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Research Article

Integrated Application of Biocompost Pressmud and Chemical Fertilizers to Enhance Biomass Production and Nutrient Accumulation of Maize

Zia-ul-hassan[1]*, Kazim Raza Suhag[1], Ghulam Murtaza Jamro[2], Naheed Akhter Talpur[1], Hassan Shah Rashdi[3], Inzamam Ali Jamali[3], Fozia Naz Memon[4], Inzamam-ul-Haque Khanzada[4]

[1]*Department of Soil Science, Sindh Agriculture University, Tandojam, Pakistan.*
[2]*Department of Soil Science, Sindh Agriculture University Sub-Campus, Umarkot, Pakistan.*
[3]*Sindh Water & Agriculture Transformation Project, Tandojam, Pakistan.*
[4]*Soil & Environmental Research Institute, Agriculture Research Centre, Tandojam, Pakistan.*

ABSTRACT

Organic amendments are known to support cost-effective plant nutrition. We assessed the response of maize (*Zea mays* L.) to varying levels of composted pressmud and chemical fertilizers in a thrice replicated completely randomized factorial experiments, involving different levels of recommended NPK fertilizers (160-80-80 kg ha^{-1}), i.e., control (0%), 25%, 50%, and 100%, and composted press mud, i.e., 0 (control), 10 and 20 t ha^{-1}. The compost was prepared in specially fabricated piles (1m × 1m × 1m), made of 6.0' long mango sticks. The piles were filled by plastic bins (19"-12"-13"), able to accommodate 17 kg pressmud. The piles were sprayed with the solution of effective microorganisms (EM) and covered with the polythene sheets. A clayey non-saline, alkaline soil was used in this study with low organic matter, phosphorus and potassium content. Ten seeds of maize (cv. Akbar) were planted in pots filled with 10 kg soil, thinned to five, and harvested after seven weeks. Chemical fertilizers and composted press mud significantly improved maize plant traits, except root to shoot ratio, against control treatment. Increased doses increased the performance. When compared to control treatment, the increase was higher in case of using 20 over 10 t ha^{-1} composted press mud for maize dry biomass (shoot: 29.8 v/s 7.1%, root: 28.9 v/s 5.3%, leaf: 29.2 v/s 8.3%, total: 29.4 v/s 7.0%), leaf area (27.8 v/s 4.9%), and nutrient content (N: 22.2 v/s 11.1%, P: no change, K: 37.5 v/s 25%). Moreover, using 20 t ha^{-1} composted press mud was more effective than 10 t ha^{-1} in increasing the dry biomass (shoot: 21.3%, root: 22.5%, leaf: 19.2%, total: 20.9%), leaf area (21.8%), and nutrient content (N: 10%, P: 0%, K: 10%). Using 20 t ha^{-1} composted press mud with 100% chemical fertilizer recorded maximum increase when compared to the control treatment in maize dry biomass (shoot: 135.1%, root: 132.0%, leaf: 135.5%, total: 137%), leaf area (127.5%), and nutrient content (N: 89.4%, P: 56.8% and K: 82.1%). We conclude that applying 160-80-80 kg NPK with 20 t ha^{-1} composted pressmud enhances biomass production, leaf area and NPK content of maize.

Keywords: Biocompost pressmud, Biomass production, Fertilizers, Growth, Maize, Nutrient availability, Organic amendments

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Correspondence
Zia-ul-hassan
zhnshah@gmail.com

