU/CINTRA6, GBC Scientific Equipment Pty

Ltd, Malaysia). Exchangeable sodium percentage (ESP) was calculated as a ratio of Na to cation exchange capacity (CEC). Soil carbon stock was calculated using the soil organic carbon and the average bulk density (1.33 Mg m^{-3}) of upland soil in South Korea [26]. The calculation followed the method described by Hwang et al. [27].

$$\text{SOC stock (Mg C ha}^{-1}\text{)} = \text{SOC (g kg}^{-1}\text{)} \times \text{BD (Mg m}^{-3}\text{)} \times \text{Soil Depth (m)} \times 0.1 \quad (3)$$

Where, SOC stock is soil organic carbon stock, SOC indicates soil organic carbon, BD is bulk density of soil, soil depth is 0.15 m, and 0.1 is the conversion factor to change units to Mg C ha^{-1} . The relative change of soil organic carbon (SOC) was calculated as the difference between the initial soil SOC with SOC of the first CS and the third CS, respectively.

Statistical analysis

The experimental data were statistically analyzed using two-way analysis of variance (ANOVA) at a significance level of p -value < 0.05 with Statistical Packages for Social Sciences (IBM SPSS Statistics 27). Duncan's multiple range test was performed to analyze the mean comparison between different treatment groups at p -value < 0.05 .

Results and discussion

Temporal changes in soil chemical properties

The FWC used in this study contains high levels of Ca and Na compared to rice straw (Ca: 0.13–0.46%, Na: $< 0.01\%$) and livestock manure compost (Ca: 0.68–0.98%, Na: 0.08–0.42%) [27]. All over three crop seasons (CS), temporal changes in soil chemical properties were observed under different fertilization treatments, as summarized in Table 3. During third CS, the soil chemical properties were found to be in an optimal range. The soil pH and EC were increased with increasing application of FWC in each season, with pH above the optimum level in the third CS except NPK (Table 3). Lee et al. [17] also showed that applying FWC eventually increases soil pH, which is allied with our findings. The EC and total N contents were highest under the FWC2 treatment of the second CS ($P < 0.001$). According to Calamai et al. [28] report, applying organic amendments increases soil EC and pH. Initial inorganic fertilizer yielded the highest EC (0.70 dS m^{-1}) compared to organic treatments, attributed to the easy solubility of ions from inorganic fertilizer by water. However, an organic amendment exhibited highest EC (0.74 dS m^{-1}), signifying the mineralization of OM from FWC by microbes over an extended period.

The available P_2O_5 and Mg contents were greatest under the first CS; however, they did not show a significant difference between the fertilization and crop seasons ($P > 0.05$) (Table 3). In the third CS, exchangeable

Table 3 Changes in soil chemical properties affected by different fertilization methods during the crop seasons

