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RESEARCH ARTICLE

Evaluating the residual effects of distillery wastes on soil resilience in paddy (*Oryza sativa* L.) cultivation

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Abstract

In India, the sugar industry is the second largest agro-based sector, producing significant quantities of by-products such as molasses, press mud etc. Distillery waste, once considered an undesirable by-product of the sugar industry, is now being repurposed to support sustainable agriculture practices. Among these by-products, treated distillery effluent (TDE), a type of wastewater, presents a valuable opportunity for reuse in agricultural. TDE can serve both as a source of irrigation water and as a supplier of essential plant nutrients. The positive impact of organic matter on soil fertility and crop productivity are well documented. Therefore, the application of TDE to soil offers dual benefit: it facilitates the safe disposal of industrial waste while simultaneously enhancing agricultural production. To investigate this potential, a field experiment was conducted to assess the residual effect of TDE and bio-compost on the chemical and biological properties of soil, using paddy (*Oryza sativa* L. variety BPT-5204) as the test crop. The results indicate that the application of TDE at a rate of 1.5 lakh L ha^{-1} (M4), in combination with 100% nitrogen supplied through bio-compost (S4), significantly improved both the soil chemical and biological properties. Therefore, this combination is recommended as a nutrient source for the residual paddy crop.

Keywords: bio-compost; paddy; residual effect; soil fertility; treated distillery effluent

Introduction

The utilization of industrial effluents in agriculture has emerged as a sustainable approach for recycling waste while simultaneously improving soil fertility and crop productivity. Among these effluents, TDE stands out due to its high concentrations of essential macronutrients such as nitrogen (N), phosphorus (P) and potassium (K), as well as variety of micronutrients crucial for plant metabolism, enzyme activation and chlorophyll synthesis (1). The application of TDE has been shown to enhance nutrient bioavailability, thereby supporting efficient nutrient uptake by plants and reducing dependence on synthetic fertilizers. Furthermore, TDE application has demonstrated significant benefits for overall soil health (2). By improving soil water retention, aggregate stability and organic matter content, TDE enhances the physical and chemical properties that are essential for maintaining long-term soil productivity. Additionally, the organic compounds present in TDE can positively influence microbial activity in the soil, which is essential for nutrient cycling and the decomposition of organic matter, thereby fostering a more dynamic and resilient soil ecosystem.

Soil nutrient status is a critical determinant of plant growth, as it governs processes such as root proliferation, photosynthetic efficiency and biomass accumulation. The interaction between nutrient availability and crop demand is particularly important in residual cultivation systems, such as paddy farming, where soil quality tends to diminish over successive growth cycles (3, 4). This study mainly aims to assess the residual impact of varying application rates of TDE on the chemical properties of soil, including pH, organic carbon content and nutrient availability, as well as on biological soil properties such as microbial biomass, enzymatic activity and overall soil health. This study aims to determine the effectiveness of TDE as a soil amendment in enhancing crop productivity and nutrient use efficiency in residual paddy cultivation, while offering insights into sustainable management practices for the utilization of industrial effluents. Ultimately, this research seeks to contribute to the understanding of TDE's role in sustainable agriculture and support the development of evidence-based policies and innovative strategies for the environmentally responsible management of distillery effluents. .

Materials and Methods

A field experiment was conducted using paddy (BPT- 5204) as a test crop. The initial field experiment was conducted in a split plot design with four main plots *viz*., control; TDE @ 0.5 lakh L ha^{-1}; TDE @ 1.0 L litres ha^{-1}; TDE @ 1.5 lakh L ha^{-1}. Different levels of N fertilizers *viz.,* 100 % N as urea, 75 % N as urea, 100 % N as bio-compost, 75 % N as bio-compost, 75 % N as urea and 25 % N as bio-compost, 37.5 % N as urea and 37.5 % N as bio-compost and a control. Each treatment was replicated twice.

A residue crop of paddy (BPT 5204) was subsequently cultivated in the same experimental plots, in which first main field experiment was conducted without disturbing the layout. After giving mammutty digging and levelling, the crop was transplanted during the Thaladi season. In all plots, including the control, a uniform nitrogen application rate of urea at 50 kg N ha^{-1} was applied in three splits (50% basal and 25% each at the tillering stage and panicle initiation stage) besides 50 kg ha^{-1} each of P and K were applied. Data collected on various parameters during the investigation were subjected to statistical analysis by ANOVA and critical differences were calculated at a 5% (p=0.05) probability level. BOD was determined using the dissolved oxygen method and COD was determined by Chromic acid-reflux method (5,6).

