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The proximate composition of vegetables enriched by incorporation of municipal solid waste into fertilizers and its impacts on environment and human health

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Abstract

The recent over production of municipal solid waste (MSW) poses a significant threat to both the ecosystem and human health. Utilizing MSW for agricultural purposes has emerged as a promising strategy to reduce solid waste disposal while simultaneously increasing soil fertility. To explore this potential solution further, an experiment was designed to assess the impact of varying concentrations of MSW (25%, 50%, and 75%) on the proximate composition of 15 different vegetable species. The experiment, conducted between 2018 and 2019, involved treating soil with different levels of solid waste and analyzing the proximate components, such as crude protein, dry matter, crude fiber, crude fat, and moisture content, in the 15 selected crops. The results indicate that the application of 25% MSW significantly increased the levels of crude protein, crude fiber, dry matter, and fat in *Spinacia oleracea*, *Solanum tuberosum*, *Solanum melongena*, and *Abelmoschus esculentus*. Conversely, the addition of 75% MSW notably elevated the moisture and ash content in *Cucumis sativus*. Correlation and scatter matrix analyses were conducted to elucidate the relationships between the protein, fiber, dry matter, ash, and fat contents. Principal component analysis and clustering confirmed the substantial impact of Treatment_1 (25% MSW) and Treatment_3 (75% MSW) on the proximate composition of the aforementioned vegetables, leading to their categorization into distinct groups. Our study highlights the efficacy of using 25% MSW to enhance the proximate composition and nutritional value of vegetables. Nonetheless, further research is warranted to investigate the mineral, antioxidant, vitamin, and heavy metal contents in the soil over an extended period of MSW application.

Keywords Biowaste, Contents of proximate, Soil fertility, Environment, Toxicity

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Introduction

Progressive life standards resulting in higher resource consumption, technological industry, and urbanization have a crucial role in the overproduction of municipal solid waste (MSW) [1]. In this respect, Pakistan is one of the top 20 MSW producers in the world [2]. Currently, about 50 tons of solid waste are dumped annually, and this is envisaged to grow to 109.24 tons day^{-1} in 2025 [3]. According to a World Bank report, per capita waste generation in Pakistan is 0.84 kg day^{-1} [4].

In Pakistan, more than 35 types of vegetables are grown under varying climate conditions, covering approximately 0.62 million ha, which is about 3.1% of the total production area in the country. Nevertheless, the daily intake per capita is about 100 g, which is lower than the recommended dose of 200 g [5]. Besides cereal crop production, the unprecedented population growth linked with agricultural soil degradation obliged researchers to focus on the production of vegetables with fewer synthetic fertilizers [6].

The loss of soil fertility is the main concern of the global agricultural community. In this regard, the addition of composted MSW to soil has been proven one of the cost-effective ways to face the aggregative generation of MSW and their related agronomic and environmental concerns. Simultaneously, this method augments soil fertility and protects it from erosion [7] MSW fertilization enriches the soil with diverse organic matter, which increases nutrient availability and maintains the chemical and physical properties of the soil [8]. Raychev et al. [9] also reported that the application of MSW reclaimed saline soil. Furthermore, MSW compost effectively provides phosphorus as inorganic fertilizer and thus builds soil quality [10]. Meanwhile, Meena and Biswas [11] reported an improvement in soil stability by increasing the humic acid and cation exchange capacity of soil by 20% to 70% from the original value. Therefore, the enrichment of soil fertility through composted MSW application is a promising tool for increasing crop productivity. Hence, more attention is required for the application of MSW to improve vegetable horticulture sectors as alternatives to synthetic fertilizers [12].

The increase in yield and growth of a wide variety of land-cultivated vegetables and fruits has been assessed under different soil conditions upon the application of MSW [13, 14]. However, none of these revealed the effects of MSW composting in proximate accumulation in edible vegetables and, thereafter, its effects on the food chain [15]. Thus, maintaining proper MSW management in terms of quantity and quality is a serious issue concerning the ecosystem and food web [7].

Therefore, Vegetables cultivated in soil amended with municipal solid waste (MSW) showed notable differences in proximate composition compared to those grown in non-amended (control) soil. These differences may stem from the nutrient content and potential contaminants in the MSW, potentially impacting the nutritional quality and safety of the vegetables. For this purpose, the current study was conducted to depict the effects of different fractions of MSW on the proximate content of 15 commonly consumed vegetables in Sargodha City in Pakistan. The investigated MSW ratio may be recommended for better nutritional quality attainment in future productivity enrichment programs for vegetables. Bio-waste utilization has been regarded as an important pathway to promote the circular economy paradigm and sustainable development for a long time.

Materials and methods

Study site, treatments, and experimental layout

During the growing seasons of 2017 and 2018, a pot experiment was conducted at Sargodha University, Sargodha District, Punjab, Pakistan. The experiment design followed a triplicated, completely randomized design with one control and three treatments of composted MSW in the soil (Table 1). The MSW was collected from different locations, including garbage disposal facilities, fruit and vegetable markets, and waste-collecting canals. There are two stages in MSW composting process: Degradation and Maturation. In the first stage, biodegradable compounds composted via the aerobic fermentation while complex organic compounds degraded in the second stage of this process. All the particles such as plastic pieces, stones, roots had been remove from the composted MSW and precede them through 2mm sieve. The composted MSW is grinded into a fine powder through of mortar and pestle and mixed them to attain homogeneity in the samples [16]. Healthy seeds of the following 15 vegetables were grown under controlled environmental conditions with different soil amendments: onion (*Allium cepa*), mint (*Menth arvensis*), round gourd (*Citrullus vulgaris*), bitter gourd (*Momordica charantia*), cucumber (*Cucumis sativus*), pumpkin (*Cucurbita pepo*), ridge gourd (*Luffa acutangula*), green chilies (*Capsicum annum*), Brinjal (*Solanum melongena*), tomato