Crop seasons	Treatments	pH	EC	Available P	Total N	K	Ca	Mg	Na	ESP
		1:5 H_2O	dS m^{-1}	$\text{mg P}_2\text{O}_5 \text{ kg}^{-1}$	%		$\text{(cmol}_\text{c} \text{ kg}^{-1}\text{)}$			%
First CS	NF	6.6 (0.0)a	0.30 (0.10)a	308 (11.4)a	0.10 (0.00)a	0.73 (0.03)a	6.6 (0.2)a	1.8 (0.0)a	0.10 (0.02)bc	1.1 (0.1)bc
	NPK	5.6 (0.3)b	0.55 (0.05)a	404 (38.4)a	0.12 (0.01)a	0.43 (0.12)b	6.3 (0.1)a	1.8 (0.0)a	0.07 (0.01)c	0.9 (0.1)c
	FWC1	6.3 (0.2)ab	0.42 (0.12)a	361 (9.1)a	0.14 (0.02)a	0.47 (0.02)b	6.8 (0.4)a	1.9 (0.1)a	0.12 (0.02)abc	1.3 (0.1)bc
	FWC2	6.1 (0.2)ab	0.45 (0.12)a	366 (55.4)a	0.13 (0.01)a	0.52 (0.02)b	6.8 (0.5)a	1.7 (0.2)a	0.15 (0.03)ab	1.6 (0.2)ab
	FWC3	6.2 (0.2)ab	0.46 (0.07)a	386 (40.2)a	0.13 (0.01)a	0.48 (0.05)b	6.6 (0.4)a	1.8 (0.1)a	0.18 (0.03)a	2.0 (0.3)a
Second CS	NF	6.8 (0.0)a	0.21 (0.01)b	234 (2.4)a	0.13 (0.00)c	0.59 (0.03)a	6.2 (0.1)b	1.7 (0.0)a	0.12 (0.01)b	1.3 (0.1)b
	NPK	6.3 (0.2)bc	0.70 (0.16)a	308 (24.6)a	0.19 (0.03)ab	0.25 (0.02)b	6.2 (0.1)b	1.7 (0.1)a	0.08 (0.01)c	0.9 (0.1)c
	FWC1	6.2 (0.1)c	0.23 (0.02)b	237 (19.4)a	0.15 (0.01)bc	0.24 (0.02)b	6.2 (0.1)b	1.7 (0.0)a	0.11 (0.01)bc	1.4 (0.1)b
	FWC2	6.7(0.2)ab	0.74 (0.17)a	265 (27.6)a	0.20 (0.02)a	0.22 (0.02)b	7.1 (0.2)a	1.7 (0.1)a	0.32 (0.01)a	2.7 (0.4)a
	FWC3	6.7(0.1)ab	0.72 (0.14)a	288 (13.1)a	0.19 (0.01)ab	0.27 (0.03)b	7.3 (0.3)a	1.8 (0.1)a	0.32 (0.04)a	3.3 (0.3)a
Third CS	NF	6.7(0.1)ab	0.28 (0.00)a	304 (19.7)a	0.10 (0.01)bc	0.72 (0.01)b	6.7 (0.1)b	1.8 (0.0)a	0.13 (0.01)c	1.3 (0.1)c
	NPK	6.2(0.1)c	0.26 (0.03)a	313 (9.6)a	0.10 (0.00)c	0.56 (0.02)d	6.2 (0.1)c	1.7 (0.0)a	0.12 (0.00)c	1.4 (0.0)c
	FWC1	6.6(0.1)b	0.29 (0.02)a	338 (12.4)a	0.11 (0.00)ab	0.64 (0.02)c	7.0 (0.1)ab	1.8 (0.0)a	0.17 (0.01)b	1.8 (0.1)b
	FWC2	6.8(0.0)ab	0.32 (0.03)a	342 (11.7)a	0.11 (0.00)a	0.81 (0.00)a	7.0 (0.2)ab	1.6 (0.0)b	0.20 (0.00)a	2.1 (0.0)a
	FWC3	6.9(0.1)a	0.34 (0.03)a	290 (21.0)a	0.11 (0.00)abc	0.84 (0.03)a	7.1 (0.2)a	1.6 (0.0)b	0.21 (0.00)a	2.2 (0.0)a
Optimal range		6.0–6.5	≤ 2	350–450	-	0.65–0.80	5.0–6.0	1.5–2.0	-	-
Effects		Probability $> F$								
Treat (T)		< 0.001	0.041	0.032	0.020	< 0.001	< 0.001	0.357	< 0.001	< 0.001
Crop Season (CS)		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.049	0.027	0.002	< 0.001
T $\times$ CS		0.078	0.002	0.099	0.046	< 0.001	0.139	0.705	0.003	< 0.001

Treat-Treatment; CS-Crop Season; NF-No fertilizer; NPK-Inorganic fertilizer, FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer; ESP-exchangeable sodium percentage. The optimal range is recorded in RDA 2022. Values are expressed as means ($n=9$) with standard deviation. Different letters within the same column indicate statistically significant differences at P value < 0.05 , and the same letters within the column are statistically not significant at P value > 0.05 .

cations, particularly K, Ca, and Na contents, increased with continuous cultivation under the FWC treatment ($P < 0.05$), which could be related to its high organic matter from continuous and excessive application of FWC [29]. This result aligns with Ramos et al. [29], who reported the content of exchangeable cations increased with increasing soil organic matter. The sodium (Na) content was considerably elevated in FWC2-3, which might be associated with the interaction of fertilization methods and crop seasons ($P < 0.05$). In the case of exchangeable sodium percentage (ESP), soil ESP was highest at FWC3 during all cultivation periods ($P < 0.001$) and was approximately twice that of NPK (Table 3). These results suggest that elevated soil Na levels might cause a decline in both microbial population and activity in the soil [17, 30].