During the first field experiment, both bio-compost and TDE were applied and their characteristics are detailed as follows. Bio-compost was produced using press mud, an organic solid by-product from the sugar industry, as the primary raw material. The composting process employed a mechanized open-window system, utilizing TDE and bio-inoculants over a period of 70 to 80 days. After this period, the compost is sun-dried, ground and sieved using a mechanical separator and it is ultimately enriched with bio-fertilizers.

Results

Initial characteristics

The soil of the experimental field is classified as Typic Haplustert, characterized by a neutral pH of 7.58 and low electrical conductivity (EC) of 0.30 dSm^{-1}. The organic carbon content was measured at 4.00 g kg^{-1}, while the available nitrogen content, determined using the alkaline $KMnO_4$ method, was found to be low at 162 kg ha^{-1}. The Olsen-P level was moderate at 16 kg ha^{-1} and the ammonium acetate-extractable potassium (K) level was moderate at 205 kg ha^{-1}. The microbial populations in the soil included a bacterial count of 10.2 x 10^6 CFU g^{-1}, a fungal population of 14 x 10^4 CFU g^{-1} and actinomycetes at 5.1 x 10^3 CFU g^{-1}. Enzyme activities were assessed, revealing urease activity at 4.5 µg NH_4-N g^{-1} dry soil hr^{-1} and dehydrogenase activity at 2.5 µg TPF g^{-1} dry soil hr^{-1}.

The analysis of the bio-compost revealed a neutral pH of 7.56 and a considerable high electrical conductivity (EC) of 6.74 dSm-1. The compost was rich in organic carbon (21.86%), nitrogen (1.58%), phosphorus (2.32%), potassium (4.56%), calcium (2.78%), magnesium (1.62%) and sodium (1.76%). Additionally, it also contained trace amounts of essential micronutrients such as zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn) and exhibited a favourable carbon-to-nitrogen ratio of 20.4. The bio-compost also demonstrated significant enzymatic activity and a robust microbial population. Overall, bio-compost produced derived from distillery effluent, with a neutral pH ranging from 6.5 to 7.5, making it an excellent amendment for enhancing soil health.

The TDE exhibited a dark brown colouration, primarily attributed to the presence of melanoidin and was characterized by an unpleasant odour, likely due to compounds such as skatole, indole and various sulphur compounds. The effluent maintained a neutral pH of 7.71 but was rich in both organic and inorganic salts, resulting in a high electrical conductivity (EC) of 34.6 dS m^{-1}. Chemical analysis of the TDE revealed a total solids content of 51200 mg L^{-1}, with suspended solids measured at 5610 mg L^{-1} and dissolved solids of 45590 mg L^{-1}.

Due to its plant-based origins, the TDE was notably high in organic carbon (28500 mg L^{-1}), potassium (12650 mg L^{-1} as K_2O), calcium (2250 mg L^{-1}) and magnesium (1560 mg L^{-1}), with a significant nitrogen content of 2000 mg L^{-1}. In contrast, phosphorus levels were relatively low at 246 mg L^{-1} and micronutrients were present in the following order: iron (Fe) > manganese (Mn) > zinc (Zn) > copper (Cu). The TDE contained substantial amounts of basic cations, predominantly calcium, followed by magnesium and sodium.

The BOD and COD of the TDE designated for land application were recorded at 7890 mg L^{-1} and 38562 mg L^{-1}, respectively. Additionally, the TDE exhibited appreciable counts of fungi, bacteria and actinomycetes. Importantly, the sodium adsorption ratio, residual sodium carbonate and soluble sodium percentage were below critical limits; however, the potential salinity exceeded critical levels according to irrigation water quality standards.

Residual effect of TDE and bio-compost on soil nitrogen availability

The available nitrogen content in the soil ranged from 132 kg ha^{-1} in treatment M1S1 at the post-harvest stage to 305 kg ha^{-1} in treatment M4S4 at the active tillering stage (Table 1). Overall, the available nitrogen content of the soil showed a marked decline at the post-harvest stage (220 kg ha^{-1}) compared to the panicle initiation stage (227 kg ha^{-1}) and the active tillering stage (231 kg ha^{-1}).

