

Article

Comparison of Effects of Chemical and Food Waste-Derived Fertilizers on the Growth and Nutrient Content of Lettuce (*Lactuca sativa* L.)

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Abstract: The current high rate of food waste production, concomitant with the global increase in population and food demand, has adverse effects on environmental and socio-economic conditions. However, food waste has been shown to be an efficient and safe source of fertilizer in agriculture practice. Moreover, minimizing the application of chemical fertilizers is a goal of sustainable agriculture. Considering these facts, we aimed to compare the effect of chemical fertilizer (CF-3,8 g·pot⁻¹) and different doses of mixed food waste-derived fertilizer (MF-10.6 g·pot⁻¹), two-fold MF (MF × 2), four-fold MF (MF × 4), and six-fold MF (MF × 6) in a popular salad crop, *Lactuca sativa* (lettuce). Our results showed the growth rates of lettuce plants receiving CF, MF, and MF×2 applications were essentially the same; however, plant biomass significantly dropped with MF × 6 treatment. The CF, MF, and MF × 2 treatments enhanced the chlorophyll content, chlorophyll fluorescence, and photosynthetic rate of the plants and improved transpiration efficiency and stomatal conductance. With respect to mineral elements, the K⁺ content was significantly enhanced with MF × 2 and MF × 4 treatment, whereas MF × 6-treated plants showed lower concentrations of Ca, P, Mg, and K⁺ as well as higher Na⁺ concentration. Biochemical analysis showed the elevation of abscisic acid level with increasing dose of MF, except in the MF × 6 treatment. The level of super oxide dismutase (SOD) dropped with CF treatment, was unchanged with MF, and significantly increased in MF×2 and MF × 4 treated plants. Subsequently, higher flavonoid content was observed in MF×2 and MF×4 plants. The current results demonstrate the potential of food waste as a source of organic fertilizer and a significant substitute for chemical fertilizer in the conventional agricultural practice driven by high production cost and environmental pollution.

Keywords: food; chemical fertilizer; environment; mineral; salt; sustainable agriculture



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1. Introduction

The world's population continues to rise and is expected to reach 9.6 billion by 2050 [1]. The food demand by 2050 will increase by 60% [2]. It is reported that, with the current food consumption rate and trend, overall production should be increased by over 70% to sustain the entire population (FAO 2009) [3]. The worldwide agricultural output grew at 2.54% between 2001 and 2014; however, there is increasing concern that agricultural productivity is slowing down globally [4]. Despite the higher food production rate, it is estimated that 870 million people are reported as being malnourished; at the same time, approximately 1.3 billion tons/year (1/3rd) of the food produced for human consumption is wasted [5]. According to research conducted by the Food and Agricultural Organization

(FAO) of the United Nations, the food waste in the United States alone is estimated at nearly \$166 billion each year [3]. This amount of waste is detrimental to food security and has negative impacts on socio-economic and environmental conditions worldwide. Sustainable development goals related to hunger, environment, and climate action can be achieved only when these levels of food waste can be reduced.

There are a number of definitions of food waste and most of these are similar to the definition given by the FAO, which considers food waste as the degradation in the quantity or quality of food resulting from choices and activities by actors in the food supply chain: producers, foodservice providers, and consumers [5,6]. Food waste occurs in all aspects of the food system, including agricultural operations, post-harvest handling, food processing, and meal preparation. Apart from the food losses that occur on farms, 42% of food waste occurs at the household level, 38% during food processing, and an additional 20% is distributed along the whole chain [7].

In general, a massive amount of food waste is burnt or dumped in landfill sites. The food wastes at buried or landfill sites have been creating several problems, such as air and water pollution [8]. Unmanaged food waste in urban localities has severely destroyed the aesthetic value and beauty of cities in developing countries; additionally, food waste can serve as a host of infectious disease vectors that may exacerbate disease epidemics [9]. Management of waste in a scientific manner is a fundamental prerequisite of sustainable development [10]. For this to happen, the bioconversion of organic waste that includes food, human excreta, organic materials from animal and plant origin is vital [11].

Global food production widely depends on synthetic chemical fertilizers and the world has now recognized the importance of sustainable agriculture which defines production based on minimal expenses of resources to maintain environmental resilience [12,13]. According to FAO estimates, the global consumption of nitrogen, phosphorus, and potash (NPK) was approximately 186.67 million tons in 2016, and P demand increased by 2.2% in 2020, although the utilization efficiency by a crop is limited to 10–15% [14]. As the use of chemical fertilizers and pesticides increases, so does the risk of detrimental effects, such as water eutrophication, salinity, and heavy metal contamination [15,16]. To address these challenges alongside meeting the increasing demand for food globally, higher crop yields are required while keeping chemical fertilizer levels low, conserving energy, and managing food waste in an environmentally sustainable manner [17]. Researchers are now formulating several approaches of bioconversion of organic waste that includes food, human excreta, and organic materials from animal and plant origins [11].

