



Modeling of mineral elements uptake and localization in cabbage inflorescence (*Brassica oleracea* var. *capitata*) grown on sugar mill pressmud-amended soils

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Abstract Sugar mill pressmud is highly considered and used as a supplement to improve soil fertility and crop yield, especially in India. This study investigated the growth and yield performance of cultivated cabbage (*Brassica oleracea* var. *capitata*) on sugar mill pressmud amended soil. Pot experiments were performed using various pressmud amendment rates (0, 50, 100, and 150 g/kg soil) to study the fertilization impact on cabbage inflorescence

yield (g) and size (diameter: cm). Moreover, mineral element (Cd, Cr, Cu, Fe, Mn, and Zn) accumulation in the cabbage inflorescence was also studied using a modified polynomial non-linear model. Results showed that the sugar mill pressmud had significantly ($p < 0.05$) higher nutrient elements which induced their concentration in the soil after mixing. Also, the highest yield (849.25 ± 7.47 g), size (15.10 ± 1.50 cm diameter), and dry weight (42.13 g) of cabbage inflorescence were attained using 100 g/kg pressmud treatment with a maximum significant ($p < 0.05$) accumulation of mineral elements. However, the highest accumulation of mineral elements was observed in the outer zones (Z1 and Z2) of leafy inflorescence as compared to inner zones (Z3 and Z4), respectively. The mineral elements in both outer and inner zones of cabbage followed an order of $\text{Fe} > \text{Mn} > \text{Zn} > \text{Cu} > \text{Cr} > \text{Zn}$. Furthermore, the developed modified polynomial quadratic model precisely predicted the total mineral element uptake (mg dwt.) by cabbage inflorescence. The models had good fitness as described by the coefficient of determination ($R^2 > 0.992$) values. This study suggested that sugar mill pressmud was a promising resource for cabbage cultivation, and the developed models were helpful in the precise prediction of mineral elements accumulated by its inflorescence.

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Introduction

Due to an exponential growth in industrialization and urbanization, the need for industrial and domestic wastewater treatment plants has consequently increased globally (Rout et al., 2021; Zhang et al., 2020). The wastewater treatment process includes some sequential stages: primary, secondary, and tertiary treatments. During the primary and secondary stages, sedimentation and filtration techniques are used to eliminate the suspended loads (Chen et al., 2020; Kehrein et al., 2020). However, sludges which are settleable fractions (solid and semi-solid) and composed of organic and inorganic materials are, thus, produced in the wastewater treatment plant (Qrenawi & Rabah, 2021). Sludge may create environmental pollution due to the presence of organic and inorganic pollutants such as phosphorus, nitrogen, sulfur, mineral elements, hydrocarbons, pesticides, etc., if disposed of to the environment without proper treatments (Cieřlik et al., 2015). Therefore, there has been an increasing need to develop efficient techniques for sustainable sludge management.

The sugar industry plays a major role in the economic development of any nation by the revolution of the agricultural sector (Lee et al., 2020; Solomon, 2011). The sugar industry in India uses sugarcane as the major raw material for the production of sugar and its derivatives. After the filtration of sugarcane juice, a huge quantity of solid and semi-solid sludge commonly known as pressmud or filter cake mud is produced (Tabinda et al., 2021; González et al., 2020). The produced pressmud contains a high load of nutrients, including organic carbon, nitrogen, phosphorus, potassium, mineral elements, etc. (Kumar et al., 2016). Due to the high rate of its generation, proper management of the pressmud is the most difficult task for the sugar mill industries. As pressmud is often discarded in open lands, it creates numerous environmental problems, including pollution of the upper soil layer and leaching of mineral elements in the groundwater (Arshad et al., 2020). However, farmers of nearby villages collect the pressmud and apply it to the upper layer of their soil fields, leading to an increase in soil fertility and, consequently, better crop yields. This practice of pressmud

utilization has become a common practice throughout India. Recently, many reports also confirmed that pressmud was helpful to increase the growth and productivity of various crops, including eggplant (0 to 100% w/w; Kumar et al., 2016), pigeon pea and wheat (2% w/w; Mandal et al., 2013), finger millet (10 tons/ha; Prabhavathi & Ramakrishna Parama, 2019), and wheat (0 to 100% w/w; Chattha et al., 2019).

Pressmud for soil fertilization possesses a threat of hazardous element (Cd, Cr, Pb, As, etc.) accumulation in the crops (Swati & Hait, 2017). Some toxic elements may be transferred in higher amounts, which could lead to the human health risk of the consumers (Boudebouz et al., 2020). While mineral elements are considered micronutrients for plants and humans, the different chemical compounds, however, have different chemical properties with different toxicities in humans (Kumar et al., 2020). Therefore, it is necessary to monitor the nutrient dynamics between soil and plants. In this regard, prediction modeling has been widely used to study the bioaccumulation of mineral elements into crop plants (Jaskulak et al., 2020; Kumar et al., 2019, 2020). Previously, numerous reports are available on the development of linear and non-linear prediction models to understand the uptake behavior of cucumber (Eid et al., 2018), sunflower (Zhao et al., 2019), cauliflower (Kumar et al., 2020), pea (Eid et al., 2020a), wheat (Eid et al., 2020b), etc. These reports revealed that mathematical models could be the most efficient tools for the minimization of the health risk associated with contaminated crop products.