SOC stock changes under the FWC application

During the first CS, SOC stock declined in NF (−12.7%), NPK (−12.2%), and FWC1 (−1.9%) when compared to the initial soil, while FWC2 and FWC3 applications led to increases of 4.7% and 8.2%, respectively (Table 4).

These results imply that organic amendments can improve soil organic carbon contents and carbon sequestration process [31, 32]. Although SOC stock initially increased in FWC1 of the first CS, this effect was considered temporary and depended on the amount of organic amendment applied. This increased SOC could be linked to reduced soil aggregation caused by high salinity of the amendments [8, 33–36]. Kaiser et al. [37] also demonstrated that the presence of high sodium (Na) in FWC weakens soil aggregation and structure, leading to releasing more organic matter from compost and SOC adsorbed on the clay particles because of the solvation effect of salts. Another study by Nelson et al. [38, 39] noted that sodium (Na) enhances SOC solvation owing to its higher solubility than Ca, stimulating

SOC mineralization. In the present study, increased initial SOC under high FWC (FWC3-18.6 Mg C ha^{−1}) of the first CS application could be related to the solvation effect of salts.

The FWC treatments yielded higher SOC stocks than NPK, and it was increased with their continuous applications. This suggests that organic amendments like FWC, enriched with humified livestock manure, could enhance SOC stocks more effectively than inorganic fertilizers and rice straw due to their resistance to microbial decomposition [34]. This result aligns with the study by Rahman et al. [35], who observed a similar trend in SOC stock (3.0%, 4.9%, and 1.0%) following three years of cattle manure, poultry manure, and rice straw applications, respectively. After 3 years of continuous cultivation, the SOC stock increased in NF (16 Mg C ha^{−1}), NPK (16.7 Mg C ha^{−1}), and FWC1 (18.5 Mg C ha^{−1}) compared to the first CS. In contrast, it decreased under FWC2 (17.4 Mg C ha^{−1}) and FWC3 (17.2 Mg C ha^{−1}), reversing the trends observed in the first CS (Table 4). The FWC1 had a significantly higher SOC stock than the other treatments in the third CS ($P < 0.05$). The decreased SOC stock in FWC2 and FWC3 may be related to the prolonged presence of soluble salts, including Na⁺ and Cl[−], in the soil resulting from the continuous application of FWC. This may raise the osmotic potential, which in turn suppresses microbial populations and enzyme activity, and slows the decomposition of organic amendments, thereby significantly decreasing SOC stock, as shown in Table 4 [40, 41]. Additionally, Hwang et al. [27] and Lee et al. [33] reported SOC stock decreased by −13.3% and −2.0%, respectively, in soil without fertilizer applications, indicating that continuous cultivation without fertilization can reduce SOC stocks, eventually influencing soil health and crop productivity [27]. However, excessive FWC application during the third CS could contribute to the loss of soluble organic matter and SOC through leaching, runoff, and CO₂ emission [39, 42]. This suggests that optimal application of FWC can improve SOC stocks, while prolonged and excessive doses may lead to a decrease in SOC stocks.

Table 4 Change of soil organic carbon stock in first CS and third CS under different fertilization methods

Treatment	SOC stock (Mg C ha ^{−1})			Relative SOC change (%)	
	Initial soil	First CS	Third CS	First CS	Third CS
NF	17.1 (0.6)	15.1 (0.9)a	16.0 (0.2)b	−12.7	−6.5
NPK		15.2 (1.1)a	16.7 (0.1)b	−12.2	−2.3
FWC1		16.8 (1.1)a	18.5 (0.6)a	−1.9	+7.9
FWC2		17.9 (1.4)a	17.4 (0.5)ab	+4.7	+1.8
FWC3		18.6 (2.4)a	17.2 (0.1)ab	+8.2	+1.0

Relative SOC was compared with the initial soil, First CS, and Third CS, respectively. SOC-soil organic carbon; NF-No fertilizer; NPK-Inorganic fertilizer; FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer. Values are expressed as means (n = 9) with standard deviation. Different letters within the same column indicate statistically significant differences at P value < 0.05 , and the same letters within the column are statistically not significant at P value > 0.05 .

