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THE ROLE OF FERMENTED FARMYARD MANURE IN PROMOTING SOIL HEALTH AND ECONOMIC SUSTAINABILITY IN COTTON FARMING UNDER CHANGING CLIMATE

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ABSTRACT

Climate change, soil degradation, and resource limitations pose significant challenges to cotton productivity and economic sustainability. Developing sustainable and resilient agricultural practices is essential to address these challenges and ensure long-term farm profitability. This study aimed to evaluate the impact of fermenter-applied farmyard manure (FYM) as a regenerative approach to enhance soil health, cotton yield, and economic returns under changing climatic conditions. Farmyard manure was applied through a fermenter at a rate of 2.76 tons acre^{-1}, and its effects were compared with conventional fertilizer treatments. Results demonstrated that fermenter-applied FYM significantly improved soil nutrient status, with nitrogen, phosphorus, potassium, and organic matter levels reaching 7.30 ppm, 8.27 ppm, 178 ppm, and 1.38%, respectively, compared to conventional treatments. Cotton yield was enhanced, achieving the highest seed cotton yield of 881 kg acre^{-1} with reduced irrigation requirements (11 irrigations) under FYM treatments, surpassing conventional fertilizer yields of 742 kg acre^{-1} in 2024. Fiber quality parameters including ginning outturn (37.9%) and staple length (28 mm), were consistently superior under FYM application. Economic analysis revealed that fermenter-applied FYM resulted in the highest net profit of Rs. 122,852 acre^{-1} and a benefit-cost ratio (2.90) compared to Rs. 81,939 acre^{-1} and a benefit-cost ratio of 2.08 with conventional fertilizers in 2024. These findings highlight the potential of fermenter-applied FYM to improve nutrient availability, water-use efficiency, and soil health while enhancing cotton yield and economic profitability. This approach offers a sustainable strategy for regenerative agriculture, promoting climate resilience and long-term economic stability in cotton farming systems.

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INTRODUCTION

Cotton is one of the most economically significant crops worldwide, playing a central role in global agricultural production, trade, and industry. In Pakistan, cotton is a cornerstone of the economy, providing more than 50% of foreign exchange earnings through textile exports (Hussain et al., 2024). The cotton industry has a vast value chain, from cultivation to manufacturing, generating income for millions of smallholder farmers and creating employment opportunities (Abubakar et al., 2023; Kabish et al., 2024). Given its importance, maximizing cotton yields while ensuring the sustainability of production systems has become a crucial focus for researchers, agriculturalists, and policymakers (Mukhtar, 2024). The demand for cotton continues to rise, driven by an ever-expanding population and the increasing need for textile products (Ruteri, 2023). However, this demand has placed significant pressure on the resources required for cotton cultivation, particularly water and soil nutrients. Additionally, climate change is negatively affecting both cotton yields and quality (Ahmad et al., 2023; Hussain et al., 2024). Traditional cotton farming relies on synthetic fertilizers and inputs, which has increased short-term productivity but at the cost of long-term soil health, biodiversity, and environmental sustainability (Hussain et al., 2024; Vitale et al., 2024). Given these challenges, there is a growing emphasis on adopting climate-resilient, sustainable, and regenerative agricultural practices (Hussain et al., 2024). These practices aim to maintain or improve cotton yields while minimizing environmental impacts, and ensuring the sustainability of cotton production in the face of a changing climate (Hussain et al., 2024; Saleem et al., 2024). One such sustainable approach is the use of farmyard manure (FYM) as an organic amendment in cotton cultivation. Farmyard manure possesses essential macronutrients nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients like copper (Cu), zinc (Zn), boron (B), etc. (Jamal et al., 2023; Dhaliwal et al., 2023). When applied properly, FYM can significantly improve soil health by enhancing soil structure, increasing organic matter content, stimulating microbial activity, and improving water-holding capacity (Rastogi et al., 2023; Hussain et al., 2024). The carbon content in manure serves as a vital energy source for native soil microorganisms, promoting an increase in microbial biomass (Xiao et al., 2024; Sharma et al., 2024). Manure enhances the diversity of soil microbial populations, which is crucial for nutrient cycling as it helps convert nutrients into forms that plants can readily absorb (Mahawar et al., 2024; Mastiholi et al., 2024). Additionally, these microbes expedite the decomposition of organic matter and facilitate the mineralization of organic N, P, K, etc. found in manure, transforming them into inorganic forms that are available to plants (Kumar et al., 2024). Previous literature shows that the application of FYM significantly enhanced soil properties, and reduced soil bulk density (Thakur et al., 2023). Additionally, soil moisture content can be improved substantially by the application of FYM. Similarly, the use of FYM also positively influences soil pH, organic carbon content, available P, N, K, S, and other micronutrients (Alemu and Lishan, 2024).