Excess food that becomes waste can instead be converted to a source of organic fertilizer and bio-energy through biodegradation (composting) processes [18]; however, food waste may contain higher salt content, which upon exposure in soil may induce salinity stress in plants [8]. In addition, the ammonia (NH_3) emission from food waste is linked to account excessive nitrogen loss which may result in various environmental impacts [19]. It is thus important to determine the appropriate salt content application dose in food waste fertilizer and ammonia loss to minimize the adverse environmental impacts. It has been reported that the continued application of food waste organic fertilizer was effective in enhancing soil quality and improving crop yields, as well as having a positive influence on the growth of soil microbes [8]. However, Chiew et al. [20] reported that digested food waste fertilizer contributes to global warming and has more negative effects than does chemical fertilizer. These findings need to be considered, as well as the fact that the earth's crust offers a limited supply of the components in chemical fertilization; some researchers have concluded that the soil is in danger of further degradation until it can no longer respond to externally applied fertilizer [17,21].

It has been reported that by Adelodun et al. [22] that approximately 15Mt of food wastage produced from different supply chains—equivalent to 15 billion m^3 of water resources in between 2007–2017 across Korea—resulted in 20 Mt $\text{CO}_2\text{eq.}$ of greenhouse gas emissions, with a predicted increase potential of 13% by 2030. In the current study, we have used the food waste fertilizer produced from the company Seyen Co., Ltd., Kyungsan

Korea, which uses different food resources, processes them, and derives them as a fertilizer. We tested its significance with regard to whether it should be commercially applied for crop production. Moreover, lettuce is a very popular salad crop and is widely consumed in major parts of the world. Since the use of food waste fertilizer may contain higher salt content or some other harmful elements, this may have an adverse effect on production and public health; thus, we believe the current research could provide insight into an economical approach for developing commercial food waste fertilizer, crop nutrient value, soil toxicity, and exploring it in the farmers' field. Furthermore, considering the urgent need for sustainable agriculture, our goal in the present study was to test an alternative to chemical fertilizer, namely food-waste derived fertilizer, in commercial agricultural production with high nutritive value.

2. Materials and Methods

2.1. Plant Experiment and Physicochemical Properties of Soil

This study was conducted in a greenhouse at Kyungpook National University, Daegu, The Republic of Korea during the summer months (June–August 2021). The lettuce seedlings var. “Tomalin” were grown for two weeks in a tray (27.94 × 53.34 × 4.5 cm) filled with soil containing peat moss (10–15%), zeolite (6–8%), coco peat (45–50%), and perlite (35–40%), along with NO₃ (≈0.205 mg·g⁻¹), NH₄⁺ (≈0.09 mg·g⁻¹), KO (≈0.1 mg·g⁻¹), and PO (≈0.35 mg·g⁻¹). Each of the pots (33.0 × 27 × 33 cm³) was filled with a 2500 g, of field soil obtained from Kyungpook National University, Agriculture field site located at a latitude of 35.857655° N and longitude of 128.587655° E, and the seedlings were transplanted, with eight replicates for each treatment. Each pot consisted of a single seedling, and all the seedlings were equally sized. The experimental treatments included: no treatment-control (NT); chemical fertilizer (CF) consisting of 3.8 g per pot of N-P₂O₅-K₂O:12-6-6 from Poweralchandeul, Farmhannong Co., Ltd., Korea; mixed food waste fertilizer (MF), 10.65 g per pot, consisting of (castor oil-cakes 49%, rapeseed oil-cake 21%, food waste powder 30%) from Seyen Co., Ltd., Kyungsan, Republic of Korea); MF × 2 (Quantity of MF was doubled); MF × 4 (MF-four-fold); and MF × 6 (MF-six-fold) Table 1 (Experimental plan work). The food ingredients were mixed and dehydrated at 110 °C, powdered and finally used as fertilizer. The food waste fertilizer and CFs were applied according to the treatments described above. The amount of chemical fertilizer for the crop was applied based on the amount of nitrogen in the fertilization prescription standard of The National Academy of Agricultural Science (NAAS, 2010), *Soil chemical analysis method, RDA, The Republic of Korea*.