Among the main plot treatments, the application of TDE @ 1.5 lakh L ha^{-1} (M4) during the first crop registered higher available N status of 285 kg ha^{-1} when compared to other treatments *viz*., M3 (257 kg ha^{-1}), M2 (212 kg ha^{-1}) and M1 (150 kg ha^{-1}).

Table 1. Residual effect of TDE and bio-compost on soil available nitrogen (kg ha^{-1}) in paddy

Treatments	Active Tillering Stage (St 1)					Panicle Initiation stage (St 2)					Post-Harvest Stage (St 3)				
	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean
S1	144	201	238	263	**211**	138	195	231	256	**205**	132	186	223	249	**197**
S2	152	215	262	290	**229**	148	211	258	286	**225**	142	204	248	274	**217**
S3	149	213	259	287	**227**	144	209	255	283	**222**	139	199	244	268	**212**
S4	165	229	275	305	**243**	162	226	272	300	**240**	154	222	265	292	**233**
S5	162	225	272	301	**240**	158	220	268	296	**235**	152	213	263	289	**229**
S6	156	219	266	294	**233**	152	215	262	290	**229**	146	209	255	284	**223**
S7	158	221	268	296	**235**	154	216	263	292	**231**	148	211	257	286	**225**
Mean	**155**	**217**	**262**	**291**	**231**	**151**	**213**	**258**	**286**	**227**	**145**	**206**	**250**	**277**	**220**

Treatments	Pooled Mean (Stages)				
	M1	M2	M3	M4	Mean
S1	138	194	230	256	**204**
S2	147	210	256	283	**224**
S3	144	207	252	279	**220**
S4	160	226	270	299	**239**
S5	157	219	267	295	**235**
S6	151	214	261	289	**229**
S7	153	216	262	291	**230**
Mean	**150**	**212**	**257**	**285**	**226**

	Stage	M	S	M at St	S at M	S at St	S at St x M
SEd	2	3	3	4	7	6	11
CD(5%)	4	5	7	NS	NS	NS	NS

Among the subplot treatments, the application of 100% N as bio-compost (S4) to the earlier crop registered higher available nitrogen of 239 kg ha^{-1}, followed by 75% N as bio-compost (S5), which was comparable with 75% N as urea+ 25% N as bio-compost(S6) and 37.5 % N as urea + 37.5 % N as bio-compost (S7), registering higher available nitrogen contents of 235 kg ha^{-1}, 229 kg ha^{-1} and 230 kg ha^{-1} respectively, in the soil over the rest of the treatments. The control recorded the lowest content of 204 kg ha^{-1}. Interaction of main x subplot treatment was found to be non-significant.

Residual effect of TDE and bio-compost on soil phosphorus availability

The available P content in the soil exhibited a progressive decline over the stages of crop growth, decreasing from 18.89 kg ha^{-1} at the tillering stage to 18.21 kg ha^{-1} at the post-harvest stage (Table 2). Among the main plot treatments, the residual effect of applying TDE @ 1.5 lakh L ha^{-1} resulted in the highest phosphorus availability of 21.17 kg ha^{-1}, while the control recorded the lowest of 15.20 kg ha^{-1}.

Within the sub plot treatments, the application of 100% N as bio-compost (S4) at the earlier crop registered higher available phosphorus content of 19.48 kg ha^{-1}, followed by 75% N as bio-compost (S5) and 37.5% N as urea +37.5% N as bio-compost (S7). The application of 75% N as urea +25% N as bio-compost (S6) recorded higher phosphorus content than rest of the treatments but it was on par with S7. The control (S1) recorded the lowest value of 16.89 kg ha^{-1}. The above trend of results was found at all stages of crop growth. Interaction of main plot X subplot treatments was found to be non-significant.

Residual effect of TDE and bio-compost on soil phosphatase activity

The application of TDE and bio-compost to the first crop significantly increased soil phosphatase activity in the subsequent residue crop. Among the main plot treatments, the application of TDE @ 1.5 lakh L ha^{-1} (M4) to the earlier crop recorded the highest phosphatase activity, at 2.41 µg p-nitrophenol g^{-1} dry soil hr^{-1}, followed by M3 (application of

Table 2. Residual effect of TDE and bio-compost on Soil available phosphorus (kg ha^{-1}) in paddy