However, traditional methods of FYM application often fall short in terms of nutrient efficiency. The slow decomposition and release of nutrients from FYM can lead to a delayed supply of nutrients to crops (Tania et al., 2024), limiting their immediate uptake and utilization. This can result in suboptimal crop growth and yield. Additionally, the variability in nutrient content and quality of traditional FYM can make it challenging for farmers to accurately predict and manage nutrient availability. To overcome these limitations, innovative techniques and technologies can be employed to optimize the use of FYM. For instance, composting and the application of FYM through fertigation. By addressing these challenges and adopting sustainable practices, farmers can maximize the benefits of FYM and promote healthy, productive agroecosystems. The application of FYM through a fermenter is a novel and effective approach. The use of a fermenter for the decomposition of FYM has gained attention as a promising solution to enhance nutrient efficiency in cotton farming under a changing climate. Fermenter accelerates the breakdown of FYM, producing a more homogenous and nutrient-rich end product that is readily available for crop uptake. Keeping this in mind, a two-year field study was conducted to assess the impact of fermented FYM on soil health, cotton yield, and economic profitability.

METHODOLOGY

This study was carried out at the REEDS research area in Rahim Yar Khan during 2023 and 2024. The treatments of the trial were the application of conventional fertilizers such as urea (N 115 kg/acre), phosphorus (P_2O_5 45 kg/acre), and potash (K_2O 38 kg/acre), the conventional practice of farm yard manure (FYM) application at the rate of 5 tones/acre and FYM through fermenter (2.56 tons/acre). All of the P and K were applied at sowing. In the conventional practice of applying FYM, the entire quantity was added right after the wheat crop harvest. It was then incorporated into the soil through cultivation and subsequent soil preparation. The field was cultivated twice using a tractor-driven cultivator, followed by planking. It was then rotavated to create a well-prepared seedbed, and 75 cm-wide beds were formed. For the application of FYM through a fermenter, a fermenter with a capacity of 6000 liters was constructed. Two hand-trolley loads (20 kg each trolley) of FYM were added to the fermenter. To accelerate the fermentation process, 1 kg of chickpea flour and 1 kg of raw sugar (gur) were added to the fermenter. The mixture was left to decompose for 10–12 days, after which the fermented manure was applied to the field through irrigation water. This process was repeated in successive cycles during each irrigation. Throughout the crop season, a total of eight and nine irrigations were applied in 2023 and 2024, respectively. The total quantity of FYM through the fermenter was 360 kg in 2022 and 330 kg in 2023 in a treatment plot of 30 m × 17 m (1/8th of an acre). The cotton variety was Bt-NIAB-878, which was sown on beds having a width of 75 cm. The spacing between plants was 30 cm. The seedbed was prepared after two cultivations, followed by planking, and then beds were made using a planter. The crop was sown manually on April 20, 2023, and April 14, 2024, using 8 kg of seed per acre. Irrigation was provided as per the crop's needs. Weeds were managed manually. All other agronomic practices were the same, except for the treatments mentioned above. After harvesting of wheat crop and before sowing of cotton, soil samples were taken from 0~15 cm and 16~30 cm depth using an auger. These samples were sent to the Soil and Water Testing Laboratory in Rahim Yar Khan for detailed analysis of P, K, organic matter (OM), and pH.