Table 1. Experimental work plan.

Symbol	Treatment
NT	Control (Irrigated with water only)
CF	Chemical fertilizer (CF-3.8 g·pot ⁻¹)
MF	Mixed food waste-derived fertilizer (MF-10.6 g·pot ⁻¹)
MF × 2	Two-fold MF (MF × 2- 10.6 × 2 g·pot ⁻¹)
MF × 4	Four-fold MF (MF × 4- 10.6 × 4 g·pot ⁻¹)
MF × 6	Six-fold MF (MF × 6- 10.6 × 6 g·pot ⁻¹)

The two-week-old lettuce seedlings were transplanted in a pot filled with soil as prepared (treatments) and grown for three weeks. The photosynthetic characteristics were measured, and—once the sample was harvested—the morphological attributes were measured, and the plant sample was freeze-dried for further biochemical analysis. The moisture level was maintained at 70–100% by the addition of water and measurement of moisture content in the soil by using the soil pH, and humidity tester (Model DM-5, Takemura Electric Works, LTD., Tokyo, Japan). In addition, the physicochemical properties of the experimental soil, such as pH, electrical conductivity (EC), organic matter (OM), available phosphorus (AP), potassium (K), calcium (Ca), magnesium (Mg), and sodium

(Na) content, were measured. The same parameters were studied after the completion of the experiment. The OM and mineral content were measured according to the method described by Kang et al. [23]. In brief, for the measurement of pH and EC, the soil was collected and sieved through a 2-mm mesh to remove impurities, after which 5 g of soil was mixed with 25 mL of water and kept in a shaker for 30 min. The solution was then filtered, and electrical conductivity and pH were measured with an EC and pH meter (HMM-100Pro, Hanyoung system, Seoul, Korea). The AP was quantified based on the leaching method using molybdenum blue with 1-amion2-naphthol-sulfanic acid that quantity the enzymatically hydrolyzable phosphorus in soil. The nitrogen was quantified through processing NH_4^+ adsorbed on soil particles and the digestate obtained from the Kjeldahl-N distiller. The exchangeable bases (K, Ca, Mg, Na) were measured through the Inductive Coupled Plasma, Mass Spectrophotometry (ICP-MS) method.

2.2. Measurement of Photosynthetic Attributes

The stomatal conductance, transpiration rate, chlorophyll content, chlorophyll fluorescence, and photosynthetic rate were measured. The chlorophyll content was measured using Chlorophyll Content Meter (CCM300, Opti-Sciences, Hudson, OH, USA), chlorophyll fluorescence using OS5p+ (Opti-Sciences Inc. 8 Winn Avenue, Hudson, OH, USA), and photosynthesis using infrared gas analyzer Lcpro (ADC BioScientific, Hoddesdon, UK).

2.3. Biochemical Analysis of Plants

2.3.1. Quantification of Abscisic Acid (ABA)

The method described by Adhikari et al. [24] was used to quantify the ABA content in plant shoots. In brief, one gram of lyophilized sample was suspended with isopropanol and acetic acid (95:5 *v/v*) for 1 h in a shaker at 140 rpm. The solvent was extracted and filtered and an internal standard [$(\pm) -3,5,5,7,7,7\text{-d}^6$] was added. The extract was washed with 1 N NaOH, and chlorophyll was then removed using dichloromethane (CH_2Cl_2). Subsequently, polyvinylpyrrolidone was added, and the solution was stirred for 1 h, after which it was filtered, evaporated, and finally extracted through ethyl acetate/diethyl ether. The ABA extracts were dried with N_2 , and, methylation was performed with diazomethane, and the product was washed with CH_2Cl_2 . The ABA was analyzed through injection on GC-MS/SIM (6890 N Network GC System and 5973 Network Mass Selective Detector: Agilent Technologies, Santa Clara, CA, USA).

2.3.2. Quantification of Mineral Elements in Plant Shoots

The quantification of mineral content (K, Ca, P, and Mg) of the plant shoots was determined by following the method described by Lee et al. [25]. In brief, the freeze-dried samples were suspended in HNO_3 (Ultrapure water: Milli_Q Advantage A10) and digested with H_2O_2 . The solvent obtained was quantified using ICP-MS (Optima 7300DV, PerkinElmer, Waltham, MA, USA) by microwave digestion system (MDS: Ultrawave, milestone). The gas flow rate was maintained as follows: plasma gas $15 \text{ L}\cdot\text{min}^{-1}$; auxiliary gas $0.2 \text{ L}\cdot\text{min}^{-1}$; nebulizer gas $0.6 \text{ L}\cdot\text{min}^{-1}$, and the sample pump flow was maintained at $1.5 \text{ mL}\cdot\text{min}^{-1}$.