Treatments	Active Tillering Stage (Stage 1)					Panicle Initiation Stage (Stage 2)					Post-Harvest Stage (Stage 3)				
	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean
S1	14.31	16.38	19.60	19.90	**17.55**	13.78	16.03	19.11	19.41	**17.08**	12.68	15.12	18.02	18.41	**16.06**
S2	15.36	17.36	20.79	21.30	**18.70**	15.48	17.16	20.59	21.20	**18.61**	14.69	16.91	20.38	20.99	**18.24**
S3	15.17	17.16	21.59	21.11	**18.76**	15.42	16.97	20.40	21.00	**18.44**	14.59	16.81	20.22	20.80	**18.10**
S4	16.32	18.53	21.88	22.39	**19.78**	16.08	18.33	21.68	22.20	**19.57**	15.59	17.85	21.19	21.79	**19.10**
S5	15.94	18.24	21.58	22.09	**19.46**	15.75	18.06	21.39	21.99	**19.29**	15.46	17.60	20.97	21.56	**18.90**
S6	15.55	17.55	20.99	21.49	**18.90**	15.63	17.36	20.79	21.40	**18.79**	14.98	17.17	20.52	21.15	**18.45**
S7	15.75	17.85	21.19	21.69	**19.12**	15.50	17.65	20.99	21.49	**18.91**	15.17	17.31	20.69	21.30	**18.62**
Mean	**15.48**	**17.58**	**21.09**	**21.42**	**18.89**	**15.37**	**17.36**	**20.71**	**21.24**	**18.67**	**14.74**	**16.96**	**20.28**	**20.85**	**18.21**

Treatments	Pooled mean (Stages)				
	M1	M2	M3	M4	Mean
S1	13.59	15.84	18.91	19.24	**16.89**
S2	15.18	17.14	20.59	21.16	**18.51**
S3	15.06	16.98	20.73	20.97	**18.43**
S4	16.00	18.23	21.58	22.13	**19.48**
S5	15.71	17.96	21.31	21.88	**19.22**
S6	15.39	17.36	20.77	21.34	**18.71**
S7	15.47	17.60	20.96	21.49	**18.88**
Mean	**15.20**	**17.30**	**20.69**	**21.17**	**18.59**

	Stage	M	S	M at St	S at M	S at St	S at St x M
SEd	0.05	0.06	0.08	0.11	0.17	0.15	0.29
CD(5%)	0.11	0.13	0.17	NS	NS	NS	NS

TDE @ 1.0 lakh L ha^{-1}) recording 2.16 µg p-nitrophenol g^{-1} dry soil hr^{-1}(Table 4). The control (S1) recorded the lowest phosphatase activity of 1.21 µg p-nitrophenol g^{-1} dry soil hr^{-1}.

Among the N fertilizer levels, S4 (100% N as bio-compost) recorded the highest phosphatase activity of 2.00 µg p-nitrophenol g^{-1} dry soil hr^{-1}, which was followed by S5 (1.96 µg p-nitrophenol g^{-1} dry soil hr^{-1}) and S7 (1.93 µg p-nitrophenol g^{-1} dry soil hr^{-1}).

The interaction effect of M × S treatment was found to be significant. Application of TDE @ 1.5 lakh L ha^{-1} along with 100 % N as bio-compost (M4S4) recorded highest phosphatase activity of 2.54 µg p-nitrophenol g^{-1} dry soil hr^{-1} followed by the application of TDE @ 1.5 lakh L ha^{-1} along with 75% N as bio-compost (M4S5) recording higher phosphatase activity of 2.51 µg p-nitrophenol g^{-1} dry soil hr^{-1}.

Residual effect of TDE and bio-compost on soil urease activity

Among the main plot treatments, the application of TDE @ 1.5 lakh L ha^{-1} (M4) to the first crop recorded the highest urease activity, at 7.41 µg NH4-N g^{-1} dry soil hr^{-1}, followed by M3 (application of TDE @ 1.0 lakh L ha^{-1}) which recorded 6.66 µg NH4-N g^{-1} dry soil hr^{-1}. The control recorded the less urease activity of 3.73 µg NH4-N g^{-1} dry soil hr^{-1} (Table 5).

Among the N fertilizer levels, S4 (100 % N as bio-compost) applied to the earlier crop recorded the highest urease activity of 6.15 µg NH4-N g^{-1} dry soil hr^{-1}, which was followed by S5 (6.04 µg NH4-N g^{-1} dry soil hr^{-1}) and S7 (5.95 µg NH4-N g^{-1} dry soil hr^{-1}).