Table 1 Percentage composition of soil and municipal solid waste used for vegetable crops

Treatments	Abbreviations	Description
Control	Control	100% soil
MSW + Soil	T_1	25% of MSW + 75% soil
	T_2	50% of MSW + 50% soil
	T_3	75% of MSW + 25% soil

(*Lycopersicon esculentum*), okra (*Abelmoschus esculentus*), potato (*Solanum tuberosum*), coriander (*Coriandrum sativum*), bottle gourd (*Lagenaria siceraria*), and spinach (*Spinacia oleracea*). The experiment included fifteen vegetables, chosen because they are widely consumed in the area and offer a cost-effective source of nutrition. For control soil (T0), loamy texture soil was observed. In our study, the control treatment consisted of 100% clean garden soil, providing a baseline for comparing the effects of different levels of municipal solid waste (MSW) on vegetable composition. List of treatments applied to the experimental soil are soil amended with 25% (5t/ha) of MSW (T1), soil amended with 50% (10 t/ha) of MSW (T2), and soil amended with 75% (15 t/ha) of MSW (T3) [17]. To imitate normal field conditions, MSW was mixed into the top 15 cm of soil.

Proximate analysis

Proximate analysis was conducted to evaluate the moisture, ash, crude fiber, fat, crude protein, and dry matter (DM) contents of the edible parts of the abovementioned vegetables by following the standard procedures of the Association of Official Analytical Chemists [18].

Moisture content

$$\text{Moisture content } = (W_{\text{initial}} - W_{\text{final}})/W_{\text{final}} \times 100$$

where W_{initial} is the initial weight of the sample before drying, and W_{final} is the final weight of the sample after drying.

The samples were placed in an oven (Carbolite Gero oven) at 100℃-110℃, and the moisture content was calculated using the equation

Ash content

About 1 g of the weighted samples was kept in a muffle furnace (Carbolite Gero Furnace) at 550°C, and the ash contents of the samples were determined.

$$\text{Ash content} = \text{W}_{\text{ash}}/\text{W}_{\text{sample}} \times 100$$

W_{ash} is the weight of the measured ash, and W_{sample} is the weight of the original sample.

Crude *fiber*

The crude fiber was estimated through the complete extraction of the samples with H_2SO_4 acid (1.25%) and NaOH solution (1.25%) after the filtrate was ash; thus, the loss in weight was recorded as the crude fiber.

Fat content

Petroleum ether was extracted from the samples (boiling point of 40°C-60°C) using the Soxhlet apparatus. The fat content was determined by the difference between the initial sample weight and the weight of the dried residue after extraction and expressed as the fat percentage.

Crude protein

The nitrogen contents of the vegetable samples were determined using the micro Kjeldahl method involving the digestion, distillation, and, finally, titration of the samples. The crude protein contents were determined by multiplying the nitrogen content by a factor of 6.25.

Dry matter content (DM)

The DM content was calculated using the following formula:

$$\text{DM}(\%) = 100 - \text{moisture content}.$$

Statistical analysis

First, we analyzed the vegetables' proximate content data using the one-way analysis of variance followed by the Tukey test at a significance level of $p \leq 0.05$. Second, a scatter matrix plot with a histogram was generated using the XLSTAT software (2016) to evaluate the variable correlation and illustrate a pairwise scatter plot of the variables in a matrix format. Third, heat map analysis was conducted using a heat mapper. Lastly, principal component analysis (PCA) was designed to further elucidate the effects of different soil treatments on the proximate contents. The hierarchical clustering approach was based on the Euclidean distance matrix to explain the clusters of species by visualizing them in a dendrogram. All the figures were organized using the XLSTAT (2016) software.

Results

Our results demonstrated significant differences among various proximate contents (i.e., moisture, ash, crude fiber, fat, crude protein, and DM) (Table 2).

Moisture content

Cucumis sativus and *Abelmoschus esculentus* retained their maximum and minimum average moisture contents when they were grown in T3- and T1-treated soils, respectively Tables 3 and 4. The moisture contents ranged between 75.41% and 89.51% in 2018 and from 80.44% to 96.63% in 2019 (Figs. 1 and 2).

Ash content

The application of MSW increased the ash content of vegetables compared with those in the conventional case

Table 2 Analysis of variance for the proximate compositions of the vegetables under the effect of soil amendments ($n = 4 \times 15 \times 3$)

Parameters	Growing Year	Plant	Treatment (T)	Plant × T
Moisture	Year 1	59.016**	395.938**	3.145**
	Year 2	128.248**	269.761**	1.962**
Ash	Year 1	11.5821**	33.2196**	0.1423**
	Year 2	12.4438**	37.7871**	0.0899**
Fiber	Year 1	67.1485**	40.3948**	0.4649**
	Year 2	65.3018**	61.9765**	0.4524**
Fat	Year 1	0.22148**	0.51840**	0.00476**
	Year 2	0.20834**	0.63174**	0.00525**
Protein	Year 1	150.474**	61.936**	1.166**
	Year 2	131.557**	75.531**	1.530**
DM	Year 1	58.972**	395.164**	3.124**
	Year 2	128.249**	269.763**	1.963**

T0: control; T1: 75% clean soil and 25% MSW; T2: 50% clean soil and 50% MSW; and T3: 25% clean soil and 75% MSW

** Highly significant ($p < 0.01$)

(T0), where T3 (75% MSW) markedly raised the ash contents in *S. tuberosum* and *L. siceraria*; in contrast, *C. sativus* had the lowest ash content Tables 3 and 4. Over 2 years, the experimental study revealed that the ash content varied from 1.68% to 8.03% (Figs. 1 and 2).