Cabbage (*Brassica oleracea* var. *capitata*) belongs to the family *Brassicaceae*. It is a commonly used vegetable of the Indian subcontinent (Singh et al., 2012a, b). The most common method of consumption is cooking the leafy inflorescence as a veggie, salad, and also in various fast foods like burgers, and Chinese noodles. There are more than 10 varieties of *Brassica oleracea* vegetables in India. The production of cabbage (*capitata* variety) is estimated at 9036.69 tons per annum (NHBI, 2020), which signifies its rate of consumption and importance in India, a country with the largest number of vegetarians in the world (NHBI, 2020). In the selected study area, most of the farmers grow cabbage at least once in a year and supply them to local and interstate markets. Based on a preliminary survey, sugar

mill pressmud is being applied in those agricultural fields. The farmers in the Saharanpur district of Uttar Pradesh (India) often apply the sugar mill pressmud on their agricultural lands to cultivate various vegetables including cabbage. Also, the application of sugar mill pressmud resulted in higher cabbage yields making their agri-business profitable. Therefore, it is necessary to evaluate the effects of pressmud application on the growth and productivity of cabbage along with the potential risk of mineral element contamination. In this study, outdoor pot experiments were conducted to assess the impact of sugar mill pressmud amendment rates (0, 50, 100, and 150 g/kg soil) on the yield and morphological parameters of cultivated cabbage. Also, a modified non-linear model was used to monitor the mineral element uptake and their localization in different classified zones of cabbage inflorescence.

Materials and methods

Experimental materials and design for cabbage cultivation

For this study, pressmud was collected from the Uttam Sugar Mills Ltd. situated at Shermau village of Saharanpur district, Uttar Pradesh, India (29° 51' 06" N, 77°15' 54" E). The farmers of nearby villages often collect pressmud from the industry's disposal point and mix it with their field soil (500–1000 tons/ha) using moderate plowing to enhance its fertility. Pressmud was collected in sterile polyethylene bags of 1 kg capacity. Besides this, a high-yielding variety of cabbage (Pusa mukta) was procured from the local market of Nakur town, Saharanpur, India (29°54'41" N, 77°17'51" E). The selected cabbage variety, i.e., Pusa mukta, is popular among the local market due to its high yield, short time of cropping (90 days), and good taste. Cabbage cultivation was done in an artificial greenhouse constructed at Kulheri village of Nakur town (29°52'54.0"N, 77°16'17.8"E) from September 2020 to December 2020. The average temperature of the cropping period was recorded as 17.6 °C. Polyethylene bags of 25 kg capacity were filled with 20 kg of garden soil (GS) and an appropriate dose of pressmud. In this regard, a total of four triplicated pressmud treatments were given to optimize the

cabbage growth such as 0 g/kg as control (20 kg GS), 50 g/kg (19 kg GS + 1 kg pressmud), 100 g/kg (18 kg GS + 2 kg pressmud), and 150 g/kg (17 kg GS + 3 kg pressmud) as illustrated in Fig. 1. The seeds of cabbage were scooped at a soil depth of 5 cm and immediately watered using borewell water. Thus, a total of five watering was done in the 90 days of cabbage cropping.

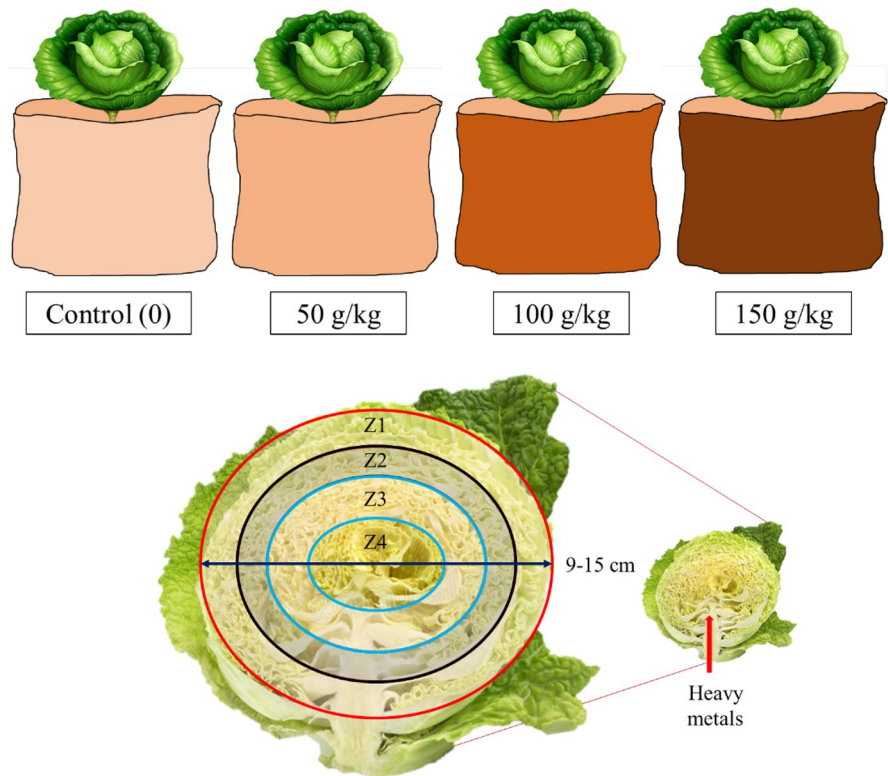
Monitoring of cabbage growth and harvesting