Effect of FWC on growth, yield, and nutrient contents of Chinese cabbage

Figure 1 shows that cabbage height was notably increased under FWC2 treatment during both the first ($P < 0.001$) and second CS ($P < 0.001$) while FWC1 exhibited higher in the third CS ($P < 0.001$) (Fig. 1a). In contrast, there was insignificant difference observed in cabbage length among fertilized treatments across all seasons ($P > 0.05$) (Fig. 1b). Continuous cultivation led to a consistent decrease in the height, length, and yield of Chinese cabbage in each year ($P < 0.001$). Zhao et al. [43] also reported a reduced cucumber yield under continuous

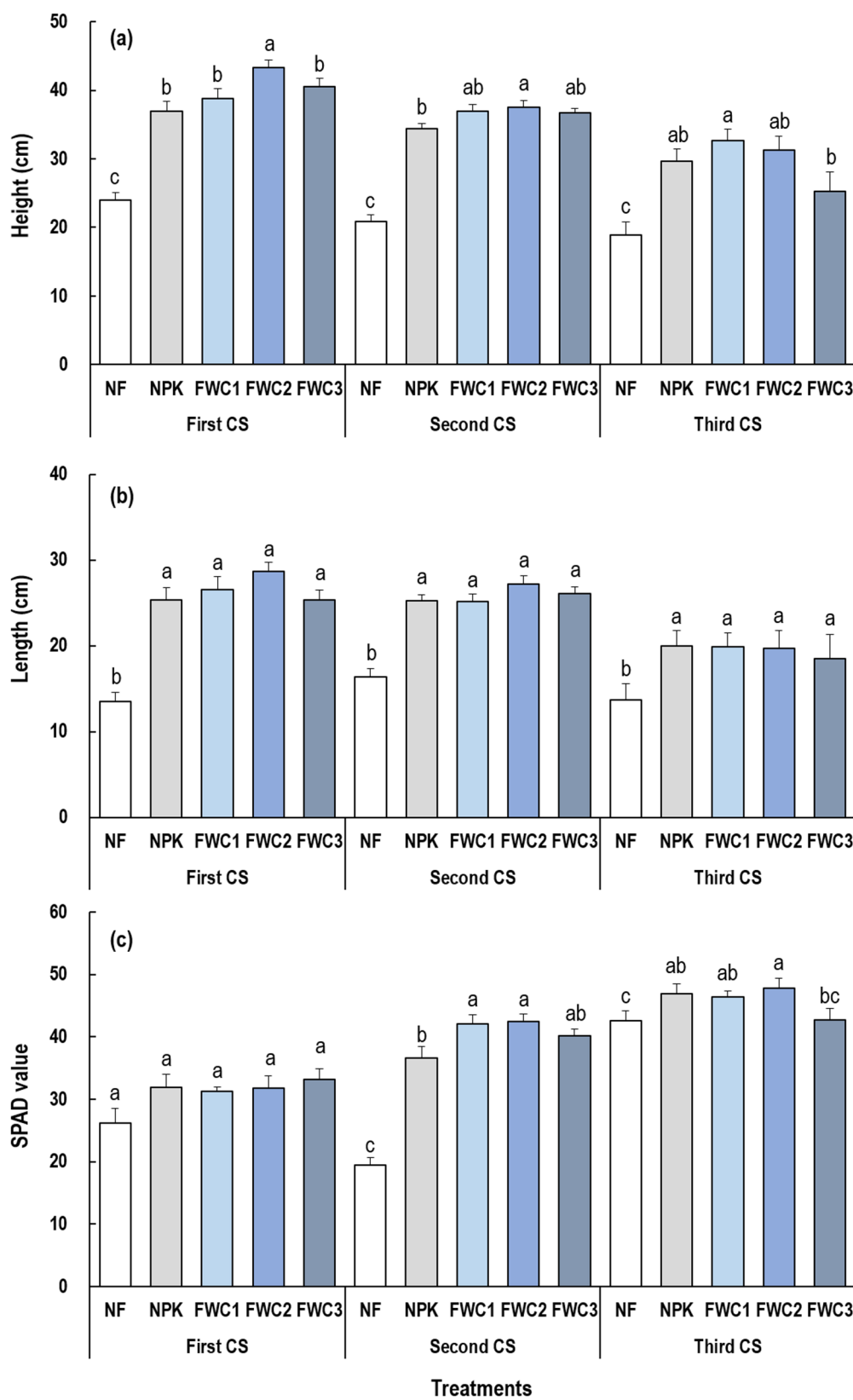


Fig. 1 Chinese cabbage growth characteristics under different fertilizers: **(a)** height, **(b)** length, **(c)** SPAD value. The treatments were NF-No fertilizer; NPK-Inorganic fertilizer; FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer. The same letters in the figure indicate insignificant differences (Duncan's test, $P < 0.05$)

cultivation with various fertilizer treatments, including manure compost. A similar result was also observed in rice, peppers, and cabbage crops, where yields decreased as ESP exceeded (1.9%) [8]. In the present study, soil ESP increased with applications of FWC during the second and third CS compared to the first CS (Table 3). These elevated soil ESP levels and other unfavorable soil conditions might be responsible for declining crop yields over continuous cultivation. The SPAD values, indicative of chlorophyll content, showed insignificant differences during the first CS ($P > 0.05$). However, significant differences were noted in the second and third CS ($P < 0.05$) (Fig. 1c). The continuous fertilizer application likely resulted in nitrogen accumulation in the soil, which contributed to the gradual increase in SPAD values across seasons ($P < 0.001$). This increased SPAD value reflects a positive correlation with nitrogen supply, as reported by previous studies [40, 43].