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INTRODUCTION

Maize (*Zea mays* L.) is a globally recognized cereal crop. In Pakistan, maize crop occupies an area of 1641.4 thousand ha with a total production of 9739.0 thousand tons and an average yield of ~5933.4 kg ha^{-1}. This average yield is low when compared to the neighboring countries, e.g. China (~6532 kg ha^{-1}) (GoP, 2025). It is generally believed that soil degradation, as a result of erosion, nutrient mining, etc., has been reported as major causes of soil organic matter loss in agricultural lands, which may lead to crop yield reduction (Zia-ul-hassan and Arshad, 2006; Ahmed *et al.*, 2024; Ameer *et al.*, 2024). Maize is a heavy feeder of nutrients and requires balanced amounts of fertilizers to offer optimum yield, especially that of potassium (K) fertilizer (Nawaz *et al.*, 2006, Mastoi *et al.*, 2013). Very little is known about the nutritional requirements of maize crop, especially the integrated use of various organic amendments and chemical fertilizers (Arshad *et al.*, 2007). Composting organic waste materials increases their macronutrient (NPK) and micronutrient (Cu, Zn, Fe, Mn) content, and hence, improve their carbon to nutrient ratios (Ahmad *et al.*, 2007), soil water conservation, mineralization (Ahmad *et al.*, 2008) and aggregate stability (Roy, 2000). Composted organic materials are also known to enhance shoot and root growth, biomass production, crop yield, and grain quality of various crop species, including maize (Asghar *et al.*, 2006; Ahmad *et al.*, 2007, 2008; Talpur *et al.*, 2025; Zia-ul-hassan *et al.*, 2025).

Kubar *et al.* (2013) highlighted the benefits of using chemical K fertilizer in integration with a novel organic K fertilizer in equal amounts (30 kg ha^{-1}) on the growth and biomass production, and K concentration of maize. In another study, Channa *et al.* (2013) reported that blending 10 mg auxin precursor L-tryptophan per kg of organic K fertilizer improved growth, biomass production and K nutrition of maize. Some other studies also advocated the beneficial effects of composted organic materials. Organic amendments are believed to support crop production through mitigating plant biotic and abiotic stresses (Arshad *et al.*, 2024; Zahoor *et al.*, 2024). Integrated application of composted waste and spent wash reportedly increased nutrient availability (Choudhary *et al.*, 2017). Soil organic carbon and total nitrogen are shown to increase linearly by the application of composted organic material, thereby increasing the crop yields (Liu, 2018). A recent study reported that organic amendments, such as biochar, improved morpho-physiological traits of crops, including drought tolerance in maize (Iqbal *et al.*, 2023).

Pressmud is the organic by-product of sugarcane processing. It has been advocated that it has a great potential to support plant nutrition in sustainable agriculture systems. Sarangi *et al.* (2008) demonstrated the potential of composted pressmud, especially with distillery spent wash, to enhance the fertility of soil and promote sustainable farming activities. A recent study Poria *et al.* (2022) advocated that the pressmud is a rich source of nutrients and organic matter, and hence, can be exploited to develop value-added products, viz. composts and biofertilizers.

Several studies have confirmed that pressmud compost improves soil physical, chemical, and biological properties. It has been reported that pressmud enhanced soil organic carbon, improved soil texture, and increased the availability of macro- and micronutrients (Kumar *et al.*, 2017). The application of pressmud, alone or in combination with mineral fertilizers, improves post-harvest soil fertility status, bulk density and increases microbial biomass. These qualities make it a reliable amendment for the reclamation and restoration of poorly fertile degraded soils (Shehzad *et al.*, 2023). Soil application of pressmud, in integration with chemical fertilizers and microbial inoculants, has been reported to enhance nutrient availability and plant uptake, e.g., increased solubilization of phosphorus and potassium, thereby increasing nutrient-use-efficiency of maize (Naeem *et al.*, 2022).

The application of pressmud has been witnessed to improve the vegetative growth, biomass production, and grain yield of maize The co-application of pressmud with K fertilizer or farmyard manure promoted plant height, root development, and K uptake. Soil application of pressmud biofertilizer with 50% fertilizer K offered maximum maize yield and K efficiency (Bashir *et al.*, 2021; Budiyanto, 2021; Naeem *et al.*, 2022). Integrated use of pressmud and chemical fertilizers (in equal amounts) is known to improve wheat yield and soil fertility as against their single application, and hence possess the potential to check soil degradation in poorly fertile soils requiring high fertilizer input (Shehzad *et al.*, 2023). This strong evidence advocates that composted or bioaugmented pressmud can be successfully utilized as a highly beneficial amendment to promote soil quality indices, nutrient bioavailability, and sustainable crop production (especially cereals like wheat and maize). The sugar industry of Pakistan annually produces ~1.2 million tons of filter cake. Such precious organic materials can be recycled by effective composting and returned back to the soil system. These composted organic materials will then not only improve soil properties but also lower the soil-crop system demand for chemical fertilizers by providing essential nutrients (Ahmad, 2000). This field study was conducted to assess the growth, biomass production and nutrient accumulation of maize under the integrated use of composted pressmud and chemical fertilizers at varying levels.