The growth of cultivated cabbage was monitored throughout the experiments. In this, the growth of cabbage was divided into two phases: seedling and inflorescence growth of 30 and 60 days, respectively. When the pin-head formation was started, the relative diameter of the inflorescence was measured using a Vernier scale at an interval of 15 days. Further, the matured heads of inflorescence were cut and washed thoroughly in distilled water. After wiping inflorescence using a muslin cloth, its fresh weight (g) was measured using a digital scale (ZL200, Samson, IN) and then cut into two halves as shown in Fig. 1. Finally, heads were divided into four equal zones namely Z1 (outer zone), Z2, Z3, and Z4 (inner zone), and then fresh leaves from each zone were taken out separately. These leaves were oven-dried at 105 °C until complete dehydration again weighted to describe dry weight (g).

Chemical and instrument analysis

The GS and pressmud used in this study were analyzed for selected physicochemical and mineral element parameters, including pH, electrical conductance (EC), organic carbon (OC), total Kjeldahl's nitrogen (TKN), total phosphorus (TP), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). Standard laboratory methods were adopted for GS and pressmud analysis (Latimer, 2012; Trivedy & Goel, 1984). A 1:10 suspension of GS/pressmud and distilled water was used for the chemical analysis. A microprocessor-based multimeter (1611, ESICO, IN) was used for pH and EC estimation, while OC was determined using the chromic acid oxidation method. Besides this, TKN and TP were determined by using acid digestion/distillation and spectroscopic (Cary 60

Fig. 1 Experimental setup for cabbage cultivation and spatial zonation of its inflorescence



UV–Vis, Agilent, USA) methods, respectively. The mineral element contents of GS and pressmud were determined after digesting the samples in a di-acid mixture (80% HNO_3 + 20% HClO_4). Similarly, the dried inflorescence from each zone was also separately digested and further used for the estimation of mineral element concentration using the atomic absorption spectroscopy (AAS) instrument (AAS-4129, ECIL, IN). For this, certified reagent materials (Merck, IN) were used for the calibration of the AAS instrument using 1, 5, 10, 30, 50, and 100 mg/L standardized mineral element solutions. The instrument calibration, detection limits, and conditions were described in a previous study (Kumar et al., 2020). The grounded pressmud sample (2 g) was analyzed using Fourier's transform spectroscopy (FTIR) instrument (FTIR-8400S, Shimadzu, USA) while considering KBr (IR Spectroscopy grade dried at 105 °C for 1 h) as reference material. The die-set O-ring of pressmud and KBr was prepared under a 6000-kg/cm pressure for 10 min. The relative transmittance (%) of the

different peaks ranging from 400 to 4000 $1/\text{cm}$ was used to present the spectrum. A 2% smoothing of the obtained peaks was done to reduce the noise in the spectra.

The physicochemical and mineral element properties of GS and pressmud are given in Table 1. It was evidenced by the results that both GS and pressmud had slight neutral and alkaline pH reactions (7.22 and 8.06) with EC values of 2.04 and 5.05 dS/m, respectively. However, pressmud showed higher contents of other nutrient parameters, i.e., OC, TKN, and TP, as compared to GS. Similarly, pressmud had a significantly higher load of mineral elements as indicated from Student's *t* test ($p < 0.05$). On the other hand, the FTIR analysis of pressmud showed the dominance of different bonding groups accountable for organic and other nutrient matters. Figure 2 provides the FTIR spectrum of pressmud as relative transmittance of wavenumbers starting from 400 to 4000 $1/\text{cm}$. From the spectrum, numerous wavenumbers corresponding to different functional groups including 400–450 $1/\text{cm}$ (X–C=O in the plane), 460–540 $1/\text{cm}$

Table 1 Comparative characteristics (mean $\pm$ standard deviation, $n=3$) of soil and sugar mill pressmud

Characteristics	Soil	Sugar mill pressmud	Student's <i>t</i> test	
			<i>t</i> value	<i>p</i>
pH	7.22 $\pm$ 0.08	8.06 $\pm$ 0.10*	11.36	< 0.05
Electrical conductivity (dS/m)	2.04 $\pm$ 0.16	5.05 $\pm$ 0.65*	7.79	< 0.05
Organic carbon (mg/kg)	0.91 $\pm$ 0.03	4.37 $\pm$ 0.82*	7.30	< 0.05
Total Kjeldahl's N (mg/kg)	23.83 $\pm$ 1.04	236.35 $\pm$ 12.07*	30.38	< 0.05
Total P (mg/kg)	32.19 $\pm$ 3.25	139.48 $\pm$ 5.46*	29.25	< 0.05
Cd (mg/kg)	0.19 $\pm$ 0.02	10.74 $\pm$ 0.64*	28.52	< 0.05
Cr (mg/kg)	2.32 $\pm$ 0.20	25.33 $\pm$ 2.05*	19.35	< 0.05
Cu (mg/kg)	2.17 $\pm$ 0.10	80.48 $\pm$ 4.93*	27.51	< 0.05
Fe (mg/kg)	5.05 $\pm$ 0.71	444.46 $\pm$ 15.44*	49.24	< 0.05
Mn (mg/kg)	1.24 $\pm$ 0.28	230.44 $\pm$ 19.02*	20.87	< 0.05
Zn (mg/kg)	2.25 $\pm$ 0.14	93.96 $\pm$ 5.04*	31.51	< 0.05