Observations

During the study, data on yield and yield related were taken. Plant height was measured using a measuring tape from the base of the plant to the top of the plant. For this, 10 plants were randomly selected from three sites within each treatment plot, and their heights were measured. Similarly, the number of bolls per plant was counted from the same plants from plant height. The seed cotton yield was recorded upon the completion of all pickings. For cotton quality traits like fiber length, strength, fineness, and uniformity, after picking, cotton samples were sent to the fiber testing laboratory of Central Cotton Research Institute (CCRI), Multan. To determine the ginning outturn (GOT), 250 g samples of seed cotton were collected from each plot. These samples were ginned. Through a ginning machine, lint from the seed cotton was separated. The lint weight was then recorded, and GOT was calculated (Hussain et al., 2024).

$$\text{Ginning out turn (\%)} = \frac{\text{Lint yield}}{\text{Seed cotton yield}} \times 100 \qquad (1)$$

Throughout the growing season, the number of irrigations was documented. To assess soil health, soil samples were collected for analysis of OM, soil carbon, P, K, electrical conductivity (EC), and pH. Soil samples were sent to the Soil and Water Testing Laboratory, Rahim Yar Khan. The crop was irrigated using canal water, with each field plot managed independently to ensure precise monitoring and control of soil moisture levels. A digital soil moisture meter (Misol WH0291, China) was used to accurately measure soil moisture content, with daily readings recorded. This approach allowed for close monitoring and informed irrigation decisions based on maintaining an optimal soil moisture level of 25%. When the average soil moisture content in a plot reached this threshold, irrigation was applied to replenish the water deficit, supporting optimal conditions for cotton growth and development (Hussain et al., 2024).

Economic Analysis

An economic analysis was conducted at the season's end to evaluate the profitability of the different treatment methods used on the cotton crops.

Statistical Analysis

Data analysis was performed using Statistix 8.1 software, applying a Least Significant Difference (LSD) test at a 5% significance level to evaluate treatment differences (Steel, 1997).

RESULTS AND DISCUSSION

The application of farmyard manure significantly influenced the physiochemical properties of the soil across two years (2023 and 2024). Results are summarized in Table 1. In 2023, the soil amended with FYM through a fermenter at 2.76 tons acre^{-1} exhibited significantly higher nitrogen N, P, K, and OM content compared to conventional fertilizers and conventional FYM applications. For instance, nitrogen content increased to 4.50 ppm in FYM-treated soils, whereas conventional fertilizers resulted in only 3.10 ppm. Similarly, potassium and organic matter were significantly enhanced with FYM through the fermenter, reaching 139 ppm and 0.89%, respectively. In 2024, the trend persisted, with FYM through the fermenter resulting in the highest improvements. Nitrogen, phosphorus, and potassium levels peaked at 7.30 ppm, 8.27 ppm, and 178 ppm, respectively, with organic matter increasing to 1.38%. Conventional fertilizers consistently showed the lowest nutrient and organic matter values, while conventional FYM application resulted in intermediate improvements. No significant differences were observed in soil pH or electrical conductivity (EC) across treatments in either year. The improvements with fermenter-applied FYM demonstrate its potential as an efficient soil amendment for enhancing nutrient availability and soil health under sustainable farming systems.

The application of FYM significantly influenced the agronomic traits and productivity of cotton during 2023 and 2024 (Table 2). In 2023, the use of FYM through a fermenter reduced the number of irrigations required to 12, compared to 13 in plots receiving conventional fertilizers. This treatment also resulted in the highest seed cotton yield (824 kg acre^{-1}), which was significantly greater than yields obtained with conventional fertilizers (761 kg acre^{-1}) and conventional FYM application (803 kg acre^{-1}). Although plant height, bolls per plant, and open boll weight showed no significant differences among treatments, the FYM fermenter application consistently resulted in slightly higher values. In 2024, the trend was more pronounced. FYM applied through the fermenter reduced irrigations to 11, achieved the greatest plant height (151 cm), and significantly increased the number of bolls per plant (46) and seed cotton yield (881 kg acre^{-1}). Conventional fertilizer treatments consistently resulted in the lowest performance across all measured parameters.