Crude *fiber* content

Concomitantly, the control (T0) and T1 treatments crucially enhanced the crude fiber content compared with those of other treatments in both years Tables 3 and 4. There was a variation in the fiber content that ranged from 0.817% (*C. sativus*) to 11.71% (*S. oleracea*) (Figs. 1 and 2).

Crude fat content

The fat contents of *S. tuberosum* and *S. melongena* significantly increased in treatments T1 and T0 during the 2-year experiment Tables 3 and 4. Meanwhile, supplementation with 75% MSW showed the lowest fat content in *C. sativus*. The range of fat contents in the different vegetables was from 0.174% to 0.968% across 2 years (Figs. 1 and 2).

Table 3 Proximate analysis of 15 different vegetables grown under MSW treatments in the year 2017 under effects of soil amendments ($n = 4 \times 15 \times 3$)

	Moisture (%)	Ash (%)	Fiber (%)	Fat (%)	protein (%)	DM (%)
Treatments						
T0	83.55±0.34B	4.422±0.155D	5.589±0.350B	0.672±0.021B	6.794±0.518B	16.45±0.34C
T1	78.57±0.37D	5.139±0.150C	6.367±0.371A	0.750±0.022A	7.660±0.521A	21.43±0.37A
T2	79.58±0.37C	5.771±0.144B	4.966±0.347C	0.580±0.021C	5.919±0.523C	20.42±0.37B
T3	84.65±0.31A	6.429±0.151A	4.132±0.329D	0.504±0.019D	4.925±0.528D	15.36±0.31D
Vegetables						
L. siceraria	80.60±0.91GH	6.655±0.256AB	6.046±0.412C	0.769±0.040B	4.901±0.695FG	19.40±0.91EF
C. vulgaris	80.43±0.76HI	6.249±0.266BC	5.735±0.352CD	0.698±0.028C	5.029±0.330EF	19.57±0.76DE
M. charantia	80.73±0.82G	6.249±0.266BC	4.382±0.422FG	0.654±0.056CD	3.901±0.512H	19.27±0.82F
C. sativus	88.04±0.34A	6.249±0.266BC	1.698±0.152I	0.328±0.026H	1.760±0.135J	11.96±0.34L
C. pepo	81.19±0.93EF	5.347±0.213DE	4.441±0.263EF	0.548±0.027EF	3.912±0.307H	18.81±0.93GH
L. acutangula	81.19±0.93EF	5.686±0.283D	5.636±0.341D	0.593±0.022E	5.279±0.350E	16.96±0.79J
C. annum	81.19±0.93EF	5.725±0.311D	5.603±0.236D	0.537±0.037F	2.547±0.192I	19.76±0.42CD
S. melongena	79.97±0.60K	6.141±0.178C	4.086±0.200GH	0.861±0.022A	6.196±0.419D	20.03±0.60B
L. esculentum	83.57±1.05B	5.482±0.229D	1.543±0.175I	0.463±0.027G	10.777±0.349B	16.43±1.05K
A. esculentus	78.52±0.79L	6.153±0.201C	9.530±0.277B	0.679±0.030CD	10.915±0.359B	21.48±0.79A
S. tuberosum	78.52±0.79L	6.686±0.215A	5.540±0.247D	0.807±0.037B	10.917±0.250B	19.91±0.95BC
A. cepa	82.42±0.99D	4.449±0.182F	3.977±0.179H	0.685±0.020CD	2.594±0.298I	17.61±0.98I
M. arvensis	81.43±1.02E	4.939±0.203E	5.464±0.205D	0.549±0.023EF	8.969±0.163C	18.57±1.02H
C. sativum	82.54±0.79D	4.468±0.219F	4.755±0.186E	0.589±0.021E	4.659±0.227G	17.46±0.79I
S. oleracea	81.01±0.73F	5.005±0.269E	10.518±0.257A	0.642±0.024D	12.511±0.239A	18.99±0.73G

Means ± standard errors sharing different letters in a column are statistically significant at $p < 0.05$ with the Tukey test. T0: control; T1: 75% clean soil and 25% MSW; T2: 50% clean soil and 50% MSW; and T3: 25% clean soil and 75% MSW