*Statistically significant at $p < 0.05$ using unpaired Student's *t* test

cm (X–C=O deformation), 600–780 1/cm (X–C=O and C–X stretch of ketones and iodides), 910–960 1/cm (C–C=O and C–C stretch), 1105–1130 1/cm (C–C skeletal), 1190–1210 1/cm (C–H bending), 1445–1470 (C–H bending), 1780–1825 1/cm (C=O stretching), and 2855–3000 1/cm (C–H stretching of alkyl) were identified, respectively.

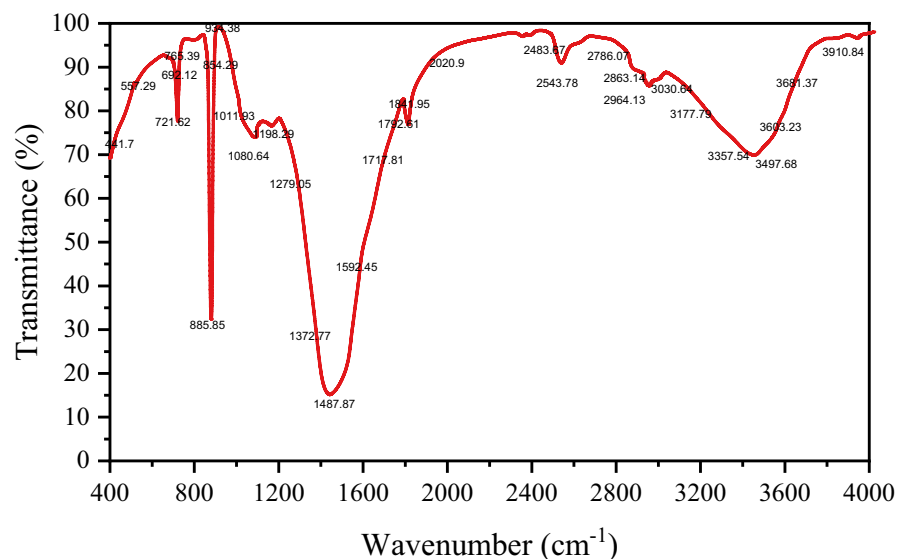
Prediction model for total mineral elements uptake by cabbage inflorescence

To evaluate the total mineral elements uptake by the cabbage fluoresces, we implemented a modified

polynomial model. This model was developed for the prediction of total fresh biomass using inflorescence diameter as a relative function. Since it was not possible to determine the fresh biomass directly during the cabbage growth phases, we established an interrelation between the cabbage inflorescence size (diameter: cm) and its fresh weight (g). Considering the inflorescence diameter (*D*) directly proportional to its fresh weight (FW), we obtained:

$$D \propto \text{FW} \quad (1)$$

Rearranging Eq. 1, we got

Fig. 2 FTIR spectra of pressmud collected from sugar mill industry

$$D = f \times FW \quad (2)$$

where f represented the relative growth factor of cabbage inflorescence. By using Eq. 2, the fresh biomass of inflorescence was simulated for the non-measured points of pin-head formation, i.e., 0, 15, 30, and 45 days. Further, the calculated fresh weight (y) was modeled using a second-order quadratic equation given below (Eq. 3):

$$y = at^2 + bt + c \quad (3)$$

where a , b , and c are the quadratic regression coefficients, while t is the experimental period (days) of inflorescence formation. On the other hand, the predicted fresh weight was further converted into dry weight (DW: g) using Eq. 4:

$$DW \propto y \quad (4)$$

Again, rearranging Eq. 4, we got

$$DW = d \times y \quad (5)$$

Here, d represents the dry weight factor corresponding to the measured DW. Finally, the total mineral elements (TMEs) accumulated by cabbage inflorescence (dry weight basis) was predicted using the model Eq. 6:

$$TME = \left[\left(\frac{y}{1000} \right) \times C \times BF \right] \quad (6)$$

where TME is the total mineral element uptake by cabbage inflorescence (mg), C is the mineral element concentration in the soil (mg/kg), BF is the

bioaccumulation factor of mineral elements uptake by cabbage as a ratio of the inflorescence to soil concentration, and 1000 represents weight conversion factor (g to kg), respectively.

