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REVITALIZING PEARL MILLET [PENNISETUM GLAUCUM (L.) R. BR.] PRODUCTIVITY THROUGH BIOGAS SLURRY AND IRON ENRICHMENT: IMPACTS ON SOIL HEALTH AND NUTRIENT DYNAMICS

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ABSTRACT
Pearl millet (Pennisetum glaucum L.) is a nutritionally rich cereal crop of global significance, particularly in semi-arid regions of South Asia and sub-Saharan Africa. The growing reliance on chemical fertilizers has increasingly depleted soil organic matter and disrupted micronutrient equilibria, necessitating the evaluation of eco-friendly soil amendments. A field experiment was carried out during the kharif season of 2022–23 at the Agronomy Farm, Shri Karan Narendra College of Agriculture, Jobner, Rajasthan, India, to assess the influence of biogas slurry and iron sulphate on post-harvest soil physicochemical properties, biological activity, and total nutrient uptake under pearl millet cultivation. The experiment was laid out in a Factorial Randomized Block Design (FRBD) comprising four levels of biogas slurry (0, 2.5, 5.0, and 7.5 t ha-1) and five levels of iron sulphate (0, 7.5, 7.5 + 0.5% foliar spray, 15.0, and 22.5 kg ha-1), yielding 20 treatment combinations replicated thrice. Application of biogas slurry at 7.5 t ha-1 produced the highest post-harvest values of available nitrogen (N: 156.68 kg ha-1), phosphorus (P_2O_5: 23.45 kg ha-1), potassium (K_2O: 232.35 kg ha-1), sulphur (8.79 ppm), organic carbon (0.278%), dehydrogenase enzyme activity (23.75 µg TPF g-1 soil 24h-1), and microbial biomass carbon (145.14 µg g-1 soil). Total nutrient uptake was also maximized under this treatment. Iron sulphate applied at 22.5 kg ha-1 significantly enhanced the uptake of N (88.04 kg ha-1), K (91.41 kg ha-1), S (32.32 kg ha-1), Ca (25.47 kg ha-1), Mg (9.63 kg ha-1), Fe (643.91 g ha-1), and Zn (227.86 g ha-1). The integrated use of biogas slurry and iron sulphate presents a promising, sustainable agronomic strategy for improving soil fertility and nutrient use efficiency in pearl millet-based cropping systems.

KEYWORDS: biogas slurry, dehydrogenase activity, iron sulphate, microbial biomass carbon, nutrient uptake, pearl millet

INTRODUCTION

Soil has a key function in supporting life on the planet. Nearly all of the food, consumed by people, save for what is obtained from marine habitats is cultivated on the soils of earth provides a medium to attenuate pollutants, surplus water, groundwater recharge, nitrogen cycling and home for microbes and biota. Soil is a vital component of practically every ecosystem. In cultivated areas, soil quality plays a key role in crop output since soil nutrients and soil physical qualities can directly affect yields. In terms of area cultivated to the crops, pearl millet (Pennisetum glaucum L.) ranks sixth behind rice, wheat, maize, barley, and sorghum. In semi-arid areas of Africa and the Indian subcontinent, it is a crucial crop. utilized mostly for food. Additionally, it is grown as a forage crop in South America, Australia, the United States and Southern Africa. Beyond its resilience, it is nutritionally rich, earning the title of a "nutri-cereal." It is packed with proteins, dietary fiber, essential minerals, healthy fats, and antioxidants. Crop wastes from pearl millet are used as fodder in addition to providing a grain and forage source. Especially in areas of dry terrain, the pearl millet crop is very adaptive to regional conditions. It is a hardy crop that may be cultivated on soils are unsuitable for crops like maize and sorghum in very hot, dry conditions. In comparison to sorghum and maize, pearl millet is reported to be more effective at exploiting soil moisture and has a superior level of heat tolerance. Biogas slurry can offer the macro and micronutrients needed for plant growth, while iron sulphate can repair any iron shortages and boost physiological processes in the plant. Together, these inputs can improve the physiochemical qualities of soil, making it more fertile and productive for pearl millet farming.
Intensive farming and usage of chemical fertilizers have generated an imbalance in numerous components of soil quality. India ranked 97 among 118 nations (with widespread hunger levels) on the Global Hunger Index basis in 2016, mostly due to micronutrient-induced deficiencies (1). A manure containing high NPK concentration may be advantageous in an intensive agriculture system. Biogas slurry is a byproduct of anaerobic decomposition of bovine dung or agriculture waste coming out from the outlet of biogas plant comprising roughly 93% water and 7% of dry stuff. Out of these 7 % 4.5% organic and 2.5 % inorganic stuff (2). It contains about 1.5% N,1% P2O5 and 1.5 % K2O along with minerals. It is a rich source of plant nutrients and can increase the properties of the soil (3). It has been extensively documented that production of the crops will diminish if solely inorganic fertilizers are continually applied to the soil without including organic manure. Comparing biogas slurry to FYM, it has been demonstrated to be higher grade organic manure; digested sludge often includes more nutrients. However, nutrients in FYM, notably nitrogen, are lost through leaching from rain and