The Chinese cabbage yield was highest under the FWC2 treatment in the first CS ($P < 0.001$) (Fig. 2a). The yield difference among treatments was 10% higher for FWC1, 23% higher for FWC2, and 2% lower for FWC3 compared to NPK. A similar trend was observed in the second CS, with FWC2 treatment increasing yield by 23% ($P < 0.001$), followed by FWC1 (15%), and FWC3 (1%) compared to NPK (Fig. 2b). In the third CS, FWC1 treatment produced the highest yield ($P < 0.05$), though the difference with FWC2 was insignificant (Fig. 2c).

Figures 1 and 2 indicate that the FWC application, particularly FWC2, significantly enhanced Chinese cabbage growth, including height, length, and overall yield, compared to NPK. These results could be due to FWC containing high levels of organic matter and nitrogen, as indicated in Table 2, which could be responsible for increasing soil nutrient availability, SOC, and NUE of the crops compared to NPK (Tables 3, 4 and 5; Fig. 3). Several studies have shown that the application of organic compost, especially those containing food waste, significantly improves crop growth and yield [5, 6, 42]. Sung et al. [4], Wong et al. [42], and Cai et al. [44] also found that applying compost resulted in better growth and yield of rice, wheat, and maize crops than inorganic fertilizer, which aligns with this study.

However, the FWC3 treatment resulted in lower height, length, SPAD value, and yield of cabbage across all cultivation periods compared to FWC 2 treatments and insignificant difference with FWC1 treatment. In the third CS, the cabbage yield under FWC3 was 21% lower than that of NPK, likely due to nutrient content differences between the crops and two treatments (Fig. 3; Table 3). Cabbage grown under FWC3 had lower K, Ca, and Mg than the FWC1 and FWC2, while Na content was significantly higher in each CS ($P < 0.001$) (Fig. 3). According to Sung et al. [4], FWC contains higher Na content than other organic amendments due to its raw material chemical properties. The higher Na content in cabbage grown