Statistics and software

All experiments were performed as triplicate ($n=4 \times 3$) under a natural day/night regime. Data were analyzed using unpaired Student's t test, one-way ANOVA ($p < 0.05$), and non-linear regression statistical tools. For this, Microsoft Office Excel 2016 (Microsoft Corp., USA) and OriginPro 2021 (Origin Corp., USA) software were implemented. The FTIR spectrum was analyzed using irAnalyze-RAMalyze (LabCognition Analytical Software GmbH & Co. KG) software.

Results and discussion

Effect of pressmud treatment on soil mineral elements

Table 2 shows the effect of the pressmud amendment on GS properties. We noted that pressmud treatment significantly ($p < 0.05$) enhanced the mineral element contents of GS. In this regard, the GS showed the moderate presence of mineral elements while 150 g/kg pressmud treatment exhibited the highest values. The source of mineral elements in the pressmud might be from the sugarcane processing and product manufacturing processes in which numerous

Table 2 Mean $\pm$ standard deviation ($n=3$) of mineral elements concentration (mg/kg) of the soil under different treatment of sugar mill pressmud

Mineral elements	Pressmud treatment (g/kg)				Maximum permissible limit (g/kg) ^a
	0	50	100	150	
Cd	0.24 $\pm$ 0.01	2.61 $\pm$ 0.10*	4.83 $\pm$ 0.22*	7.83 $\pm$ 0.46*	5
Cr	2.84 $\pm$ 0.18	7.55 $\pm$ 0.64*	16.87 $\pm$ 1.04*	21.46 $\pm$ 1.22*	200
Cu	1.78 $\pm$ 0.07	8.76 $\pm$ 1.03*	21.88 $\pm$ 2.40*	30.18 $\pm$ 1.94*	150
Fe	4.56 $\pm$ 1.06	12.99 $\pm$ 2.39*	28.38 $\pm$ 3.01*	42.55 $\pm$ 2.25*	40
Mn	1.33 $\pm$ 0.13	4.29 $\pm$ 0.69*	8.89 $\pm$ 1.13*	14.60 $\pm$ 1.54*	450
Zn	2.47 $\pm$ 0.33	7.67 $\pm$ 1.00*	17.45 $\pm$ 2.70*	25.98 $\pm$ 3.05*	300

*Statistically significant at $p < 0.05$

^aMaximum permissible limits for agricultural soil as described by Kabata-Pendias (2011)

chemicals are used. Also, a wide range of pesticides and fertilizers containing hazardous elements are used in sugarcane cultivation, which may increase the availability of the mineral elements within their plant parts. Thus, a high load of sugarcane extracts containing mineral elements is released into the sugar mill wastewater, from where the industrial sludge is formed after its treatment in sedimentation tanks. Although, mineral elements in all pressmud treatments were below the maximum permissible limits except for Cd and Fe in 150 g/kg treatment (Table 2). Considering the permissible limits, 100 g/kg pressmud treatment was described as the most useful treatment, which had the mineral element contents within safe limits (Kabata-Pendias, 2011).

For the study area, limited studies are available on soil quality analysis of Saharanpur District, Uttar Pradesh, India. Out of them, Prakash et al. (2017) evaluated the nutrient status of soil in the area and found that soil of Saharanpur was characterized by low to medium levels of OC (0.50%), N (193 kg/ha), P (11.79 kg/ha), and K (154.13 kg/ha), respectively. Besides this, Singh et al., (2012a, b) also analyzed different nutrient and physicochemical parameters of soil used for paddy crops and reported moderate levels of available S, Na, and P nutrients in the Saharanpur district. On the other hand, Rondina et al. (2019) studied the FTIR spectrum of pressmud activated carbon waste and reported that carbon, nitrogen, and oxygen-containing functional groups were the most dominating constituents. The strongest peaks of 3628.1 1/cm (O–H), 2303.5 1/cm (nitrile), and

1454.32 1/cm (C–H bending) showed the presence of different hydrocarbons in the pressmud. Therefore, inline findings are presented in these studies which support our results.

Pressmud has been widely used to increase the fertility of the soil, mostly in developing countries. Previously, Mushtaq et al. (2021) assessed the impact of pressmud amendment on the soil physicochemical and mineral element parameters under okra cropping. They achieved a significant increase in okra growth under pressmud and plant growth-promoting rhizobacteria treatments. Besides this, Kumar et al. (2016) evaluated the application of sugarcane pressmud for the field cultivation of eggplant (*Solanum melongena*). They also found that mineral element availability in treated field soil was significantly ($p < 0.01$) increased after pressmud treatments. Thus, our results were supported by the previously published reports on pressmud utilization for soil nutrients enhancement.