2.3.3. Analysis of Antioxidant Activity

For the analysis of antioxidants, SOD contents were measured based on the methods described by Adhikari et al. [26] and flavonoid content was measured according to the method described by Bhusal et al. [27]. In brief, the solution was obtained by Tris-HCl buffer (10 mM EDTA, 50 mM Tris, pH 8.5) for SOD analysis, and absolute methanol was used for flavonoid measurement. The absorbance was recorded at 420 nm for SOD and 510 nm for flavonoid using a spectrophotometer (Multiskan GO, Thermo Fischer, Waltham, MA, USA).

2.4. Statistical Analysis

The present study was conducted using a completely randomized design. The data were analyzed in SAS 9.4 (SAS Institute, Cary, NC, USA) and evaluated using Duncan's multiple range test at $p \leq 0.05$.

3. Results

3.1. Physicochemical Properties of Soil and Ingredients of Food Waste Fertilizer

Our results showed that the baseline pH of the soil was 6.6, which did not change during or after the treatments. However, EC was reduced from $2.8 \text{ dS}\cdot\text{m}^{-1}$ to <1 in all treatments. The OM increased in the soil after the treatments, with the maximum value in the MF \times 6 treatment group. Similarly, higher values of P, Ca, Mg, and Na content were found in MF \times 6 (Tables 2 and 3). The constituent properties of food waste dry powder are represented in Table 4.

Table 2. Physicochemical properties of the soil used for the plant experiment.

pH [1:5]	EC [1:5] ($\text{dS}\cdot\text{m}^{-1}$)	OM (%)	$\text{NO}_3\text{-N}$ ($\text{mg}\cdot\text{kg}^{-1}$)	AP ($\text{mg}\cdot\text{kg}^{-1}$)	Ex.Cation+ ($\text{cmol}\cdot\text{kg}^{-1}$)			
					K	Ca	Mg	Na
6.6	2.8	2.0	141.8	330	1.11	11.61	3.65	0.6

Table 3. Physicochemical properties of the soil after the plant experiment.

	pH [1:5]	EC [1:5] ($\text{dS}\cdot\text{m}^{-1}$)	T-N (%)	AP ($\text{mg}\cdot\text{kg}^{-1}$)	K	Ca	Mg	Na	OM (%)
					Ex. Cation+ ($\text{cmol}\cdot\text{kg}^{-1}$)				
NT	6.58	0.41	0.140	399.74	0.38	14.19	4.24	0.52	2.85
CF	6.33	0.62	0.155	465.14	0.44	14.95	4.24	0.56	2.96
MF	6.50	0.49	0.147	577.44	0.45	14.90	4.64	0.62	3.09
MF \times 2	6.78	0.31	0.135	432.87	0.44	13.72	4.24	0.52	2.89
MF \times 4	6.69	0.34	0.152	451.71	0.45	14.77	4.58	0.61	2.72
MF \times 6	6.33	0.77	0.189	516.04	0.49	14.95	5.02	0.80	3.39

EC: Electrical Conductivity, AP: available phosphorus, OM: organic matter.

Table 4. Properties of Food Waste Fertilizer.

N (%)	P (%)	K (%)	OM (%)	Moisture (%)	Salinity (%)	pH [1:10]	EC [1:10] ($\text{dS}\cdot\text{m}^{-1}$)
3.37	1.41	1.01	81.10	6.88	2.28	4.82	4.41

3.2. Effect on Morphological Attributes of Lettuce Plants

The fresh weight of the lettuce plants was significantly increased by 78% when treated with CF and by 59% when treated with MF compared to the control group. A similar trend was observed with respect to dry weight: CF and MF treatment enhanced the growth of lettuce by 44 and 66%, respectively. However, the increase in MF dose significantly hampered the growth of lettuce; by 18% with four-fold MF treatment and by 37% with the six-fold application. Moreover, the dry weight decreased by 11 and 44% with the application of MF \times 4 and MF \times 6, respectively (Table 5).

Table 5. Effect of chemical and food waste fertilizer on growth characteristics of lettuce.