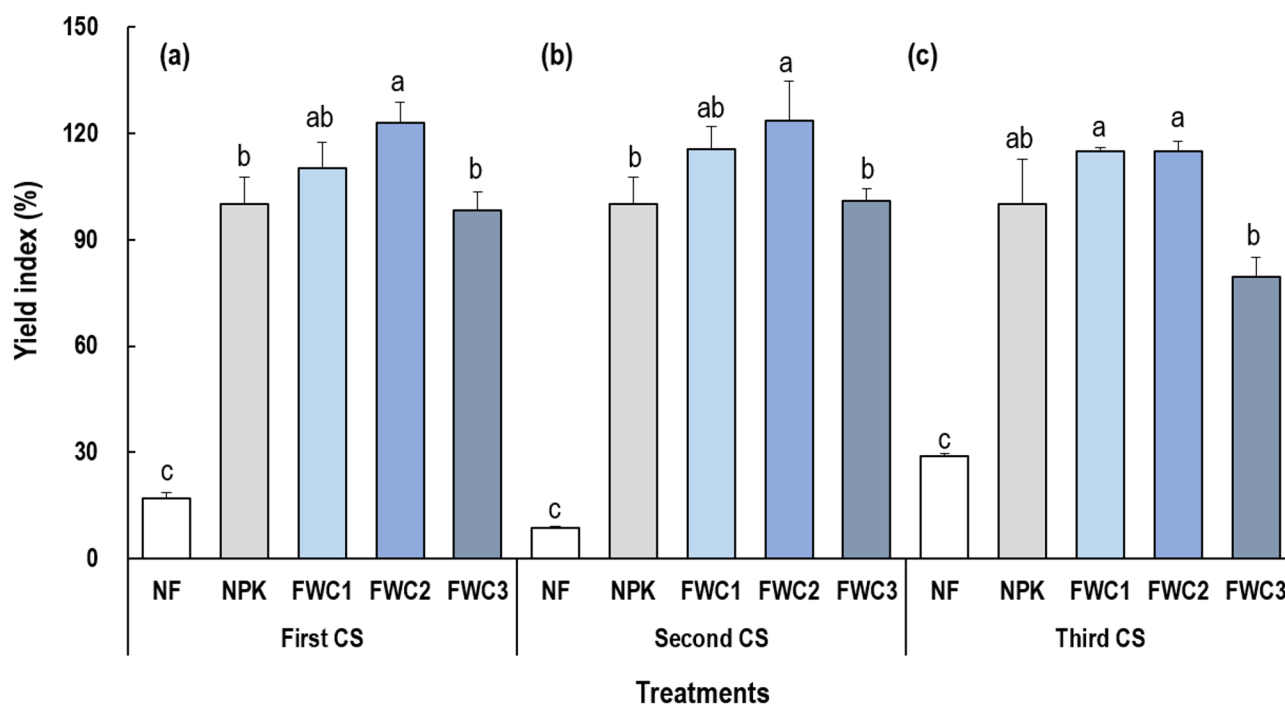


Fig. 2 The yield index of Chinese cabbage under different fertilizers: (a) first CS, (b) second CS, (c) third CS. The treatments were NF-No fertilizer; NPK-Inorganic fertilizer; FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer. The same letters in the figure indicate insignificant differences (Duncan's test, $P < 0.05$)

Table 5 Effect of different fertilizer treatments on N contents and nitrogen use efficiency (NUE) of the crop

Treatment	Nitrogen (N) (%)			NUE (%)		
	First CS	Second CS	Third CS	First CS	Second CS	Third CS
NPK	21.9 (1.1)a	20.5 (0.4)b	15.3 (1.2)b	59.2 (3.6)a	57.3 (1.3)b	42.2 (3.7)b
FWC1	22.9 (0.7)a	21.4 (0.4)ab	17.1 (0.5)a	61.3 (2.2)a	61.0 (1.2)ab	54.6 (1.6)a
FWC2	22.5 (1.0)a	23.4 (0.8)a	20.5 (0.3)a	58.4 (3.2)a	66.5 (2.4)a	52.9 (1.0)a
FWC3	18.8 (0.6)b	20.9 (0.7)b	12.2 (1.3)c	46.8 (1.8)b	58.5 (2.3)b	27.1 (4.1)c
Treat (T)	< 0.001			< 0.001		
CS	< 0.001			< 0.001		
T×CS	< 0.001			< 0.001		

Treat-Treatment; CS-Crop Season; NF-No fertilizer; NPK-Inorganic fertilizer; FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer

Values are expressed as means (n=9) with standard deviation. Different letters within the same column indicate statistically significant differences at P value < 0.05, and the same letters within the column are statistically not significant at P value > 0.05.