Effect of pressmud treatment on yield and morphological attributes of cabbage

In this study, the amendment of pressmud at different rates significantly ($p < 0.05$) enhanced the cabbage inflorescence weight (g) and its relative diameter (cm). Data provided in Table 3 showed that the average weight of finally harvested cabbage inflorescence was higher in pressmud treatments as compared to control treatment. Although, 150 g/kg treatment exhibited a slight decrease

Table 3 Measured and predicted diameter, fresh and dry weight of cabbage inflorescence using the modified polynomial model

Press-mud treatment (g/kg)	Model		Diameter (cm)		Fresh weight (g)		Dry weight (g)	Conversion factors	
	Equation	R^2	Measured	Predicted	Measured	Predicted		f	d
0	$y = -0.074x^2 + 8.157x + 5.508$	0.992	9.30 ± 0.50	9.32	529.55 ± 5.57	530.24	27.12	56.52	19.53
50	$y = -0.065x^2 + 8.949x + 4.449$	0.997	$12.40 \pm 1.00^*$	12.38	$713.78 \pm 8.90^*$	712.36	32.48	57.50	21.98
100	$y = -0.081x^2 + 11.029x + 1.451$	0.999	$15.10 \pm 1.50^*$	15.15	$849.25 \pm 7.47^*$	846.03	42.13	55.98	20.16
150	$y = -0.068x^2 + 9.707x + 2.736$	0.999	$13.60 \pm 0.60^*$	13.66	$782.52 \pm 4.28^*$	775.85	36.02	57.16	21.72

Values are mean followed by the standard deviation of three replicates

*Statistically significant at $p < 0.05$

in the inflorescence weight and diameter; therefore, 100 g/kg dose can be referred to as the best treatment for cabbage cultivation. The improved growth and productivity under different treatments of pressmud might be due to the increased availability of the soil organic and inorganic minerals which helped to grow cabbage more efficiently. Our results were supported by the previously published researches (Upadhyay et al., 2012; Kumar et al., 2016; Singh et al., 2018; Kumari et al., 2019). A study by Upadhyay et al. (2012) used a pressmud dose of 15 tons/ha and found that the cabbage yield was 419.81 g. In their study, Kumar et al. (2016) found that pressmud amendment showed an incline in eggplant yield using 40% pressmud treatment. Similarly, Singh et al. (2018) also assessed the effect of pressmud fertilization on the grain yield of *Pisum sativum* cultivar. Their results showed that the recommended dose pressmud was 2 t/ha gave better yield and biochemical constituents viz. protein, reducing sugar carbohydrate and nutrient contents. The influence of pressmud derived compost on *Vigna radiata* has been investigated by Kumari et al. (2019) while reporting maximum seed yield using 15% pressmud treatments. Therefore, the findings of our study described an efficient increase in cabbage growth and productivity using pressmud as a sustainable nutrient resource.

Prediction models for cabbage inflorescence weight and total mineral elements uptake estimation

Total mineral element uptake (mg) by the cabbage cultivated in the soils amended with different doses of pressmud was evaluated using a novel mathematical model. In this, the modified version of the model proposed by Zhao et al. (2019) has been used. The model was modified by replacing the sigmoid function with a quadratic one. By using the predictive equations given in Table 3, it was evidenced that the quadratic model was helpful to predict both cabbage inflorescence diameter and fresh weight with respect to time, efficiently. The simulated cabbage inflorescence diameter and fresh weight are illustrated in Figs. 3 and 4. Also, the conversion factors (f and d) derived from the measured values were helpful to obtain the data of non-measured points for the fresh

and dry weight estimation. In our study, the coefficient of determination ($R^2 > 0.992$) for all quadratic equations showed good fitness. Further, the final model for the prediction of mineral elements in cabbage inflorescence (mg/kg dry weight basis) identified Fe, Mn, and Zn as the most dominating elements. Moreover, the decreasing order of quantity of predicted mineral elements in all pressmud treatments was $\text{Fe} > \text{Mn} > \text{Zn} > \text{Cu} > \text{Cr} > \text{Cd}$ (Table 4).

Prediction modeling of mineral elements uptake by plants has received significant attention from the scientific community since it allows monitoring fate assessment associated with their consumption (Kumar et al., 2020; Zhao et al., 2019). The research focused on mineral element uptake by sunflower (*Helianthus annuus*) plants used a sigmoid function-based prediction model while considering soil mineral elements and bioaccumulation factors as main variables (Zhao et al., 2019). The developed model was helpful to simulate both sunflower biomass production and mineral element uptake. Recently, Kumar et al. (2020) also developed linear regression models for the uptake of the mineral elements by spinach plants grown in wastewater-contaminated soils of Haridwar, India. These reports affirm the applicability of the developed model in our study. Therefore, the proposed models are novel in monitoring the mineral element transfer from soil to edible parts of cabbage.

Mineral element uptake and spatial distribution in cabbage inflorescence

Mineral element uptake and their bioaccumulation in cabbage inflorescence are given in Table 4. Results showed that the contents of mineral elements gradually increase with the pressmud amendment rate (from 0 to 150 g/kg). For all pressmud treatments, the accumulation of all mineral elements was significantly ($p < 0.05$) higher when compared to the control treatments, except for Cd and Cu in 50 g/kg treatment. However, the BF values of all mineral elements decreased with an increase in pressmud dose, which suggested that inflorescence was capable to accumulate mineral elements more efficiently at a low treatment dose. Besides this, BF values were < 1 for all treatments of Cd, Cr, Cu, and Fe, except for Mn (all treatments) and Fe (control treatment) which