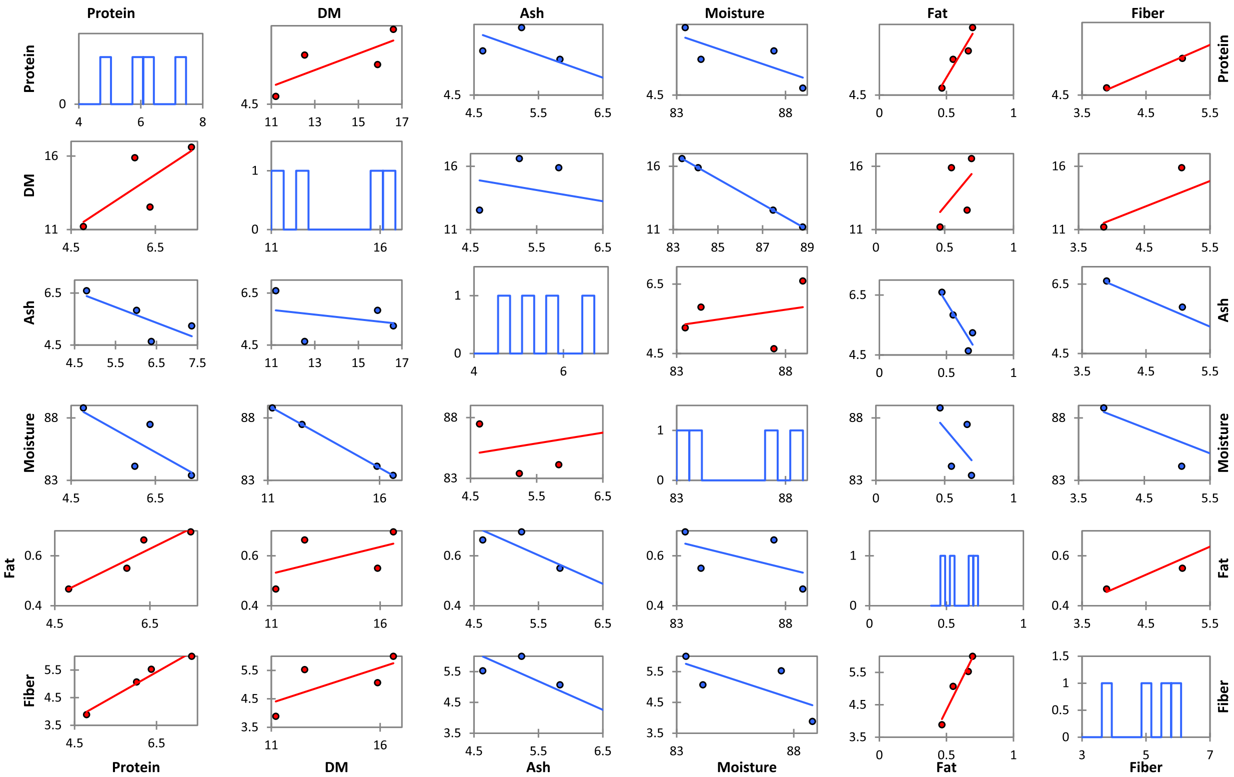

Fig. 1 Scatter matrix plot with histogram illustrating the correlations among variables (moisture, ash, fiber, fat, protein, and DM contents) under the effect of soil amendments (see Table 1) (*n* = 4 × 15 × 3)

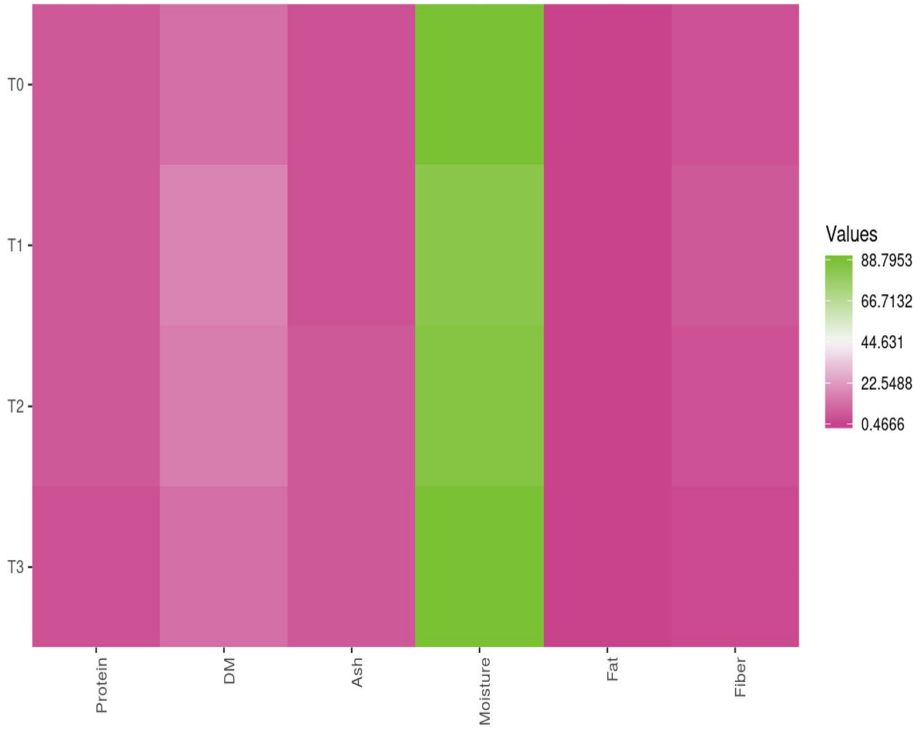

Fig. 2 Heat map analysis of the proximate contents (moisture, ash, fiber, protein, and DM) under the effects of soil treatments (see Table 1) (*n* = 4 × 15 × 3)

Table 4 Proximate analysis of 15 different vegetables grown under MSW treatments in the year 2018 under the effects of soil amendments ($n = 4 \times 15 \times 3$)