MATERIALS AND METHODS

Soil used in the study

The composite soil sample taken from a nearby fertile and under cultivation field was analyzed following standard methods as prescribed by Ryan *et al.* (2001). The soil was found to be clayey (sand: 30%, silt: 29%, 41% clay). The soil was non-saline with an electrical conductivity value of 0.64 dS m^{-1}. Based on its pH (7.9) the soil was categorised

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as alkaline. Furthermore, Moreover, the soil had poor (0.59%) organic matter content, with low content of phosphorus and potassium (AB-DTPA extractable: 6.5 mg P kg^{-1} and 117 mg K kg^{-1} soil, respectively).

Experimental setup and treatment details

The experiment was laid out in a completely randomized factorial design with three repeats. The treatments were composed of two factors, i.e. Factor A and Factor B. Factor A included four doses of chemical fertilizers, i.e., CF_1: 0-0-0 kg NPK ha^{-1} (0% recommended chemical fertilizer control), CF_2: 40-20-20 kg NPK ha^{-1}, (25% recommended chemical fertilizer), CF_3: 80-40-40 kg NPK ha^{-1} (50% recommended chemical fertilizer) and CF_4: 160-80-80 kg NPK ha^{-1} (100% recommended chemical fertilizer). Factor B was comprised of three treatments of composted pressmud, i.e., PM_1: 0 t ha^{-1} (control), PM_2: 10 t ha^{-1} and PM_3: 20 t ha^{-1}.

Application of fertilizers

The sources of chemical fertilizer used involved urea containing 46% N, di-ammonium phosphate (DAP) containing 18% N and 46% P_2O_5, and potassium sulphate (SOP) containing 50% K_2O and 18% elemental S. The requisite amount of P and K fertilizers were properly mixed with soil and then filled in the pots, before planting. The N fertilizer was divided into three equal parts. The first split was applied on the 8^{th} day of maize plants germination. The leftover splits were applied every fifteen days.

Planting maize in pots

Ten seeds of maize (cv. Akbar) were planted in each pot, filled with properly processed 10 kg soil. The rationale behind using desi maize variety Akbar is because it is a more suitable choice for short-duration, early growth studies evaluating organic amendments, since its growth response is more measurable under slow nutrient release organic amendments. After germination, the seedlings were thinned to five per pot. The plants were irrigated as and when required. The irrigation frequency and water quantity were kept the same for all treatments to avoid any confounding effect of water availability on biomass.

Preparation of compost and piles

The preparation for the bed started in the mid December. It took three days to prepare 14 specially fabricated piles for composting, having a dimension of 1m × 1m × 1m. The structure of pile was made using 6.0 feet long wooden sticks of mango trees to establish the base for material. Thereafter, the structure of pile was covered by polythene sheet. The piles were then filled using plastic bins with dimensions of 19'' × 12'' × 13''. It took two days to fill these piles. These plastic bins were able to accommodate 17 kg of pressmud. Thereafter, the piles were sprayed with the solution of effective microorganisms (EM), supplied with 47 liters of water (based upon the moisture content and the quantity of material used for composting). In the end, the piles were covered with polythene sheets (Figure 1).

Analysis of composted pressmud

The composted pressmud was analyzed for key chemical properties using standard methods described by Ryan *et al.* (2001). The average values across batches were electrical conductivity 2.72 dS m^{-1}, pH 7.7, organic carbon 389.5 g kg^{-1}, total nitrogen 28.9 g kg^{-1}, C:N ratio 13.5, available phosphorus 17.8 g kg^{-1}, and available potassium 23.8 g kg^{-1}. These values fall within the ranges commonly reported for composted pressmud, supporting the reliability of the material used.

Application of composted pressmud

The quantity of composted press mud to be applied in various treatments were calculated according to actual treatment plan, considering the weight of soil (10 kg) filled in each pot. The treatments requiring the application of composted pressmud received its requisite amount through proper mixing with the soil before filling it in the pots.