The quality parameters of cotton, including ginning outturn (GOT), staple length, fiber fineness, fiber uniformity index, and fiber strength, were evaluated under different treatments of FYM during 2023 and 2024 (Table 3). In both years, treatments involving the application of FYM, either conventionally at 5 tons acre^{-1} or through a fermenter at 2.76 tons acre^{-1}, significantly improved GOT and staple length compared to the conventional application of N, P, and K fertilizers. The highest GOT values were observed with FYM through the fermenter (37.8% in 2023 and 37.9% in 2024). Similarly, staple length improved to 28 mm with both FYM treatments, compared to 27 mm in conventional fertilizer plots. No significant differences were observed in fiber fineness, fiber uniformity index, or fiber strength across treatments in either year, indicating that FYM application had no detrimental effects on these parameters.

The economic analysis of cotton production under different FYM treatments showed significant variation in profitability and benefit-cost ratio (BCR) during 2023 and 2024 (Table 4). In 2023, the highest net profit (Rs 93,310 acre^{-1}) was observed in plots treated with FYM through a fermenter at 2.76 tons acre^{-1}, with a yield of 824 kg acre^{-1} and an income of Rs 175,100 acre^{-1}. The BCR for this treatment was 2.14. While conventional FYM application at 5 tons acre^{-1} produced slightly lower net profit (Rs 92,247 acre^{-1}), its BCR was comparable at 2.17. Conversely, conventional N, P, and K applications resulted in the lowest yield (761 kg acre^{-1}) and net profit (Rs 89,822 acre^{-1}), with a BCR of 2.24. In 2024, FYM through the fermenter exhibited the most substantial economic benefits, achieving the highest net profit (Rs 122,852 acre^{-1}) and BCR (2.90), with a yield of 881 kg acre^{-1}. Conventional FYM application also showed improved profitability (Rs 110,100 acre^{-1}) and a favorable BCR (2.76). Plots receiving conventional fertilizers had the lowest profitability metrics, including a net profit of Rs 81,939 acre^{-1} and a BCR of 2.08. These findings underscore the economic advantage of FYM applied through a fermenter in enhancing soil health, cotton productivity, and profitability.

Table 1. Effect of FYM on physiochemical properties of soil.

Treatment	2023						2024					
	Soil pH	EC (mS-cm)	N (ppm)	P (ppm)	K (ppm)	Soil OM (%)	Soil pH	EC (mS-cm)	N (ppm)	P (ppm)	K (ppm)	Soil OM (%)
Conventional fertilizers	7.88	1.90	3.10 b	4.32 b	43 c	0.67 b	7.89	1.91	3.19 c	4.30 c	51 c	0.69
Conventional application of FYM @ 5 tons acre^{-1}	7.91	1.96	4.50 a	5.40 a	131 b	0.89 a	7.94	1.93	6.25 b	7.87 b	147 b	0.95
FYM through fermenter @ 2.76 tons acre^{-1}	7.90	1.93	4.50 a	5.43 a	139 a	0.89 a	7.93	1.94	7.30 a	8.27 a	178 a	1.38
LSD at 5%	NS	NS	0.10	0.13	2.54	0.012	NS	NS	0.26	0.10	3.1	0.12

Table 2. Effect of FYM on number of irrigations, plant height, open boll weight and seed cotton yield..

Treatment	2023					2024				
	No. of irrigations	Plant height (cm)	Bolls per plant	Open boll weight (g)	Seed-cotton yield (kg acre^{-1})	No. of irrigations	Plant height (cm)	Bolls per plant	Open boll weight (g)	Seed-cotton yield (kg acre^{-1})
Conventional fertilizers	13 a	142	40	2.34	761 c	13	139 b	39 c	2.32	742 c
Conventional application of FYM @ 5 tons acre^{-1}	11 c	145	42	2.31	803 b	12	141 b	42 b	2.33	812 b

FYM through fermenter @ 2.76 tons acre^{-1}	12 b	141	43	2.33	824 a	11	151 a	46 a	2.35	881 a
LSD at 5%	0.24	NS	NS	NS	12.41	0.21	5.20	0.23	NS	15.10

Table 3. Effect of FYM on GOT, staple length, fiber fineness and fiber strength.