	Leaf Length (cm)	Root Length (cm)	Leaf Numbers (ea)	Leaf Width (cm)	Fresh Weight (g)	Dry Weight (g)
NT	9.1 ± 0.85 ab	7.3 ± 0.46 a	6.3 ± 0.33 b	5.3 ± 0.64 a	3.7 ± 1.05 ab	0.9 ± 0.16 ab
CF	9.0 ± 0.30 ab	7.2 ± 0.76 a	8.3 ± 1.20 a	5.0 ± 0.35 ab	6.6 ± 0.34 a	1.3 ± 0.18 ab
MF	10.5 ± 0.55 a	6.3 ± 0.53 ab	8.0 ± 0.58 ab	6.8 ± 0.75 ab	5.9 ± 1.12 ab	1.5 ± 0.29 a
MF × 2	9.2 ± 0.72 ab	6.1 ± 1.05 ab	7.0 ± 0.58 ab	5.8 ± 0.43 ab	4.6 ± 1.14 abc	1.1 ± 0.22 abc
MF × 4	8.6 ± 1.14 ab	5.3 ± 0.41 ab	8.3 ± 0.67 a	4.7 ± 0.81 ab	3.0 ± 1.33 bc	0.8 ± 0.16 bc
MF × 6	7.5 ± 0.91 b	4.6 ± 0.57 b	7.0 ± 1.15 ab	4.4 ± 0.58 b	2.3 ± 0.72 c	0.5 ± 0.11 c

Each value represents the mean ± SD. Each data point represents the mean of at least three replicates. Different letters in the column after mean values represent the least significant differences at $p \leq 0.05$.

3.3. Effect on Photosynthetic Characteristics of Lettuce Plants

The transpiration efficiency was significantly enhanced by 37 and 118% with the treatment of CF and MF, respectively. Similarly, the stomatal conductance rate was found to be significantly higher in MF-treated plants. Likewise, the photosynthesis rate was significantly increased by 109% by CF application and 54% by MF application. However, an increase in MF by four and six-fold reduced the photosynthetic rate by 54% and 72%, respectively (Table 6).

Table 6. Effect on photosynthesis characteristics of lettuce plants when treated with chemical and food waste fertilizer.

	Chlorophyll Contents (mg·m ⁻²)	Chlorophyll Fluorescence (Fv·Fm ⁻¹)	Transpiration Efficiency (mmol·m ⁻²)	Stomatal Conductance (mol·m ⁻² ·s ⁻¹)	Photosynthetic Rate (μmol·m ⁻² ·s ⁻¹)
NT	280.7 ± 55.21 bc	0.85 ± 0.034 a	1.6 ± 0.54 bc	0.08 ± 0.028 b	1.1 ± 0.43 bc
CF	302.0 ± 38.70 ab	0.85 ± 0.017 a	2.2 ± 0.48 bc	0.11 ± 0.030 b	2.3 ± 0.22 a
MF	315.3 ± 40.60 a	0.86 ± 0.022 a	3.5 ± 0.31 a	0.20 ± 0.027 a	1.7 ± 0.48 ab
MF × 2	302.0 ± 16.29 ab	0.84 ± 0.011 a	2.8 ± 0.41 ab	0.14 ± 0.026 ab	1.5 ± 0.19 ab
MF × 4	278.7 ± 13.04 bc	0.81 ± 0.020 ab	2.2 ± 0.21 bc	0.10 ± 0.013 b	0.5 ± 0.16 c
MF × 6	267.7 ± 17.70 c	0.76 ± 0.026 b	1.5 ± 0.23 c	0.06 ± 0.010 b	0.3 ± 0.01c

Each value represents the mean ± SD. Each data point represents the mean of at least three replicates. Different letters in the column after mean values represent the least significant differences at $p \leq 0.05$.

3.4. Quantification of Abscisic Acid in Lettuce

The ABA content was slightly increased by CF; however, the MF treatment increased the ABA content by 42%. The increase in two- and four-fold application of MF further increased the ABA content by 66% and 94%, respectively (Figure 1).

3.5. Quantification of Mineral Elements in Lettuce Shoots

The CF treatment significantly increased K content by 31%, and MF, MF × 2, and MF × 4 treatments increased the K content by 21%, 40%, and 32%, respectively. However, the six-fold application of MF tended to decrease the K content, by 10%.

A decreasing trend of Ca was observed in CF- and MF-treated plants. CF reduced Ca content by 24%; similarly, MF, MF × 2, MF × 4, and MF × 6 applications resulted in the Ca content decreasing by 26, 24, 13, and 26%, respectively. No significant differences were observed in P content with the treatment of CF and MF application. However, MF × 2 increased P content by 23% and MF × 6 lowered P content by 18%.