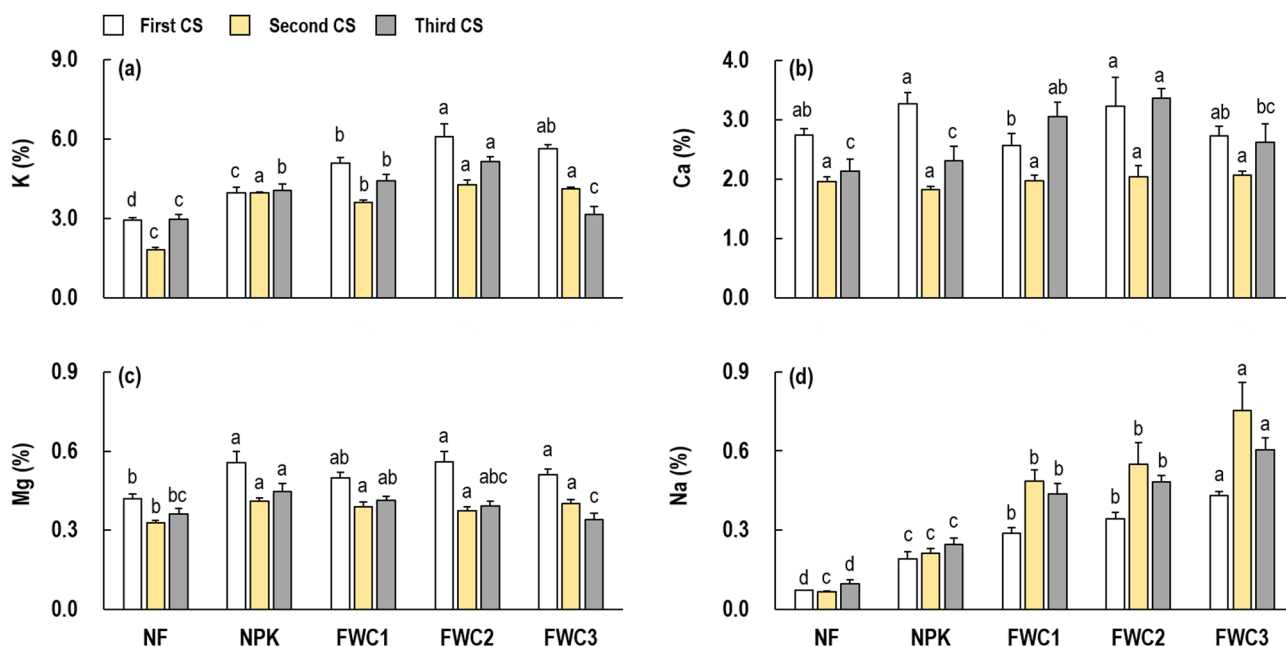


Fig. 3 Chemical properties of Chinese cabbage leaves in each crop season: (a) potassium (K), (b) calcium (Ca), (c) magnesium (Mg), (d) sodium (Na). The treatments were NF-No fertilizer; NPK-Inorganic fertilizer; FWC1, 2, and 3-Food Waste Compost 1, 2, and 3-times with inorganic fertilizer. The same letters in the figure indicate no significant difference (Duncan's test, $P < 0.05$)

under FWC3 could be attributed to two main factors: higher Na levels in the FWC raw material and the applied dose, which was three times the optimum dose of FWC. Additionally, the continuous application of FWC further promotes more Na accumulation in the crops, eventually inhibiting cabbage growth and yields [4].