	Moisture (%)	**Ash (%)**	**Fiber (%)**	**Fat (%)**	**Protein (%)**	**DM (%)**
Treatments						
T0	91.41±0.51B	4.76±0.157D	6.220±0.370A	0.658±0.020A	6.853±0.546B	8.595±0.510C
T1	87.67±0.52D	5.43±0.156C	5.602±0.352B	0.639±0.021B	6.990±0.483A	12.328±0.520A
T2	88.74±0.53C	6.04±0.149B	4.376±0.332C	0.503±0.020C	5.240±0.463C	11.263±0.530B
T3	93.03±0.38A	6.92±0.144A	3.622±0.320D	0.407±0.020D	4.314±0.469D	6.972±0.382D
Vegetables						
L. siceraria	92.60±0.56B	7.00±0.227A	5.848±0.408C	0.76±0.040B	4.766±0.721F	7.398±0.562F
C. vulgaris	92.72±0.54B	6.53±0.250B	5.239±0.426DE	0.69±0.028C	4.816±0.362F	7.278±0.539F
M. charantia	90.27±0.75E	5.69±0.267D	4.188±0.433F	0.69±0.028C	3.969±0.500G	9.730±0.752C
C. sativus	94.47±0.62A	3.16±0.314G	1.589±0.195I	0.32±0.026H	1.660±0.165I	5.527±0.624G
C. pepo	91.45±0.71C	6.16±0.265C	1.589±0.195I	0.54±0.027EF	3.790±0.353G	8.551±0.709E
L. acutangula	92.31±0.67B	6.13±0.327C	5.234±0.410DE	0.59±0.022E	4.688±0.297F	7.687±0.672F
C. annum	83.63±0.95G	5.95±0.211CD	5.104±0.252E	0.53±0.037F	2.221±0.160H	16.371±0.947A
S. melongena	90.57±0.41DE	6.54±0.254B	3.034±0.186H	0.86±0.022A	5.606±0.407E	9.430±0.412CD
L. esculentum	91.52±0.64C	5.69±0.207D	1.582±0.254I	0.46±0.027G	9.631±0.413C	8.476±0.637E
A. esculentus	83.59±0.81G	6.60±0.225B	9.399±0.390B	0.67±0.030CD	10.576±0.513B	16.409±0.815A
S. tuberosum	85.66±0.86F	7.14±0.211A	9.399±0.390B	0.67±0.030CD	10.426±0.308B	14.343±0.859B
A. cepa	91.44±0.76C	4.90±0.210F	3.744±0.249G	0.67±0.030CD	2.126±0.218H	8.558±0.756E
M. arvensis	91.52±0.47C	5.28±0.245E	5.150±0.292DE	0.67±0.030CD	7.948±0.309D	8.477±0.471E
C. sativum	90.83±0.71D	5.28±0.245E	5.150±0.292DE	0.67±0.030CD	4.004±0.270G	9.172±0.708D
S. oleracea	90.57±0.43DE	5.26±0.251E	5.150±0.292DE	0.64±0.024D	11.513±0.401A	9.433±0.434CD

Means ± standard errors sharing different letters in a column are statistically significant at $p < 0.05$ with the Tukey test. T0: control; T1: 75% clean soil and 25% MSW; T2: 50% clean soil and 50% MSW; and T3: 25% clean soil and 75% MSW

Crude protein content

For the duration of the experimental study, the minimum MSW concentration (T1) enhanced the crude protein content in *S. oleracea* by 7%. Meanwhile, the higher MSW concentration (T3) reduced the protein content in *C. sativus* Tables 3 and 4. The amount of protein ranged from 1.127% to 13.59% (Figs. 1 and 2).

DM content

The minimum MSW nearly enhanced the DM in all vegetables regardless of the growing season, whereas the maximum DM accumulation was recorded in *A. esculentus* and *C. annum*. Conversely, there was a minimum DM content (5.52% and 11.96%) in *C. sativus* Tables 3 and 4 ranging from 3.37% (*C. sativus*) to 21.48% (*A. esculentus*) for T3 and T1, respectively (Figs. 1 and 2).

Correlation analysis for the proximate contents of the selected vegetables

Pearson correlation coefficients for the proximate components of the various vegetable species averaged across two growing seasons are presented in Table 5.

Table 5 Pearson's correlation values (*r*) among the proximate contents of the 15 vegetables averaged for the years 2017 and 2018 under the effects of soil amendments ($n = 4 \times 15 \times 3$)

	Protein	**DM**	**Ash**	**Moisture**	**Fat**
DM	0.769				
Ash	−0.764	−0.284			
Moisture	−0.769	-1.000^{***}	0.284		
Fat	0.947	0.531	−0.909	−0.531	
Fiber	0.984^{**}	0.714	−0.856	−0.714	0.967^{*}

All data were determined according to the MSW effect. T0: control; T1: 75% clean soil and 25% MSW; T2: 50% clean soil and 50% MSW; and T3: 25% clean soil and 75% MSW

[*] $p < 0.05$

[**] $p < 0.01$

[***] $p < 0.001$

There were positive correlations among the protein and DM ($r^2 = 0.769$), fat ($r^2 = 0.947$), and fiber ($r^2 = 0.984$) contents. Furthermore, the DM, crude fiber, and fat contents were positively correlated. Conversely, the ash and moisture contents negatively correlated with the protein, DM, fiber, and fat contents.

Scatter matrix and heat map

The proximate datasets were visually analyzed using a scatter matrix plot and a heat map to illustrate the variation in each constitutional effect caused by different soil amendments averaged over 2 years (Figs. 1 and 2). In the scatter plot analysis, a highly positive trend was depicted between the protein, DM, fat, and fiber contents. However, moisture and ash were negatively correlated with these parameters.