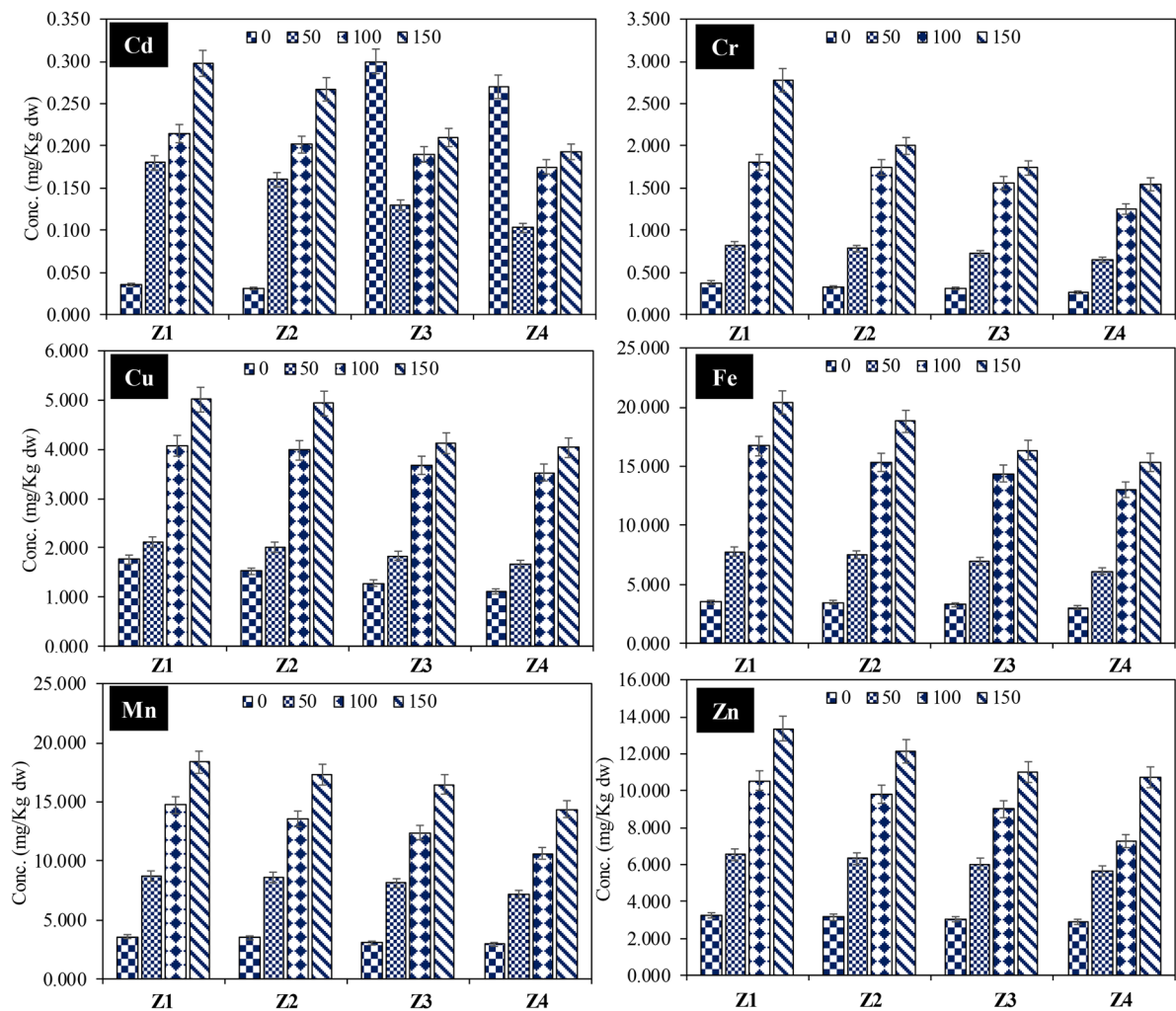


Fig. 3 Spatial distribution of different mineral elements in four zones of cabbage inflorescence grown in pressmud treated soil

reached > 1 , respectively. On the other hand, the spatial distribution of mineral elements in different zones of cabbage inflorescence is illustrated in Fig. 3. It was evidenced by the results that the Z1 (outermost layer) zone exhibited the highest accumulation of mineral elements, while the other three zones, i.e., Z2, Z3, and Z4 showed a decreasing level of mineral element localization. The higher accumulation of mineral elements in outer zones might be associated with the age of outer leaves. Since outer leaves are the foremost covering of cabbage inflorescence, mineral element accumulation in them might have started at the beginning of pin-head formation. The outer layers

may contain high levels of different mineral elements including Cd, and some residues of pesticides applied during their cultivation. For consumer's safety, some outer leafy layers of cabbage should always be discarded and vegetable parts should be washed thoroughly before their consumption.