Harvesting of plants and recording of growth traits

The experiment was terminated by harvesting the maize plants after 10 weeks. The harvested plants were properly processed in the laboratory to record their significant growth traits and biomass production. The leaf area of plants was estimated nondestructively by measuring the maximum leaf length (from ligule to tip) and three width measurements (upper, mid, lower blade). The average width was multiplied by leaf length and a correction factor of 0.75 - within the range (0.65 - 0.77) established for maize using the length × width method (van Arkel, 1978).

Plant analysis

Plant nutrient (nitrogen, phosphorus and potassium) content was determined according to standard methods (Ryan *et al.*, 2001; Zia-ul-hassan *et al.*, 2014). The nutrient accumulation was determined on whole-plant concentrations basis.

Statistical analysis

The statistical analyses were performed through Statistix ver. 8.1. Tukey's honestly significant difference (HSD) test was applied to separate treatment means alpha 0.05. Assumptions of ANOVA (normality and homogeneity of variances) were considered and reasonably met, so no data transformation was required.

Figure 1. Fabrication of piles, preparation of compost, recording initial temperature and covering of piles at Asim Agriculture Farm, Tando Soomro.

RESULTS

Shoot dry biomass (g plant^{-1})

The p-values from analysis of variance for shoot dry biomass of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction ($F \times C$) was also highly significant ($p < 0.01$). Both the sources of variance influenced shoot dry biomass of maize in an interactive manner (Table 1).

Table 1. P-values from analysis of variance of various parameters of maize in relation to integrated use of composted pressmud and chemical fertilizers

Parameter	Fertilizer (F)	Compost (C)	F × C
Shoot dry biomass	0.0000	0.0000	0.0023
Root dry biomass	0.0000	0.0000	0.0012
Leaf dry biomass	0.0000	0.0000	0.0158
Total dry biomass	0.0000	0.0000	0.0021
Root: shoot ratio	0.9763	0.3216	0.8676
Leaf area	0.0000	0.0000	0.0007
Nitrogen accumulation	0.0000	0.0000	0.0000
Phosphorus accumulation	0.0000	0.0000	0.0025
Potassium accumulation	0.0000	0.0000	0.0001

The data in Table 2 regarding shoot dry biomass of maize reveal that the maximum shoot dry biomass of maize was obtained where recommended fertilizer was applied along with 10 or 20 t ha^{-1} composted pressmud. It was followed by the shoot dry biomass produced by the treatments where recommended fertilizer was applied or where 75% of the recommended fertilizer was applied along with 20 t ha^{-1} composted pressmud. The minimum shoot dry matter was obtained where no fertilizer or composted pressmud was applied, or where the maize plants received 10 t ha^{-1} composted pressmud without any chemical fertilizers.

Root dry biomass (g plant^{-1})

The analysis of variance (p-values) are presented for root dry biomass of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.01$). These data reflected that both the sources of variance influenced root dry biomass of maize in an interactive manner (Table 1).

The data in Table 3 in relation to root dry biomass of maize depict that the maximum root dry biomass of maize was obtained where 50% or 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the root dry biomass produced by the treatments where recommended fertilizer was applied either in single or in integration with 10 ha^{-1} composted pressmud. The minimum root dry biomass was obtained where no fertilizer or composted pressmud was applied, or where the maize plants received 10 t ha^{-1} composted pressmud without any chemical fertilizers.

Table 2. Shoot dry biomass production (g plant^{-1}) of maize in relation to integrated use of composted pressmud and chemical fertilizers

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	3.7g	4.2fg	5.2e	4.4
40-20-20	5.0ef	5.2e	7.3bc	5.9
80-40-40	6.3d	6.6cd	8.2ab	7.0
160-80-80	7.7ab	8.3a	8.7a	8.2
Compost means	5.7	6.1	7.4	
	Fertilizer (F)	Compost (C)	F × C	
F-value	250.57**	92.14**	5.00**	
$HSD_{0.05}$	0.4118	0.3226	0.9338	
**: significant at alpha 0.01.				