volatilization when exposed to heat from the sun. Biogas slurry can be utilized as organic fertilizer for farming since it has low molecular weight bioactive compounds (hormones, humic acids and vitamins etc.), plentiful minerals and organic nitrogen (mainly amino acids). Essential micronutrients, including zinc, boron, calcium, copper, iron, magnesium, sulphur and secondary minerals are also found in trace amounts in the digested biogas slurry. Additionally, applying the slurry minimizes soil illness and enhances crop yields. It minimizes the requirement for mineral fertilizer.

Biogas slurry offers both macro and micronutrients essential for plant growth, while iron sulphate addresses iron deficiencies and enhances plant physiological functions. The appropriate use of biogas slurry as fertilizer should be a significant component of the spread and uptake of biogas plants since some farmers cannot afford to purchase chemical fertilizers. When used together, these inputs can enhance soil properties—both physically and chemically—leading to improved soil fertility and greater suitability for cultivating nutrient-rich pearl millet. Keeping these points under consideration, a field experiment was conducted to study the impact of biogas slurry and iron sulphate on soil properties and nutrients uptake under pearl millet cultivation.

MATERIALS AND METHODS

The experiment was conducted at agronomy farm, S.K.N. College of Agriculture, Jobner Rajasthan, during kharif season of 2022. Geographically, Jobner is situated 45 km west of Jaipur at 26o06′ North latitude and 75o28′ East longitude at an altitude of 427 meter above mean sea level (MSL). This region falls under agro-climatic zone III A (Semi-Arid Eastern Plain) of Rajasthan. The maximum and minimum temperatures during the experiment crop season ranged between 30.2 oC to 35.2 oC and 16.8 oC to 23 oC, respectively. A total of 311.7 mm rainfall was recorded during the cropping season. The relative humidity fluctuated between 42% to 70%, while the average sunshine hours ranged between 2.9 to 9.1 hrs day-1. The experiment consisting of four levels of biogas slurry (control, 2.5, 5, 7.5 ton ha-1 biogas slurry) and four treatments of iron sulphate (Control, 7.5 kg ha-1, 7.5 kg ha-1 + 0.5 % foliar spray, 15 kg ha-1 and 22.5 kg ha-1 iron sulphate), total 20 treatment combinations was laid out in factorial randomized block design and replicated thrice. Pearl millet variety RHB-223 was taken as a test crop. 4 kg ha-1 was taken as seed rate and spacing of 45 x 10 cm row to row and plant to plant respectively. The soil of the experimental field was loamy sandy in texture

i.e bulk density (1.53 Mg m-3), alkaline in reaction (pH 8.15), EC (0.36 dSm-1) poor in organic carbon (0.21 %) with low available nitrogen (135.2 kg/ha), medium available phosphorus (21.35 kg/ha), potassium (219 kg/ha), sulphur concentration (8.1 ppm), DTPA- Fe (4.21 ppm), DTPA-Mn (6.62ppm), DTPA-Zn (1.25 ppm), DTPA-Cu (3.8 ppm). Soil pH (4), electrical conductivity (5), bulk density (6), organic carbon (7), available nitrogen (8), phosphorus (9), potassium (10), sulphur (11), calcium & magnesium (5) were estimated accordingly. Soil microbial biomass carbon was estimated using Fumigation extraction (12) whereas dehydrogenase activity was estimated using TTC substrate method (13). Micronutrients like iron, manganese, zinc and copper were all measured using standard method (14). The uptakes of these nutrients were estimated by multiplying concentrations by the yield data for each nutrient. The data recorded in the field experiment for every parameter were subjected to analysis of variance for factorial randomized block design as defined by (15).