In addition, the proximate components were clustered according to the differentiation among four soil treatments in the form of a heat map (Fig. 2). This approach was based on the squared Euclidean distance between treatments using Ward's method. This heat plot demonstrated that 75% MSW (T3) increased the moisture content, whereas a small fraction of 25% MSW (T1) augmented the protein, DM, fiber, and fat contents.

PCA and cluster analysis

In this study, PCA provided an overview of the impact of different soil treatments on the proximate components and visualized the variations among different vegetables (Fig. 3A). The PCA biplot for the effects of soil treatment and variations among vegetables explained the total variability of 98.711% and 72.79%, respectively. The amended soil treatment effects on the vegetables in two biplots dispersed successfully in two components PC1 and PC2. The results revealed that T1 (25% MSW)

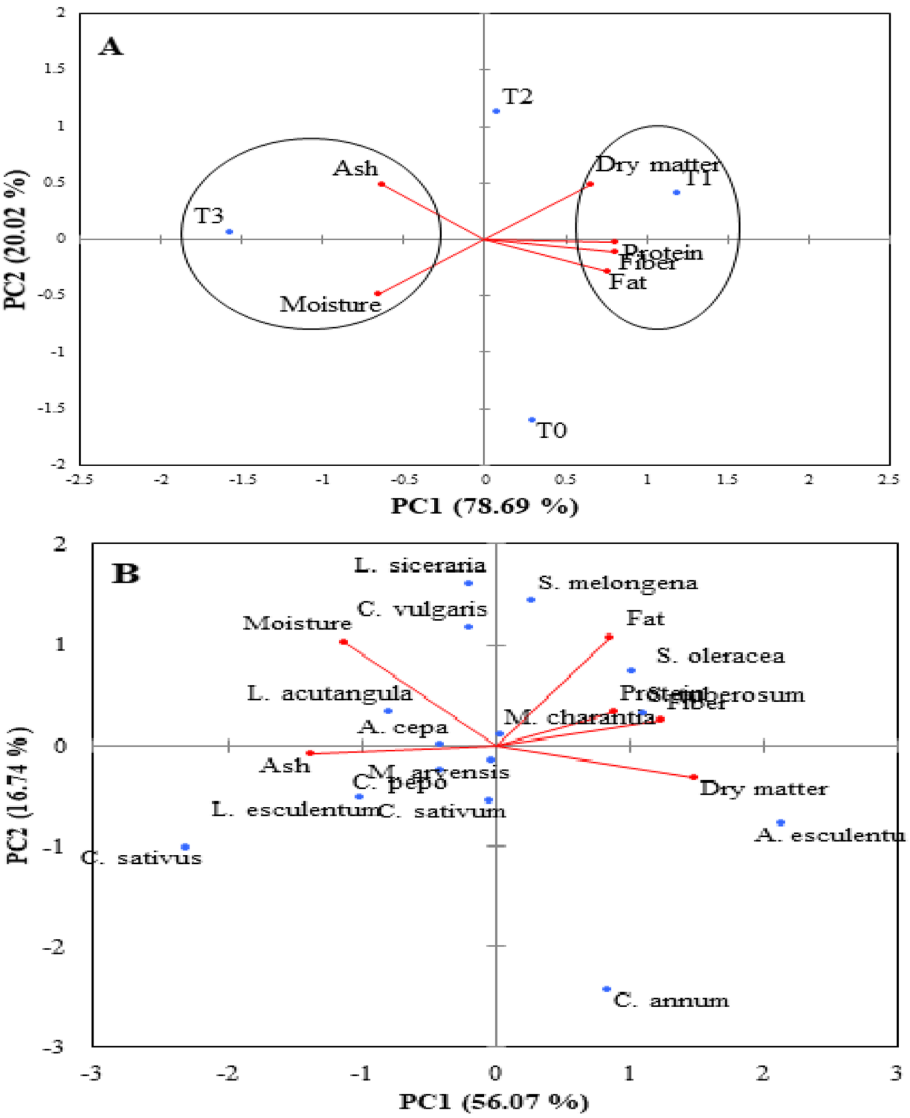

Fig. 3 Biplots PCA variance explained by the first two components for the proximate contents of 15 vegetables. Dots represent the investigated traits (moisture, ash, crude fiber, crude protein, fat, and DM), and vectors represent **A** the soil treatments and **B** the 15 vegetables

in the positive domain influenced the DM, protein, fiber, and fat contents (Fig. 3B). However, T2 and T0 also contributed to the positive domain but were not related to any constituents with a small effect. Conversely, T3 (75% MSW), moisture, and ash were correlated in the negative domain, deducing them to be the least responsible in terms of enhancing the proximate contents of the studied vegetables. The vegetables discriminated together had similar chemical contents (Fig. 3B). For example, *A. esculentus* and *C. annum* highly contributed to PC1 having higher DM content, whereas *S. oleracea* and *S. tuberosum* showed higher fiber and protein constituents. Meanwhile, *S. melongena* exhibited higher fat content, whereas *C. sativus* was characterized by its high moisture content.