Table 3. Root dry biomass production (g plant^{-1}) of maize in relation to integrated use of composted pressmud and chemical fertilizers

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	2.5g	2.8fg	3.4e	2.9
40-20-20	3.4ef	3.5e	4.9bc	3.9
80-40-40	4.2d	4.4cd	5.5a	4.7
160-80-80	5.2ab	5.5ab	5.8a	5.5
Compost means	3.8	4.0	4.9	
	Fertilizer (F)	Compost (C)	F × C	
F-value	261.40**	94.54**	5.56**	
$HSD_{0.05}$	0.2681	0.2101	0.6081	
**: significant at alpha 0.01.				

Table 4. Leaf dry biomass production (g plant^{-1}) of maize in relation to integrated use of composted pressmud and chemical fertilizers

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	3.1g	3.6fg	4.4ef	3.7
40-20-20	4.4ef	4.5e	6.3bc	5.1
80-40-40	5.3de	5.6cd	6.9ab	5.9
160-80-80	6.3bc	7.1ab	7.3a	6.9
Compost means	4.8	5.2	6.2	
	Fertilizer (F)	Compost (C)	F × C	
F-value	185.10**	78.71**	3.40*	
$HSD_{0.05}$	0.3901	0.3056	0.8846	
* and, **: significant at alpha 0.05 and 0.01, respectively.				

Table 5. Total dry biomass (g plant^{-1}) of maize in relation to integrated use of composted pressmud and chemical fertilizers.

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	9.2h	10.6gh	13.1f	11.0
40-20-20	12.8fg	13.2f	18.5cd	14.8
80-40-40	15.8e	16.6de	20.7abc	17.7
160-80-80	19.2bc	20.9ab	21.8a	20.6
Compost means	14.3	15.3	18.5	
	Fertilizer (F)	Compost (C)	F × C	
F-value	259.65**	99.61**	5.05**	
$HSD_{0.05}$	1.0026	0.7856	2.2737	
**: significant at alpha 0.01, respectively.				

Leaf dry biomass (g plant^{-1})

Table 1 presents p-values from analysis of variance for leaf dry biomass of maize in relation to the integrated use of composted pressmud and chemical fertilizers. Both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.05$). These data reflected that both the sources of variance influenced leaf dry biomass of maize in an interactive manner (Table 1).

The data in Table 4 regarding leaf dry biomass of maize highlights that the maximum leaf dry biomass of maize was obtained where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the leaf dry biomass produced by the treatments where 50% or 100% of the recommended chemical fertilizer was applied with 20 t and 10 ha^{-1} composted pressmud, respectively. The minimum leaf dry biomass was obtained where no fertilizer or composted pressmud was applied, or where the maize plants received 10 t ha^{-1} composted pressmud without any chemical fertilizers.

Total dry biomass (g plant^{-1})

Table 1 reveals the p-values from analysis of variance for total dry biomass of maize in relation to the integrated use of composted pressmud and chemical fertilizers. It is clear that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.01$). These data reflected that both the sources of variance influenced total dry biomass of maize in an interactive manner (Table 1). The data in Table 5 about total dry biomass of maize illustrated that the maximum total dry biomass of maize was obtained where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the total dry biomass obtained where recommended chemical fertilizer was applied with 10 ha^{-1} composted pressmud. The minimum total dry biomass was obtained where no fertilizer or composted pressmud was applied.

Table 6. Root: shoot ratio of maize in relation to integrated use of composted pressmud and chemical fertilizers.

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	0.682	0.666	0.661	0.669
40-20-20	0.669	0.666	0.668	0.668
80-40-40	0.672	0.666	0.675	0.671
160-80-80	0.673	0.660	0.665	0.666
Compost means	0.674	0.664	0.667	
	Fertilizer (F)	Compost (C)	F × C	
F-value	0.07 NS	1.19 NS	0.41 NS	
$HSD_{0.05}$	-	-	-	
NS: Non-significant.				

Table 7. Leaf area (cm^2 $plant^{-1}$) of maize in relation to integrated use of composted pressmud and chemical fertilizers.

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	149f	165f	198e	171
40-20-20	199e	202e	287c	229
80-40-40	246d	251d	315abc	270
160-80-80	300bc	320ab	339a	319
Compost means	223	234	285	
	Fertilizer (F)	Compost (C)	F × C	
F-value	305.46**	109.48**	6.14**	
$HSD_{0.05}$	14.180	11.111	32.158	
**: significant at alpha 0.01.				