Mg content was slightly increased by CF application but was considerably reduced (by 19%) with MF application. However, MF × 4 increased the Mg content by 17%. In

contrast, MF × 6 lowered the Mg content by 13%. No significant differences were observed in Na content in CF-treated plants. However, the trajectory of Na content tends to increase by 13%, 17%, 23%, and 34% with the application of MF, MF × 2, MF × 4, and MF × 6, respectively (Table 7).

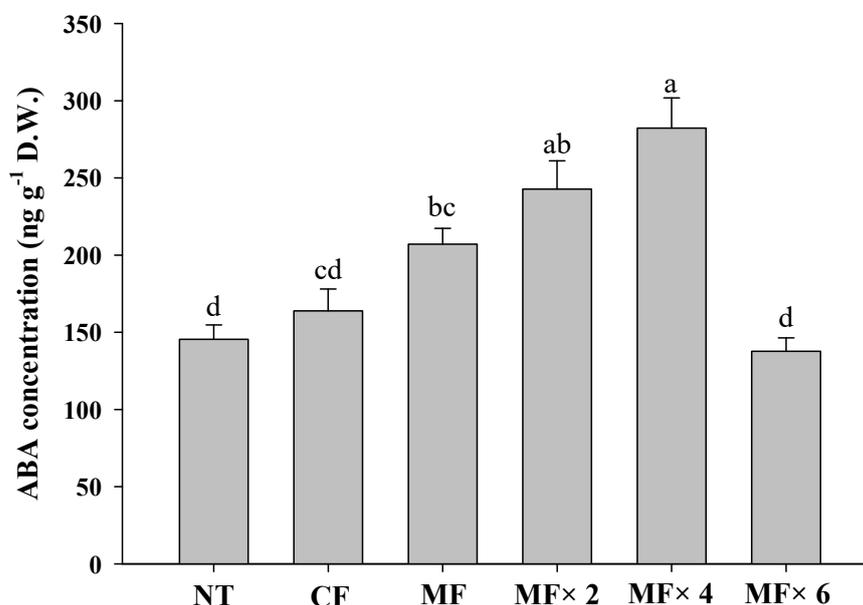


Figure 1. Effect of chemical and food waste-derived fertilizer on the abscisic acid level of lettuce plants. Each data point represents the mean of at least six replicates. Error bars represent standard deviations. Bars with different letters are significantly different from each other at $p \leq 0.05$.

Table 7. K, Ca, P, Mg, and Na content of lettuce following treatment with chemical and food waste fertilizers.

	K (mg·kg ⁻¹)	Ca (mg·kg ⁻¹)	P (mg·kg ⁻¹)	Mg (mg·kg ⁻¹)	Na (mg·kg ⁻¹)
NT	35,093.3 ± 1423.71 bc	24,218.0 ± 460.31 a	5049.6 ± 350.55 c	7978.6 ± 457.60 ab	4456.6 ± 180.96 b
CF	46,286.1 ± 5546.96 a	18,255.6 ± 1242.38 bc	5215.5 ± 174.99 bc	8744.6 ± 482.56 ab	4526.5 ± 315.79 b
MF	42,673.2 ± 2298.38 ab	17,733.4 ± 818.44 c	5487.8 ± 205.27 b	6461.9 ± 43.83b	5050.5 ± 1.52 ab
MF × 2	49,392.5 ± 2383.27 a	18,364.1 ± 215.31 bc	6249.6 ± 20.61 a	8427.0 ± 162.07 ab	5236.5 ± 407.64 ab
MF × 4	46,569.8 ± 316.65 a	20,951.2 ± 326.58 b	5200.9 ± 64.11 bc	9408.7 ± 1353.14 a	5493.9 ± 379.49 ab
MF × 6	31,550.1 ± 2352.14 c	17,887.1 ± 1013.37 c	4118.7 ± 142.82 d	6890.7 ± 241.10 b	5972.4 ± 243.39 a

Each value represents the mean ± SD. Each data point represents the mean of at least three replicates. Different letters in the column after mean values represent the least significant differences at $p \leq 0.05$.

3.6. Effect of Food Waste and CF on Antioxidant System of Lettuce

Following CF treatment, SOD content decreased, with minor differences observed in the MF-treated plants compared with the control group. However, SOD content increased by 24% with MF × 2 and MF × 4 application but was lowered by 20% (compared with NT) with the application of MF × 6. The flavonoid content was slightly increased with CF treatment compared with the control group (NT). However, MF and MF × 2 applications significantly increased the flavonoid content, by 25% and 28%, respectively. The MF × 6 application tends to decrease the flavonoid content by 6.9% (Figure 2).