Dendrogram shows the hierarchical cluster analysis of the fifteen vegetables. We obtained four clusters, and the distance between two clusters indicated the similarity among species. Cluster 1 included *C. sativus, L. acutangula, L. siceraria, C. vulgaris, A. cepa, M. charantia, C. pepo*, and *C. sativum*. This cluster was located close to cluster 3 (*L. esculentum, S. melongena, and M. arvensis*). All species showed remarkable increase in moisture and ash contents. Meanwhile, cluster 4 (*A. esculentus, S. tuberosum, and S. oleracea*) and cluster 2 (*C. annum*) were closely related. The crude protein, fiber, and DM contents were higher in these species compared with those of the others (Fig. 4).

Discussion

In this study, the treatment of soil with MSW significantly affected the quality of different vegetables. This is valuable in terms of increasing their nutritive index [19]. This was due to the positive effects of MSW on soil organic matter content and soil minerals [20]. However, the final impact of MSW amendments depends on the doses and the physicochemical properties of the added compost, which vary depending on its source and origin [21]. Previously, leafy vegetables have shown high moisture contents ranging from 72.93% to 91.83% [22]. In this study, T3 (75% MSW) markedly increased the moisture content (96.63%) compared with that in T1 (75.41%) across 2 years, particularly in *C. sativus*. Balanced plant water content is vital for various physiological functions. However, higher contents affect the quality indices of vegetables [23]. This is because high water contents trigger the decay of vegetable fruits and more certainly shorten their shelf life [24]. During harvest, this may cause preservation and marketing issues [25]. Similar effects for MSW

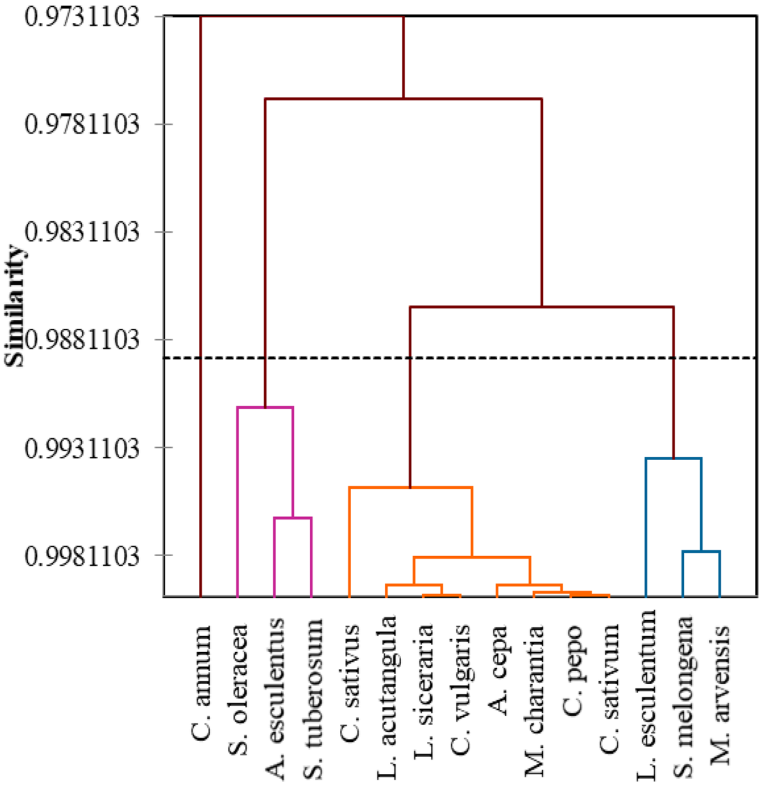

Fig. 4 Dendrogram of the 15 studied vegetables demonstrating their similarities obtained from cluster analysis calculated for the means of the proximate traits grown under the effects of soil amendments (see Table 1) (*n* = 4 × 15 × 3)

were found by Ashfaq et al. [26] and Onwudiwe et al. [27] but at lower values of the moisture content (6% to 10%). These differences may refer to the cultivation conditions that significantly affect the water levels of vegetables [28, 29]. For *A. esculentus* at T1, the observed low moisture content indicates that applying MSW may help prolong the vegetable's shelf life.

The ash content represents the total amount of noncombustible substances present in the plant, and greater ash contents suggest the greater availability of metal ions and minerals [30, 31]. The addition of 75% MSW (T3) to the soil augmented the ash content compared with those in the other treatments. Higher ash content in vegetables usually indicated an increased concentration of minerals and inorganic components. The higher ash content observed in *S. tuberosum* and *L. siceraria* with the 75% MSW treatment suggest that MSW amendments provide additional minerals and trace elements, which can improve the nutritional profile of these vegetables [32]. This finding aligns with studies showing that MSW compost enriches soil with essential nutrients, thus boosting the mineral content of crops. This could be due to its influential effect on soil mineralization and thus the vegetable mineral content [20]. Moreover, the increased moisture content in *C. sativus* upon application of 75% MSW was associated with a decrease in the ash content. These results were supported by the findings of Adekiya et al. [33] and Kumar et al. [31] Recent studies by Ashfaq et al. [26] and Ferdaus et al. [34] showed low ash values (2%) in vegetables treated with wastewater and MSW. However, higher ash contents (24–14%) for various vegetables were documented by Naz et al. [35] and Olaokiki & Adejumo, [29].

Compared with the other treatments, T0 and T1 increased the fiber content, which ranged from 0.817% (*C. sativus*) to 11.71% (*S. oleracea*). The fiber values were higher than the recorded values for other vegetables treated with MSW (2%) [26]. Hence, the 25% MSW amendment in arid soil is recommended to boost the fiber content of vegetables to provide a reliable source for the nutritional needs of mankind compared with that obtained from cereals and tubers (2%-10%) [36]. Likewise, the fat content was the maximum (0.9%) in *S. tuberosum* and *S. melongena* with T1 and T0 treatments. The fat contents for the vegetables found in the study were less than other reported values ranging from 0.08% to 11% [37, 38]. These low values confirmed that vegetables are minimal sources of saturated fat. However, 1%-2% of saturated fatty acid or lipid in the diet is sufficient to fulfill calorie demands [39, 40].