Root to shoot ratio

The analysis of variance (p-values) for root to shoot ratio of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were non-significant ($p > 0.05$). Likewise, their interaction (F × C) was also non-significant ($p > 0.05$).

These data reflected that both the sources of variance and their interaction did not influence root: shoot ratio of maize at all (Table 1). The data in Table 6 in relation to root to shoot ratio of maize depicts that the root to shoot ratio did not differ significantly as a result of various chemical fertilizer treatments or consequent to the application of composted pressmud at different rates.

Leaf area (cm^2 $plant^{-1}$)

The data regarding p-values from analysis of variance for leaf area of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.001$). These data reflected that both the sources of variance influenced leaf area of maize in an interactive manner (Table 1).

The data in Table 7 about leaf area of maize highlight that the maximum leaf area of maize was obtained where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the leaf area recorded where recommended chemical fertilizer was applied with 10 ha^{-1} composted pressmud. The minimum leaf area was obtained where no fertilizer was applied or where or composted pressmud was applied at 10 t ha^{-1}.

Table 8. Nitrogen accumulation (%) of maize in relation to integrated use of composted pressmud and chemical fertilizers.

Fertilizer application (NPK kg ha-1)	Composted pressmud application (t ha-1)			Fertilizer means
	00	10	20	
00-00-00	2.27g	2.33fg	2.30fg	2.3
40-20-20	2.47fg	2.53fg	2.93de	2.6
80-40-40	2.67ef	3.40bc	3.70b	3.3
160-80-80	3.20cd	3.70b	4.30a	3.7
Compost means	2.7	3.0	3.3	
	Fertilizer (F)	Compost (C)	F × C	
F-value	236.51**	84.17**	14.05**	
HSD0.05	0.1628	0.1275	0.3691	
**: significant at alpha 0.01.				

Table 9. Phosphorus accumulation (%) of maize in relation to integrated use of different treatments.

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	0.44d	0.47cd	0.54c	0.5
40-20-20	0.50cd	0.54c	0.67ab	0.6
80-40-40	0.54c	0.64ab	0.68ab	0.6
160-80-80	0.63ab	0.62b	0.69a	0.6
Compost means	0.5	0.6	0.6	
	Fertilizer (F)	Compost (C)	F × C	
F-value	85.65**	77.21**	4.92**	
$HSD_{0.05}$	0.0310	0.0243	0.0703	
**: significant at alpha 0.01.				

Nitrogen accumulation (%)

The analysis of variance for nitrogen accumulation of maize, as highlighted through p-values, in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.0001$). These data reflected that both the sources of variance influenced nitrogen accumulation of maize in an interactive manner (Table 1). The data in Table 8 in relation to nitrogen accumulation of maize highlight that the maximum nitrogen accumulation by maize was recorded where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the nitrogen accumulation observed in case of treatments where 50% or 100% of the recommended chemical fertilizer was applied with 20 t and 10 ha^{-1} composted pressmud, respectively. The minimum nitrogen accumulation was noted where no fertilizer or composted pressmud was applied.

Phosphorus accumulation (%)

Table 1 presents the p-values from analysis of variance for phosphorus accumulation of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant ($p < 0.0001$) while their interaction (F × C) was also highly significant ($p < 0.01$). These data reflected that both the sources of variance influenced phosphorus accumulation of maize in an interactive manner (Table 1). The data in Table 9 about phosphorus accumulation of maize indicate that the maximum phosphorus accumulation by maize was recorded where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the phosphorus accumulation observed in case of treatments where 50% of the recommended chemical fertilizer was applied with 10 t or 20 ha^{-1} composted pressmud, or where 25% of the recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. The minimum phosphorus accumulation was noted where no fertilizer or composted pressmud was applied.

Table 10. Potassium accumulation (%) of maize in relation to integrated use of composted pressmud and fertilizers.