Application of industrial and sewage sludges including pressmud has been widely accepted for sustainable crop production in recent times, although this practice involves the risk of hazardous element transfer from soils to edible parts of crops. In their study, Kumar et al. (2016) found that mineral element accumulation in a hybrid variety of eggplant

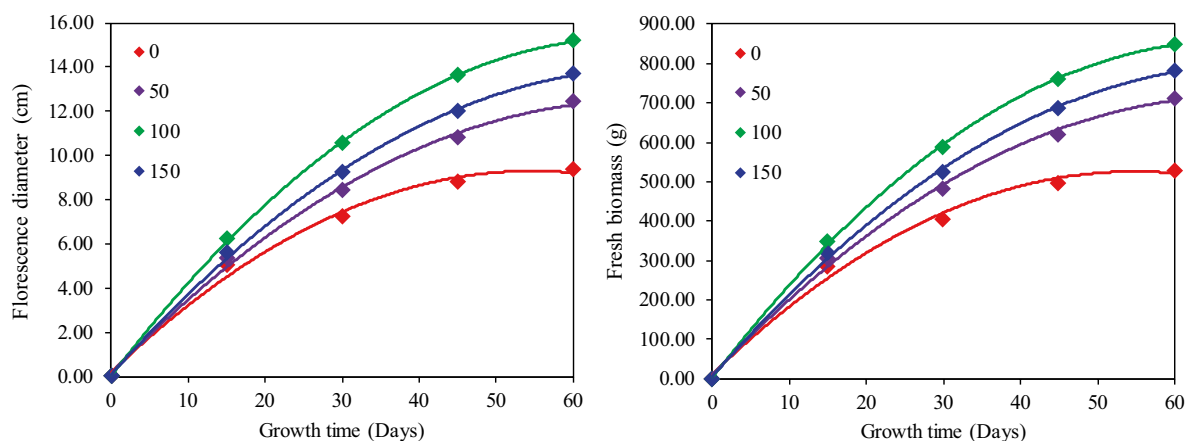


Fig. 4 Measured (points) vs. model simulated (lines) inflorescence diameter (cm) and fresh biomass (g) of cabbage grown on press-mud treated soils (points are mean of three replicates)

proportionally increased with pressmud mixing rates of 0 to 100%. Also, if pressmud is applied in combination with different biofertilizers like *Azospirillum*, the yield efficiency of cabbage can be increased significantly as reported by Upadhyay et al. (2012). Most recently, Eid et al. (2020a) studied the

accumulation of 10 mineral elements in the vegetative parts of *Pisum sativum* grown on sewage sludge-amended soil. In their report, it was evident that a higher dose of sewage sludge significantly affected the mineral element accumulation in *Pisum sativum* plant parts.

Table 4 Mineral elements uptakes by cabbage inflorescence and their bioaccumulation factor

Source	Press-mud treatment (g/kg)	Mineral elements					
		Cd	Cr	Cu	Fe	Mn	Zn
Cabbage (mg/kg dwt.)	0	0.15 ± 0.01	0.32 ± 0.01	1.42 ± 0.32	3.31 ± 0.12	3.26 ± 0.23	3.07 ± 0.11
	50	0.15 ± 0.00 ns	0.74 ± 0.02*	1.91 ± 0.41 ns	7.08 ± 0.34*	8.16 ± 0.93*	6.14 ± 0.23*
	100	0.20 ± 0.01*	1.59 ± 0.08*	3.82 ± 0.05*	14.87 ± 1.82*	12.84 ± 1.17*	9.16 ± 1.49*
	150	0.24 ± 0.01*	2.01 ± 0.05*	4.53 ± 0.08*	17.74 ± 1.20*	16.64 ± 1.09*	11.81 ± 2.43*
Bioaccumulation factor (BF)	0	0.663	0.112	0.799	0.726	2.447	1.243
	50	0.055	0.099	0.218	0.545	1.903	0.801
	100	0.040	0.094	0.174	0.524	1.445	0.525
	150	0.031	0.094	0.150	0.417	1.140	0.454
Predicted total mineral elements uptake (mg dwt.)	0	0.08	0.17	0.75	1.75	1.73	1.63
	50	0.10	0.53	1.36	5.04	5.81	4.38
	100	0.17	1.35	3.23	12.58	10.86	7.75
	150	0.19	1.56	3.52	13.77	12.91	9.16

Values are mean followed by the standard deviation of three replicates

ns not significant

*Statistically significant at $p < 0.05$

Conclusion

From the findings of this study, it was concluded that the amendment of the sugar mill pressmud significantly enhanced the growth and productivity of cultivated cabbage. The soil mineral elements were significantly increased after pressmud mixing; however, their uptake by cabbage gradually increased from 0 to 100 g/kg which again decreased in 150 g/kg treatment. However, a 100-g/kg dose of pressmud resulted in maximum yield and size of cabbage inflorescence. The spatial analysis of different zones of cabbage inflorescence revealed that the outmost leaves had higher bioaccumulation of mineral elements as compared to inner zones, respectively. Moreover, a quadratic function-based modified model was helpful to predict the fresh weight production using measured inflorescence diameter while total mineral element uptake (mg dwt.) by cabbage inflorescence. This study provided insights into the sustainable utilization of sugar mill pressmud for vegetable cultivation while monitoring the localization of different mineral elements to reduce associated health risks. Additionally, more studies are suggested on the uptake and associated health risk of other toxic elements (Pb, As, Hg, etc.) that may be present in the applied pressmud.

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Declarations

Ethics approval This article does not contain any studies with human participants or animals.

Consent to participate All authors mutually agreed to participate in this work.

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Competing interests The authors declare that there is no competing interests.

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