Table 1. Effect on pH, EC, OC, N, P2O5, K2O, S, Ca and Mg of soil after harvest

Treatment	Bulk density (mg m^{-3})	pH	EC (dS m^{-1})	OC (%)	N (kg ha^{-1})	P_2O_5 (Kg ha^{-1})	K_2O (Kg ha^{-1})	S (ppm)	Ca (cmol P^+ $100g^{-1}$)	Mg (cmol P^+ $100g^{-1}$)
Biogas slurry										
Control	1.49	8.17	0.42	0.20	134.80	21.50	219.67	8.33	3.599	1.238
Biogas slurry @ 2.5 ton ha^{-1}	1.48	8.00	0.41	0.24	143.72	22.41	225.17	8.56	3.695	1.275
Biogas slurry @ 5.0 ton ha^{-1}	1.48	7.88	0.41	0.27	153.14	23.06	229.04	8.68	3.758	1.297
Biogas slurry @ 7.5 ton ha^{-1}	1.48	7.78	0.40	0.28	156.68	23.45	232.35	8.79	3.804	1.312
SEm+	0.00	0.07	0.003	0.002	1.24	0.29	1.84	0.08	0.034	0.012
CD (P=0.05)	NS	0.20	NS	0.007	3.56	0.82	5.27	0.23	0.097	0.034
Iron sulphate										
Control	1.48	8.06	0.40	0.24	146.13	21.78	224.76	8.38	3.777	1.302
$FeSO_4$ @ 7.5 kg ha^{-1}	1.48	7.95	0.41	0.25	145.18	22.55	226.18	8.56	3.731	1.288
$FeSO_4$ @ 7.5 kg ha^{-1}+ 0.5% $FeSO_4$ foliar spray	1.48	7.95	0.41	0.25	147.81	22.65	226.37	8.57	3.733	1.288

FeSO4 @ 15 kg ha^{-1}	1.49	7.93	0.41	0.25	146.97	22.96	227.35	8.70	3.692	1.271
FeSO4 @ 22.5 kg ha^{-1}	1.49	7.92	0.42	0.25	149.34	23.09	228.13	8.76	3.638	1.252
SEm+	0.01	0.08	0.004	0.0027	1.39	0.32	2.06	0.09	0.038	0.01
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	0.25	NS	NS

Table 2. Effect on Fe, Zn, Mn, Cu, MBC and DHA of soil after harvest

Treatment	**Fe (ppm)**	**Zn (ppm)**	**Mn (ppm)**	**Cu (ppm)**	**MBC (µg g soil^{-1})**	**DHA (µg TPF g soil^{-1} 24 h^{-1})**
Biogas slurry						
Control	4.27	0.45	6.85	1.30	117.41	19.21
Biogas slurry @ 2.5 ton ha^{-1}	4.46	0.47	6.92	1.40	132.09	20.57
Biogas slurry @ 5.0 ton ha^{-1}	4.58	0.49	7.10	1.43	141.66	22.23
Biogas slurry @ 7.5 ton ha^{-1}	4.65	0.50	7.18	1.45	145.14	23.75
SEm+	0.04	0.01	0.07	0.01	1.44	0.21
CD (P=0.05)	0.11	0.04	0.19	0.04	4.14	0.59
Iron sulphate						
Control	4.26	0.49	7.08	1.41	134.16	20.96
FeSO4 @ 7.5 kg ha^{-1}	4.48	0.48	7.03	1.40	133.99	21.47
FeSO4 @ 7.5 kg ha^{-1}+ 0.5% FeSO4 foliar spray	4.48	0.48	7.03	1.40	133.98	21.47
FeSO4 @ 15 kg ha^{-1}	4.57	0.47	6.98	1.39	133.86	21.62
FeSO4 @ 22.5 kg ha^{-1}	4.67	0.46	6.94	1.37	134.40	21.67
SEm+	0.05	0.02	0.07	0.01	1.62	0.23
CD (P=0.05)	0.13	NS	NS	NS	NS	NS

Table 3. Effect on total nutrient uptake (grain + stover) by pearl millet

Treatment	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Ca (kg ha^{-1})	Mg (kg ha^{-1})	S (kg ha^{-1})	Fe (g ha^{-1})	Zn (g ha^{-1})	Mn (g ha^{-1})	Cu (kg ha^{-1})
Biogas slurry										
Control	52.56	10.60	62.31	17.74	6.81	20.31	409.20	156.51	70.20	17.78
Biogas slurry @ 2.5 ton ha^{-1}	71.64	13.42	80.16	22.29	8.58	27.33	539.56	207.27	89.06	21.72
Biogas slurry @ 5.0 ton ha^{-1}	87.95	15.59	92.05	25.22	9.70	32.29	628.03	246.06	101.83	24.70
Biogas slurry @ 7.5 ton ha^{-1}	96.78	16.54	97.58	27.15	10.24	35.70	699.77	268.56	112.73	26.30
SEm+	1.41	0.24	1.55	0.44	0.15	0.55	10.89	3.81	1.72	0.39
CD (P=0.05)	4.03	0.69	4.43	1.27	0.45	1.59	31.17	10.90	4.91	1.13