Fertilizer application (NPK kg ha^{-1})	Composted pressmud application (t ha^{-1})			Fertilizer means
	00	10	20	
00-00-00	2.74e	2.89e	3.80c	3.1
40-20-20	3.14de	3.61cd	4.33b	3.7
80-40-40	3.45cd	4.55ab	4.68ab	4.2
160-80-80	3.59cd	4.81ab	4.99a	4.5
Compost means	3.2	4.0	4.4	

	Fertilizer (F)	Compost (C)	F × C
F-value	111.74**	162.40**	7.76**
$HSD_{0.05}$	0.2183	0.1710	0.4950

**: significant at alpha 0.01.

Potassium accumulation (%)

The p-values from analysis of variance for potassium accumulation of maize in relation to the integrated use of composted pressmud and chemical fertilizers (Table 1) revealed that both the main sources of variance, viz. chemical fertilizer (F) and composted pressmud (C) were highly significant (p <0.0001) while their interaction (F × C) was also highly significant (p <0.001). These data reflected that both the sources of variance influenced potassium accumulation of maize in an interactive manner (Table 1). The data in Table 10 about potassium accumulation of maize highlights that the maximum phosphorus accumulation by maize was recorded where 100% recommended chemical fertilizer was applied along with 20 t ha^{-1} composted pressmud. It was followed by the phosphorus accumulation observed in case of treatments where 100% or 50% of the recommended chemical fertilizer was applied with 10 t ha^{-1} composted pressmud or where 50% of the recommended chemical fertilizer was applied with 20 t ha^{-1} composted pressmud.

The minimum phosphorus accumulation was noted in the case of three different treatments, i.e., where no chemical fertilizer or composted pressmud was applied, where only 25% of the recommended chemical fertilizer was applied without any composted pressmud and where 10 t ha^{-1} composted pressmud was applied without any chemical fertilizer.

DISCUSSION

Pressmud is a well-known organic by-product of sugarcane processing, which is considered as one of the potential organic amendments in improving soil quality indices, nutrient availability, plant growth traits and crop yield (Sarangi *et al.*, 2008; Poria *et al.*, 2022). Several research studies reported the significant effects of organic amendments, especially composted pressmud on soil physical, chemical, and biological properties and improving soil organic carbon, soil texture, and the availability of macro- and micronutrients (Kumar *et al.*, 2017; Naeem *et al.*, 2022; Arshad *et al.*, 2024). Organic amendments are considered as a reliable source for the reclamation and restoration of poorly-fertile degraded soils (Shehzad *et al.*, 2023) and improving stress tolerance in maize (Iqbal *et al.*, 2023).

Pressmud application, alone or in integration with the chemical fertilizers, other organic amendments, or microbial inoculants, improves the growth, biomass, grain yield, and nutrient uptake of maize (Bashir *et al.*, 2021; Budiyanto, 2021; Naeem *et al.*, 2022). The results of our study mostly endorse the findings of early workers, as described above. We found that the chemical fertilizer treatments and composted pressmud treatments were superior to their respective controls for all the plant traits of maize, except root: shoot ratio. Higher doses of chemical fertilizer or composted pressmud were superior against their lower doses. These results are in consistence with many other early studies emphasizing the benefits of using various organic amendments along with chemical fertilizers for sustainable low-input crop production. Haq *et al.* (2001) conducted an experiment to test the efficacy of various organic amendments in increasing paddy yield, viz. control, 100% gypsum requirement, 20 t ha^{-1} FYM, 2.5 t ha^{-1} pressmud, in addition to different combinations of gypsum, FYM, and pressmud. Although, all the treatments significantly enhanced paddy yield over control, highest increase (94%) was noted when gypsum, pressmud and FYM was used in integration, followed by the application of pressmud alone (60%) and its combination with FYM (57%).

Later on in an elegant study, Aruna *et al.* (2002) combined various composted organic materials with 50% and 100% NPK fertilizer. The result revealed that dry matter yield was highest (89.4 g $plant^{-1}$) in the treatment with yeast sludge mixed with pressmud combined 100% NPK. The incorporation with different composts resulted in slight decrease in pH, electrical conductivity and organic carbon while significantly increased among different treatment (ranged 0.41 to

0.74%) highest available N (166.0 kg ha^{-1}) in treatment of yeast sludge mixed with pressmud and combined with 100% NPK. Unlike other findings, Memon (2005) reported that applying 5.0 t ha^{-1} pressmud decreased maize growth and dry matter. However, maize yield increased slightly when pressmud was applied at 10 t ha^{-1}. Nonetheless, further increase in application rate from 15 to 25 t ha^{-1} caused a drastic decline in maize dry biomass.