Nitrogen use efficiency (NUE) of Chinese cabbage

The first CS showed no significant difference in NUE among the NPK, FWC1, 2, and 3 treatments ($P > 0.05$) (Table 5). During the second CS, the highest NUE was recorded under FWC2 (66.5%) ($P < 0.05$), followed by FWC1 (61.0%) (Table 5); but the difference was statistically not significant. In the third CS, FWC1 had the highest NUE (54.6%), while FWC3 exhibited the lowest NUE (27.1%) ($P < 0.001$) (Table 5). NUE is a key indicator for assessing crop efficiency under different fertilization

treatments [4]. The results demonstrate that cabbage NUE reduced as the application rate of FWC increased ($P < 0.001$). For instance, under the FWC3 treatment of the third CS, the NUE of cabbage decreased by approximately 15% compared to the NPK treatment, eventually reducing cabbage yield (Table 5), which could be due to increased nitrogen losses by volatilization, eventually lowering their availability [45, 46]. This finding aligns with studies by Sung et al. [4] and Ortiz-Monasterio et al. [47], which reported that excessive application of organic compost, such as FWC, with high nitrogen content, can hinder photosynthesis, reduce translocation efficiency, and enhance nitrogen volatilization losses, ultimately decreasing the NUE of crops. The application of food waste digest for soil amendment is reported to result in 60-70% nitrogen loss through ammonia volatilization, creating a phytotoxic environment for plants,

which supports the present study [45, 46]. Although high nitrogen levels are intended to enhance crop growth, not all absorbed nitrogen is effectively assimilated by crops [48]. The decline in NUE might be associated with reduced SPAD values and lowered crop yields [49] (Figs. 1 and 2).

Additionally, excessive applications of organic compost may pose environmental risks like GHG emissions and soil and water pollution. For instance, higher nitrogen levels in the soil can contribute to GHG emissions, such as N₂O and NO, through nitrification processes [50, 51]. Felix et al. [52] also highlighted the risk of excess nutrients leaching into water systems, including groundwater and rivers, especially during rainfall. Therefore, these findings suggest that the excessive applications of FWC not only decrease NUE and yield of crops but also pose a threat to environmental sustainability and indicate the importance of the optimum dose of FWC.

This study evaluated the effect of varying FWC application amounts on soil properties and crop productivity over time. The results demonstrated that continuous and excessive FWC application, particularly under FWC3 treatment of second and third CS, had adverse effects on soil properties, including increased soil EC, Na content, and ESP. These changes negatively affected Chinese cabbage by reducing NUE, nitrogen uptake, and impairing photosynthesis, ultimately diminishing cabbage growth and yield. However, the initial FWC application improved SOC stock, and prolonged and excessive use led to a decline in SOC levels. Notably, during the first CS, cabbage grown under the FWC2 treatment exhibited superior growth and yield. The findings of this study highlight the importance of optimizing FWC application to enhance SOC without compromising soil health and the growth performance of Chinese cabbage. This integrative assessment contributes new insights for establishing sustainable guidelines for FWC application in agriculture. Future work will focus on assessing GHG emissions (CH₄, CO₂, and N₂O) from agricultural land and associated changes in soil enzymes and microbial communities, to gain a better understanding of how alterations in soil carbon and nitrogen dynamics by different levels of FWC applications.

Acknowledgements

The authors greatly acknowledge the Rural Development Administration (RDA) for providing the research sites and experimental facilities.

Author contributions

Y-JJ: Methodology, Investigation, Writing- original draft. G.D.V, S-H.K, S-H.J & A-S.R: Investigation, Formal Analysis, Validation, Data Curation, Visualization, G.D.V & S-H.J: Manuscript Editing, Review. J-J.Y & J-H.S: Review, Supervision.

Funding

This work was supported by the 2025 RDA Fellowship Program of National Institute of Agricultural Science and the Research Program for Agricultural

Science & Technology Development (Project No. PJ017273), Rural Development Administration, Republic of Korea.

Data availability

All data generated in the study are presented in the submitted article.

Declarations

Competing interests

The authors declare that they have no competing interests.

Received: 10 July 2025 / Accepted: 12 September 2025

Published online: 31 October 2025

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