The interaction effect of M X S treatment was found to be significant. Application of TDE @ 1.5 lakh L ha^{-1} along with 100 % N as bio-compost (M4S4) recorded highest urease activity of 7.80 µg NH4-N g^{-1} dry soil hr^{-1} followed by the application of TDE @ 1.5 lakh L ha^{-1} along with 75% N as bio-compost (M4S5) recording higher urease activity of 7.72 µg NH4-N g^{-1} dry soil hr^{-1}.

Residual effect of TDE and bio-compost on Soil dehydrogenase activity

Among the main plot treatments, the application of TDE @ 1.5 lakh L ha^{-1} (M4) during the first crop recorded the highest dehydrogenase activity, at 25.02 µg TPF g^{-1}dry soil hr^{-1}. followed by M3 (application of TDE @ 1.0 lakh L ha^{-1}) recording 22.47 µg TPF g^{-1}dry soil hr^{-1} (Table 6). The control treatment recorded the lowest dehydrogenase activity of 12.58 µg TPF g^{-1} dry soil hr^{-1}.

Among the subplot treatments, S4 (100 % N as bio-compost) applied to the earlier crop recorded the highest dehydrogenase activity of 20.76 µg TPF g^{-1}dry soil hr^{-1}, followed by S5 (20.40 µg TPF g^{-1}dry soil hr^{-1}) and S7 (20.07 µg TPF g^{-1}dry soil hr^{-1}).

The interaction effect of M X S treatment was found to be significant. Application of TDE @ 1.5 lakh L ha^{-1} along with 100 % N as bio-compost (M4S4) recorded the highest dehydrogenase activity of 26.35 µg TPF g^{-1}dry soil hr^{-1} followed by the application of TDE @ 1.5 lakh L ha^{-1} along with 75% N as bio-compost (M4S5) recording higher dehydrogenase activity of 26.07 µg TPF g^{-1}dry soil hr^{-1}.

Table 3. Residual effect of TDE and bio-compost on soil available potassium (kg ha^{-1}) in paddy

Treatments	Active Tillering Stage (Stage 1)					Panicle Initiation Stage (Stage 2)					Post-Harvest Stage (Stage 3)				
	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean	M1	M2	M3	M4	Mean
S1	138	264	347	389	**284**	133	256	338	380	**276**	125	246	328	368	**266**
S2	156	283	376	410	**306**	150	273	367	400	**297**	137	258	353	382	**282**
S3	149	278	372	405	**301**	144	268	362	394	**292**	130	245	339	369	**270**
S4	192	327	406	441	**341**	187	321	400	436	**336**	173	303	386	420	**320**
S5	183	322	401	436	**335**	178	312	391	426	**327**	163	298	376	410	**312**
S6	167	297	386	420	**317**	159	287	376	409	**307**	135	268	356	380	**285**
S7	173	303	394	426	**324**	163	294	385	414	**314**	152	283	367	399	**300**
Mean	**165**	**296**	**383**	**418**	**316**	**159**	**287**	**374**	**408**	**307**	**145**	**271**	**358**	**390**	**291**

Treatments	Pooled mean (Stages)				
	M1	M2	M3	M4	Mean
S1	132	255	337	379	**276**
S2	147	271	365	397	**295**
S3	141	264	357	389	**288**
S4	184	317	397	432	**333**
S5	174	311	389	424	**324**
S6	153	284	373	403	**303**
S7	163	293	382	413	**313**
Mean	**156**	**285**	**371**	**405**	**304**

	Stage	M	S	M at St	S at M	S at St	S at St x M
SEd	3	3	5	6	9	10	16
CD(5%)	6	7	9	NS	NS	NS	NS

Table 4. Residual effect of TDE and bio-compost on soil phosphatase activity

Treatments	Phosphatase activity (µg p-nitrophenol g^{-1} soil hr^{-1})							
	S1	S2	S3	S4	S5	S6	S7	Mean
M1	1.11	1.19	1.16	1.29	1.27	1.22	1.24	**1.21**
M2	1.58	1.74	1.70	1.88	1.81	1.78	1.80	**1.75**
M3	1.93	2.14	2.10	2.29	2.27	2.20	2.22	**2.16**
M4	2.16	2.38	2.33	2.54	2.51	2.46	2.48	**2.41**
Mean	**1.69**	**1.86**	**1.82**	**2.00**	**1.96**	**1.91**	**1.93**	**1.88**