Treatments	2023					2024				
	GOT (%)	Staple length (mm)	Fiber fineness (µg/inch)	Fiber uniformity index (%)	Fiber strength (tppsi)	GOT (%)	Staple length (mm)	Fiber fineness (µg/inch)	Fiber uniformity index (%)	Fiber strength (tppsi)
Conventional application of N, P & K	37.2 b	27 b	4.2	87	93	37.1 b	27 b	4.2	87	93
Conventional application of FYM @ 5 tons acre^{-1}	37.8 a	28 a	4.2	87	93	37.7 a	28 a	4.2	87	93
FYM through fermenter @ 2.76 tons acre^{-1}	37.8 a	28 a	4.2	87	93	37.9 a	28 a	4.2	87	93
LSD at 5%	0.10	0.10	NS	NS	NS	0.11	0.10	NS	NS	NS

Table 4. Effect of FYM on economic analysis of cotton.

Treatments	2023					2024				
	Yield (kg/acre)	Income (Rs/acre)	Production cost (Rs/acre)	Net profit (Rs/acre)	Benefit cost ratio (BCR)	Yield (kg/acre)	Income (Rs/acre)	Production cost (Rs/acre)	Net profit (Rs/acre)	Benefit cost ratio (BCR)
Conventional application of N, P & K	761	161712	71890	89822	2.24	742	157675	75736	81939	2.08
Conventional application of FYM @ 5 tons acre^{-1}	803	170637	78390	92247	2.17	812	172550	62450	110100	2.76
FYM through fermenter @ 2.76 tons acre^{-1}	824	175100	81790	93310	2.14	881	187212	64360	122852	2.90

Discussion

The findings of this study underscore the significant benefits of FYM application, particularly through fermenter-based treatments, in enhancing soil health, cotton yield, and economic returns. The application of FYM through a fermenter significantly improved key soil properties, including N, P, K, and OM content during 2023 and 2024. The observed increase in N, P, K, and OM content suggests a substantial improvement in soil structure and nutrient retention capacity. Farm Yard Manure significantly enriches soil fertility. It directly contributes N, P, K, and K, essential nutrients for plant growth. Furthermore, FYM increases OM content, leading to improved soil structure, enhanced nutrient availability, and stimulation of beneficial microbial activity (Zheng et al., 2024). These combined effects contribute to healthier plants and ultimately, higher crop yields.

Moreover, the absence of significant differences in soil pH and electrical conductivity (EC) across treatments confirms that FYM application did not adversely affect soil chemical stability, ensuring its long-term suitability as a soil amendment (Jan et al., 2023). Similarly, FYM applied through a fermenter exhibited notable advantages in agronomic performance in plant height, bolls per plant, and final yield, including reductions in irrigation frequency. The application of FYM enhances soil structure, improving water infiltration and retention, while also providing essential nutrients. This improved soil environment stimulates root development, allowing plants to access more water and nutrients, and reducing reliance on irrigation. Additionally, FYM promotes beneficial soil microorganisms, which contribute to nutrient cycling and disease suppression, leading to healthier plants and higher yields (Verma et al., 2023; Jan et al., 2023; Abrol et al., 2024).

The consistent improvements in ginning outturn (GOT) and staple length with FYM treatments further emphasize the role of organic amendments in enhancing cotton fiber quality. The fermenter-applied FYM resulted in the highest GOT values and improved staple length without compromising fiber fineness, uniformity, or strength. This indicates that improving soil structure and nutrient availability due to FYM resulted in an increased boll production and ultimately higher ginning outturn. Moreover, the balanced nutrient supply from FYM supports the development of longer and stronger fibers, resulting in increased staple length, a crucial quality parameter for cotton (Hussain et al., 2023; Ramazanoglu et al., 2024). The economic analysis demonstrated that fermenter-applied FYM provided the highest net profits and benefit-cost ratios (BCR) in both years. The significant increase in BCR observed in 2024 underscores the long-term profitability of this approach, further validating its adoption in sustainable cotton production systems.

CONCLUSIONS

Overall, the results highlight the potential of fermenter-applied FYM as an efficient and sustainable alternative to conventional fertilizers and traditional FYM applications. By improving soil health, reducing irrigation requirements, enhancing cotton productivity, and increasing economic returns, this method aligns with the principles of sustainable agriculture and offers a viable pathway for farmers to adapt to climate challenges while maintaining profitability. Further research is recommended to explore the long-term impacts of this approach on soil health and crop performance across different agro-climatic zones.

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