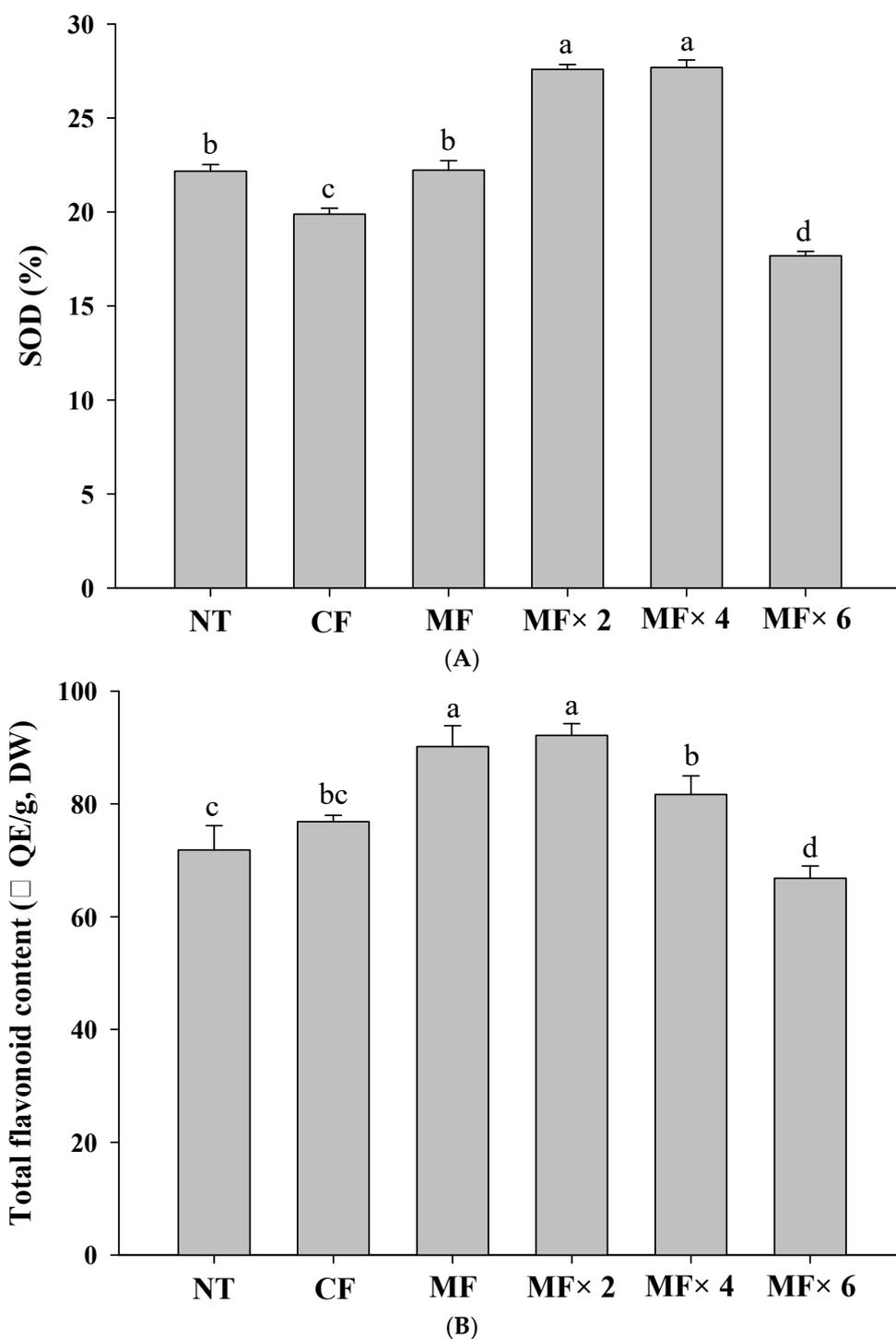


Figure 2. Effect of chemical and food waste-derived fertilizer on antioxidant-like activities, measured as SOD% (A), and flavonoid content (B) in lettuce plants. Each data point represents the mean of at least six replicates. Error bars represent standard deviations. Bars with different letters are significantly different from each other at $p \leq 0.05$.