	M	S	M at S	S at M
SEd	0.03	0.01	0.03	0.01
CD(5%)	0.08	0.02	0.08	0.02

Table 5. Residual effect of TDE and bio-compost on soil urease activity

Treatments	Urease activity (µg NH_4-N g^{-1} soil hr^{-1})							
	S1	S2	S3	S4	S5	S6	S7	Mean
M1	3.39	3.66	3.58	3.96	3.91	3.77	3.82	**3.73**
M2	4.86	5.35	5.22	5.80	5.57	5.46	5.52	**5.39**
M3	5.93	6.59	6.48	7.04	6.98	6.77	6.82	**6.66**
M4	6.66	7.33	7.17	7.80	7.72	7.58	7.63	**7.41**
Mean	**5.21**	**5.73**	**5.61**	**6.15**	**6.04**	**5.89**	**5.95**	**5.80**

	M	S	M at S	S at M
SEd	0.08	0.01	0.08	0.01
CD(5%)	0.25	0.02	0.25	0.02

Discussion

Residual impact of distillery wastes on soil nitrogen

The results from the residual crop have shown that N transformation and the plant availability in soil were greatly influenced by the application of TDE and bio-compost during the first crop. Among the various treatments, the application of TDE @ 1.5 lakh L ha^{-1}(M4), recorded the highest available N level of 285 kg ha^{-1}, representing a 47% increase over the control. The higher rate of mineralization and the release of N from soil, fertilizers and TDE likely contributed to the increased availability of N in the soil.

Among the subplot treatments, the application of 100% N as bio-compost (S4) registered the highest available nitrogen content (239 kg ha^{-1}), followed by 75% N as bio-compost (S5) registering 235 kg ha^{-1}. At almost all observation stages, the application of bio-compost was found to be superior to the control. This increase can be ascribed to the sustained mineralization of organic manures, which facilitated a gradual release of nitrogen (7-11).

Higher N availability in the soil could be due to both the direct contribution of nitrogen supply as well as increased microbial activity due to the added organic matter and partial pressure of carbon dioxide in the effluent treated soil (TDE and bio-compost added during the first crop) resulting in an enhanced availability of N in soil (9, 12, 13). A significant and positive correlation observed between the available N and yield ($r = 0.975^{**}$) also supported the above findings.

A notable decline in soil nitrogen availability was observed as the crop progressed, likely due to continuous uptake by the growing plants and nitrogen losses during transformation processes. A slight decrease in available nitrogen was noted at the harvest stage, which could be attributed to volatilization losses. However, the overall reduction during crop growth was primarily due to nitrogen absorption by the crop. .

Residual impact of distillery wastes on soil phosphorus

TDE and bio-compost applied during the first crop remarkably increased the available P in the soil after the residual crop. Among the different treatments, the application of TDE @ 1.5 lakh L ha^{-1}(M4) recorded the highest available P. This increase may be attributed to the TDE applied during the first crop, along with the subsequent dissolution of soil mineral phosphorus, particularly apatite-P. Although TDE is not inherently acidic, its decomposition releases organic acids that can solubilize native soil phosphorus, thereby increasing $NaHCO_3$-extractable phosphorus during the first crop - an effect that persisted into the residual crop (11, 14,15)

Among the sub plot treatments, the application of 100% N as bio-compost (S4) resulted in the highest available phosphorus content. It was followed by 75% N as bio-compost (S5) registering 235 kg ha^{-1}. At nearly all observation stages, the application of bio-compost was superior to the control (16-18). The decomposition of easily degradable organic matter likely reduced the binding energy and P sorption capacity of the soil, favouring higher P availability in the soil (19). A significant and positive correlation between P and yield ($r = 0.970^{**}$) further supported the above findings.

The observed decline in available phosphorus at the harvest stage may be due to crop uptake and various physico-chemical transformations (adsorption, precipitation) into insoluble forms or due to microbial immobilization (20).

Residual impact of distillery wastes on soil potassium

The application of TDE at 1.5 lakh L ha^{-1} (M4) resulted in a significantly higher availability of potassium (K) compared to the other main plot treatments. A notable increase of 405 kg ha^{-1} in available K was observed due to TDE application relative to the control. The enhancement in available K content in the surface soil was sustained even after harvest, indicating that the application of effluent contributed to a continued increase in soil potassium levels (15, 21).