The 25% MSW enhanced not only the ash, fiber, and fat contents but also the protein content, which increased to 13.59% for *S. oleracea* compared with 1.12% for *C. sativus* at T3. These results suggest that 25% MSW might increase nitrogen availability and uptake, subsequently enhancing the protein and cytosol contents [28]. Shah et al. [41] reported protein contents ranging from 23% to 33%, whereas the present investigation reported an adequate or moderate level of protein. Furthermore, higher protein content (21.9%-66.66%) was estimated by Okezie et al. [42], Oulai et al. [37] and Asaolu et al. [43]. Also Igwe et al. [44] published a protein content of 8.15% to 16.52% in leafy vegetables in nearby polluted areas, and lowered protein content in vegetables (1.9%-3%) was reported by Tayyeb et al. [45]. Although vegetables are cheap and excellent sources of protein, these factors still depend on the vegetable type, climate, and habitat conditions [29].

The enhancement effects of 25% MSW application on the ash, fiber, fat, and protein contents were associated with higher DM content, particularly in *A. esculentus* (24.59%) and *C. annum* (19.56%). The findings from this study indicate that municipal solid waste (MSW) application significantly affects the dry matter (DM) content in various vegetables, with observed variations across seasons and species. Applying the minimum amount of MSW consistently increased the DM content in all vegetables, irrespective of the growing season. This implies that even a modest amount of MSW can positively impact DM accumulation, likely due to the supplementary nutrients and organic matter promoting plant growth and development. This increase may have been due to the adequate availability of nutrients for plant uptake, which further translocated to source organs and increased DM [46] Furthermore, the vegetables' DM contents were irrevocably related to their moisture indices, where the increased water content of *C. sativus* of 75% was reflected by their decreased DM accumulation (3.37%). The lower DM contents of some vegetables growing with different irrigation treatments (3.91%-5.60%) were recorded by Stoyanova et al. [46]. Contrarily, Gogo et al. [47] reported higher DM contents (45.5%-32.8%).

The correlation investigation revealed positive correlations among the protein, fiber, fat, and DM contents. This indicates that different plant traits are interdependent for better proximate contents, particularly upon 25% MSW application to arid soil. However, moisture and ash were negatively correlated with the parameters depicting their opposing effects on the quality of vegetables. Both PCA and hierarchal cluster multivariate analysis were disclosed to cluster and represent similarities or variations between the studied factors [48]. In this study, PCA revealed that T1 (25% MSW) is different from the rest given its close association with the DM, protein, fiber, and fat contents, confirming its key role in increasing nutritive values, particularly in *A. esculentus, S. oleracea, S. tuberosum, S. melongena, L. siceraria,* and *C. annum.*

Conclusion

This study illustrated the potential application of MSW in enhancing soil fertility and its effects on the proximate contents in randomly chosen vegetable species. The results revealed that a minimum of 25% of MSW concentration significantly enhanced the crude protein (12.74%), crude fiber (13.92%), fat (11.60%), and DM (30.27%) contents of the studied vegetables, specifically in *S. oleracea, S. tuberosum, S. melongena,* and *A. esculentus*. Meanwhile, the highest MSW concentration (75%) increased the moisture content by 1.4% in *C. sativus*, followed by the ash content by 45% in *S. melongena* and *L. siceraria*.

These findings highlight the crucial role of MSW amendments in influencing vegetable composition and enhancing drought resilience. By improving moisture retention and nutrient content, MSW treatments can bolster the drought resilience of vegetables, which is essential for sustainable agriculture.

Moreover, the study underscores the potential for MSW to be used effectively in sustainable land management. Using MSW as a soil amendment not only aids in waste reduction but also enhances the nutritional quality of vegetables. This strategy supports soil fertility and crop productivity, integrating waste management with agricultural practices to optimize land use and resource management in a more sustainable manner. Thus, we recommend a minimum of 25% MSW concentration to enhance soil fertility for a vegetable cultivation program with improved nutritional quality. However, further studies under different field conditions are required to validate the present results and assess the long-term effects of repeated MSW applications on the soil.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

Asma Ashfaq wrote the original manuscript collected and analyzed the samples. Zafar Iqbal Khan supervised the study; Muhammad Arif and Ghulam Abbas revised the original draft; Toqeer Abbas worked on methodology; Mansour K. Gataesheh reviewed and funded the articl; Shifa Shaffique reviewed and edited the article. Anis Ali Shah proofread and revised the manuscript. All authors contributed in the manuscript.

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Availability of data and materials

Data is provided within the manuscript or supplementary information files.

Declarations

Ethics approval and consent to participate

The Institutional Ethics and Guideline Committee of the University of Sargodha (Approval No. 38-B33/2020 UOS) has allowed all the protocols used in this experiment. All the experimental methods of this study followed all the appropriate guidance and regulations.

Consent for publication

All subjects gave their "informed consent" for the publication of details within the text ("informed consent") to be published in the above Journal and Article. Written "informed consent" was obtained from all authors for the publication of this manuscript.

Competing Interests

All authors declare that there are no competing interests.

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