4. Discussion

Chemical fertilizer application has been raising environmental hazards yet remains the major source of plant nutrition in conventional agriculture [28,29]. South Korea has launched a campaign called “Pay-As-You-Thrash,” since the country has been recognized as one of the major producers of food; approximately ninety full-scale anaerobic digestion (AD) plants are in operation to treat food waste [22,30]. In the present study, we explored

the appropriate use of food waste-derived fertilizer as a substitute for chemical fertilizers; here we discuss how the food waste-derived fertilizer could improve the soil and promote the growth and nutritional value of the target crop, salad lettuce.

The organic matter constituents and soil microorganisms may severely deteriorate with the continuous application of chemical pesticides and fertilizer [31,32]. Our results showed that the MF treatment significantly enhanced the OM content of the soil. Our results are in line with studies published by Gryta et al. [33] and Cesarano et al. [34] who reported the beneficial effect of OM in replenishing soil microbiome and fertility. Optimum productivity of plants can be ensured only with vital bio-available nutrients in the soil [33,34]. In the current study, the available phosphorus in the soil was increased with the application of MF and reached a maximum with the six-fold (MF \times 6) treatment. A similar trend was observed with respect to Ca and Mg contents. Organic fertilizer increases soil respiration and water holding capacity [35]. Our results showed that the addition of MF enhanced the OM% of soil without affecting the pH level. The composition of MF (N 3.3%, P 1.4%, K 1.01%, OM 81.1%, salt 2.2%, pH 4.8, and EC 4.4) might have played a major role in the higher values for available P and OM%.

CFs are now the main source of nutrient input in commercial crops, and the demand for chemical fertilizers continues to rise despite the environmental threats they pose and the limited supply of the required elements in the earth's crust [36,37]. We found that MF and MF \times 2 application significantly improved the growth and physiological parameters of the lettuce plants, to a degree that was equal to that of CF. Our results are in line with the study by Cerevera-Mata et al. [38], who reported that the application of spent coffee grounds enhanced the growth and nutritional content of lettuce plants. Similarly, Corinna et al. [39] reported vermicompost made through urban waste improved the Ca, Mg, P, and K content of lettuce plants. Furthermore, our results correspond with the finding of Mahmood et al. [40] who showed that food waste application with low moisture allows the growth of phyto-beneficial-cum-functional microbes and enhances the growth rate of lettuce and *Brassica rapa* to the same degree as organic and chemical fertilizers.

Enriching the soil nutrient status improves the physiological attributes of the plants, such as endogenous phytohormones and antioxidants, and mitigates environmental stress [41,42]. In the present study, the antioxidant activities, such as SOD and flavonoid level, were significantly increased with the application of MF and MF \times 2. Our results are in line with those of Cavalheiro et al. [43] who showed that organic fertilizer manufactured from vegetable residues improved the growth and antioxidant activity of lettuce plants. Our results are also supported by several studies [44–46] in which an improvement in antioxidant levels in plants was obtained with the application of organic waste fertilizer.

Endogenous phytohormones play a significant role in signaling and combating abiotic stress in plants [47]. ABA is known to regulate stomatal conductance through control of guard cell activity [48]. In our study, the level of ABA was enhanced with MF application in the lettuce plants. The higher level of ABA indicates a possible response to stress. However, this outcome depends largely on environmental conditions [49]. The increase in Na content might have triggered the ABA accumulation in plants, which is corroborated by the findings of several authors [50,51]. Moreover, the higher stomatal conductance rate observed in MF-treated plants correlated with the increase in ABA content.

Organic fertilizer is largely being reported to replenish soil organic matter and sustain the soil microorganisms that reduce the toxicity imposed by various abiotic stresses, including salt stress [52,53]. Although we obtained significant results with the application of MF, we also observed certain drawbacks of MF fertilizer when applied at a higher dose; MF \times 6 application resulted in higher Na⁺ concentrations in lettuce shoots and lowered growth, photosynthetic rate, and nutritional content. The influx of excess sodium ions results in a greater loss of potassium ions, leading to ionic imbalance, cellular damage, and necrosis [54,55]; therefore, it is crucial to select the appropriate dose of food waste-derived fertilizer to prevent salinity stress in the crops.

5. Conclusions

We found that the increase in lettuce growth parameters obtained with MFx2 application was similar to the results obtained with chemical fertilizer application. However, excess concentration of food waste fertilizer may result in pernicious effects, as seen in the MF x 6 treatment. Hence, it can be recommended that optimum doses of food waste fertilizer within the MF-to-MF x 2 range could be an environment-friendly approach for sustainable farming. Moreover, minimizing the salt concentration in deriving food waste fertilizer may yield greater benefits to crop growth and development.

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