Among the subplot treatments, the application of 100% nitrogen as bio-compost recorded the highest available potassium content at 333 kg ha^{-1}, representing a 17.1% increase over the control. This was followed by 75% nitrogen as bio-compost, which recorded 324 kg ha^{-1} a 14.8% increase over the control. The observed increase may be attributed to

Table 6. Residual effect of TDE and bio-compost on soil dehydrogenase activity

Treatments	Dehydrogenase activity (µg TPF g^{-1} soil hr^{-1})							
	S1	S2	S3	S4	S5	S6	S7	Mean
M1	11.45	12.37	12.10	13.37	13.19	12.71	12.89	**12.58**
M2	16.40	18.04	17.59	19.58	18.79	18.44	18.62	**18.21**
M3	20.02	22.21	21.86	23.74	23.56	22.85	23.03	**22.47**
M4	22.47	24.72	24.18	26.35	26.07	25.58	25.76	**25.02**
Mean	**17.58**	**19.33**	**18.93**	**20.76**	**20.40**	**19.89**	**20.07**	**19.57**

	M	S	M at S	S at M
SEd	0.27	0.01	0.27	0.03
CD(5%)	0.85	0.03	0.86	0.06

the mineralization of potassium and the addition of potassium-rich manures applied during the first crop, which contributed to the release of K into the soil solution (8, 11, 22-26). A significant and positive correlation between available K and yield (r = 0.975**) further corroborates these findings.

The availability of potassium in the soil decreased progressively with crop growth, likely due to its uptake by the growing crop.

Residual impact of distillery wastes on soil enzyme activities

Soil enzyme activity serves as an indirect indicator of microbial activity, which is directly associated with the soil microbial population. In the present study, increased activities of dehydrogenase, urease and phosphatase were observed in response to the application of TDE. The treatment that received TDE at 1.5 lakh litres ha^{-1} along with 100% nitrogen as bio-compost (M4S4) exhibited significantly higher enzyme activities compared to the control.

TDE, being liquid organic manure, contributed to an increase in organic matter and nutrient content in the soil, thereby enhancing microbial biomass. The application of a high dose of TDE in combination with the recommended NPK dose resulted in the highest enzyme activity values. This suggests that integrated application of organic and inorganic nutrient sources creates a nutrient-rich environment conducive to microbial proliferation and enzyme synthesis (27). A positive correlation has been reported between organic residue addition and the activities of dehydrogenase, β-glucosidase, urease and protease in the soil (28). Moreover, increased enzyme activity has also been attributed to the application of distillery effluent (29).

In general, the addition of organic manures enhances microbial activity, which subsequently promotes the synthesis of various soil enzymes. These enzymes play a crucial role in nutrient biotransformation, influencing nutrient availability and crop uptake. The rate of organic phosphorus mineralization is particularly relevant to phosphorus nutrition and phosphatase activity in soil. Thus, elevated enzyme activities observed in the study indicate enhanced mineralization of nitrogen and phosphorus, likely facilitated by the application of spent wash (11).

Conclusion

This study highlights the potential of TDE as a liquid organic manure, demonstrating its capacity to significantly enhance soil organic matter, nutrient content and microbial biomass. The application of higher doses of TDE, in conjunction with the recommended NPK levels, effectively optimized nutrient availability and enhanced enzymatic activity in the soil. The residual effect of TDE and bio-compost applied during the first crop substantially increased soil nutrients availability for the subsequent crop, indicating that the integration of organic and inorganic nutrient sources fosters a nutrient-rich environment conducive to microbial growth and enzyme synthesis.

Therefore, it can be concluded that the application of TDE @ 1.5 lakh L ha^{-1} (M4) during the first crop resulted in the highest availability of soil nutrients and enzymatic activity, significantly outperforming other treatments. Among the fertilizer levels, S4 (100 % N as bio-compost) recorded the highest availability of soil nutrients and enzymatic activity. Regarding the treatment combinations, application of TDE @ 1.5 lakh L per ha along with 100 % N as bio-compost (M4S4) which were applied to the earlier crop recorded the highest availability of soil nutrients and enzymatic activity.

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Authors' contributions

LAD, RP, EK, SKS, RN, MK, SR have participated equally in data collection, analysis, drafting the original manuscript, editing and reviewing.All authors read and approved the final manuscript.

Compliance with ethical standards

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