In another experiment, Mirani (2005) planted maize using composted banana waste, farmyard manure, and pressmud. Fertilizer nitrogen offered highest plant height, dry matter, and NPK content. However, using raw banana waste, FYM, and PM reduced maize growth and dry matter. While both the raw and composted forms of organic amendments improved various maize traits as against control treatment, maize responded to chemical fertilizer application more. The pressmud appeared to be the most effective organic treatment. Muhammad and Khattak (2009) conducted a pot study to evaluate the effects of pressmud application (0, 5, 10, and 20 t ha^{-1}) on maize. They found that increasing pressmud up to 20 t ha^{-1}) consistently enhanced maize plant height and biomass, especially in saline-sodic soils. They advocated that the even higher doses of pressmud could further enhance maize yields depending on soil and water quality.

Aziz *et al.* (2010) evaluated the effect of various organic amendments, viz. farmyard manure, poultry manure and pressmud applied at 10 t ha^{-1}, on soil properties and maize growth. It was noted that all the organic amendments enhanced soil organic matter content and nutrient (P and K) availability, and subsequent nutrient uptake by maize plants, in addition to increasing the plant height, leaf area, and shoot and root biomass. Better growth performance of maize was correlated with the enhanced nutrient availability. Among the organic amendments, poultry manure offered the highest plant P, while farmyard manure registered the highest K concentration. The improved N and K uptake with pressmud application may be linked to its organic matter content, which enhances soil microbial activity and cation exchange capacity, thereby increasing nutrient mineralization and availability to plants (Ashraf *et al.*, 2021).

Better N and K uptake with pressmud may be due to more active soil microbes and improved nutrient holding capacity, which make nutrients easier for plants to use. Sajid *et al.* (2024) showed that adding *Bacillus* to pressmud compost increased nitrogen and phosphorus content. Interestingly, even though composted pressmud and fertilizers boosted total biomass, the root-to-shoot ratio remained steady. This aligns with recent meta-analysis results (Lopez *et al.*, 2023) showing that with adequate nutrients, plants tend to grow roots and shoots in proportion, so the ratio doesn't change. These findings not only compliment the results obtained in this study but are also in-line with the results highlighted in some recent studies that are presented at the start of this section. Hence, in the light of these results the pressmud appeared to be a potential source of organic amendment which can not only supplement the chemical fertilizers to reduce their input cost but also offers a variety of other benefits to enhance the sustainability of agricultural systems. Nonetheless, since this study was conducted only for 10 weeks, the results mainly reflect vegetative growth, and any long-term effects on yield should be interpreted with care.

In addition, as this was a pot study, the restricted soil volume may have limited root growth compared to field conditions, and this should be kept in mind when extending the findings. Overall, recycling pressmud into compost not only improves soil fertility and crop nutrition but also supports sustainable farming practices by turning a sugar industry by-product into a useful resource, consistent with circular economy and waste management goals (Mohamad *et al.*, 2024).

CONCLUSION

We conclude that the integrated use of recommended chemical fertilizers (160-80-80 kg NPK ha^{-1}) along with 20 t ha^{-1} composted pressmud can potentially improve the growth, biomass production, and nutrient (nitrogen and potassium) content of maize. At a larger scale, using composted pressmud could reduce reliance on chemical fertilizers, lower input costs, and recycle an industrial by-product in an environmentally friendly way.

AUTHOR CONTRIBUTIONS

Zia-ul-hassan and Ghulam Murtaza Jamro conceived the idea, supervised research work, technically assisted in biocompost formulation and edited all drafts of manuscript; Kazim Raza Suhag conducted pot study, collected data, prepared biocompost, and wrote first draft of the manuscript; Naheed Akhter Talpur supervised laboratory analyses, processed data and performed statistical analysis; Hassan Shah Rashdi helped during pot study; Inzamam Ali Jamali reviewed literature and helped in writing introduction and discussion sections; Fozia Naz Memon and Inzamam-ul-Haque Khanzada performed soil and plant analyses in the laboratory. All authors checked and endorsed final draft of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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