Iron sulphate										
Control	64.15	13.24	71.62	19.53	7.70	23.45	470.88	204.94	86.71	20.95
FeSO4 @ 7.5 kg ha^{-1}	73.68	14.01	80.43	21.94	8.55	28.18	540.97	216.67	91.59	22.33
FeSO4 @ 7.5 kg ha^{-1}+ 0.5% FeSO4 foliar spray	77.15	14.62	84.20	23.96	9.00	30.20	591.58	223.52	95.18	23.07
FeSO4 @ 15 kg ha^{-1}	83.14	14.23	87.47	24.61	9.31	30.38	598.36	225.01	95.95	23.23
FeSO4 @ 22.5 kg ha^{-1}	88.04	14.09	91.41	25.47	9.62	32.32	643.91	227.86	97.85	23.55
SEm+	1.57	0.27	1.73	0.49	0.17	0.62	12.17	4.26	1.92	0.44
CD (P=0.05)	4.51	0.77	4.96	1.42	0.50	1.77	34.85	12.18	5.49	1.26

RESULTS AND DISCUSSION

Application of 7.5 ton ha-1 biogas slurry showed higher increase in the content of available N (156.68 kg ha-1), P2O5 (23.45 kg ha-1), K2O (232.35 kg ha-1), S (8.79 ppm), Ca (3.804 cmol P+
100g-1), Mg (1.312 cmol P+ 100g-1), Fe (4.65 ppm), Mn (7.18 ppm), Zn (0.50 ppm) and Cu (1.45 ppm) in soil. Moreover, amount of microbial biomass carbon (145.14 µg g soil-1) and dehydrogenase enzyme activity (23.75 µg TPF g soil-1 24 h-1) of soil increased significantly due to addition of biogas slurry in soil. This might be due to the need for higher levels of biogas slurry to optimize nutrient availability and enhance soil health in pearl millet cultivation. However, the observed decrease in soil pH warrants careful monitoring, as excessively low pH levels could lead to nutrient imbalances or potential toxicity over time. Similar findings were reported by (16, 17). Application of FeSO4 @ 22.5 kg ha-1 increased the content of available S (8.76 ppm) and Fe (4.67 ppm) on soil is ascribed to the fact that increased iron availability in soil due to high acidulation impact of iron and the process of its absorption and translocation in plants is increased. Similar findings observed by (18,19).

The addition of biogas slurry might have increased the availability of these nutrients in soil and consequently resulted in the higher uptake of nutrients by plant. It is evident from results that the application of 7.5 ton ha-1 biogas slurry significantly improved the total uptake of N (96.78 kg ha-1), P (16.54 kg ha-1), K (97.58 kg ha-1), S (35.70 kg ha-1), Ca (27.155 kg ha-1), Mg (10.245
kg ha-1), Fe (699.77 kg ha-1), Mn (112.73 kg ha-1), Zn (268.56 kg ha-1) and Cu (26.30 kg ha-1) by pearl millet followed by 5 ton ha-1 biogas slurry. The improvement in properties of soil as observed in the present study coupled with steady and slow release of macro and micro nutrients during microbial decomposition of biogas slurry. Resulting in increased availability of nutrients, in soil which increased absorption of nutrients by plants without any hindrance which resulted might have in improved photosynthesis, production of assimilates and their efficient partitioning into different sinks resulting into higher nutrient content and uptake by seed and stover. Similar results were also reported by (20, 21).

The beneficial role of iron in chlorophyll formation and involved in a large number of metabolically active compounds like cytochromes and other functional metalloproteins. Application of iron sulphate @ 22.5 kg ha-1 significantly increased the total uptake of N (88.04 kg ha-1), K (91.41 kg ha-1), S (32.32 kg ha-1), Ca (25.473 kg ha-1), Mg (9.625 kg ha-1), Fe (643.91 kg ha-1) and Zn (227.86 kg ha-1) whereas, decreased the P content significantly. This may be due to the beneficial role of iron in chlorophyll formation and involved in a large number of metabolically active compounds like cytochromes and other functional metalloproteins. Iron is related to vitamins and certain enzymes help in Cu, Zn, Mn and Mg metabolism. Similar findings were reported by (22, 23).

CONCLUSION

The integrated use of biogas slurry and iron sulphate significantly improved soil characteristics by enhancing microbial activity and increasing organic carbon levels—both essential for sustaining soil health and fertility. These findings highlight the effectiveness of biogas slurry as an eco-friendly soil amendment that boosts nutrient availability while fostering a healthy microbial environment, ultimately improving soil productivity. This approach presents a promising strategy for enhancing soil quality and nutrient uptake in pearl millet cultivation.

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