

IMPLICATIONS OF HERBICIDES AND PLANT NUTRIENTS CONTINUOUS USAGE ON SOIL HEALTH AND RICE YIELD IN ACID SOILS OF ASSAM, INDIA

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Abstract

Appropriate weed and fertilizer management is important for sustaining soil health and enhancing crop productivity to achieve food security. Field experiment was conducted for 14 years at Assam Agricultural University, Jorhat, India, in randomized block design with five treatments. The experiment consisted of application of pre-emergence herbicide Butachlor and post emergence herbicide 2,4-D in summer rice and application of pre-emergence herbicide Butachlor and Pretilachlor and post emergence herbicide 2,4-D in winter rice. Continuous use of herbicides for 14 years significantly reduced the weed density and dry matter accumulation by weeds compared to farmers practice (FP). Application of fertilizers and herbicides produced significantly higher grain yield over FP. It can be concluded that sequential application of butachlor/pretilachlor + 2,4-D at recommended rate along with balanced use of fertilizer either alone or with organic source is required for sustaining soil health and indicated an increase in summer and winter rice yields by 49.92 and 42.80 % over FP.

Introduction

Rice is the principal staple crop of Assam and the wider Northeast Indian region, sustaining food security and rural livelihoods. However, rice productivity remains below its potential, largely due to soil acidity, nutrient imbalance, and severe weed infestation. Recent studies and policy reports emphasize that integrated management of nutrients for achieving sustainable yield improvement under such constraints (Kumar *et al.* 2023). A large proportion of Assam's cultivated land is characterized by acidic soils (pH <5.5), which restrict the availability of phosphorus, calcium, and magnesium while increasing aluminium and iron toxicity. These conditions reduce fertilizer-use efficiency and root development, ultimately limiting yield (Singh *et al.* 2022). Acidic soils in Northeast India are often associated with low organic carbon, poor microbial activity, and nutrient imbalances. Recent research indicates that integrated nutrient management, involving chemical fertilizers, organic manures, and biofertilizers, improves soil biological and chemical properties in acidic environments (Das *et al.* 2021). The use of both inorganic and organic fertilizers can significantly alter soil characteristics, including soil organic carbon content, pH levels, physical properties of the soil, and the availability of nutrients for plant uptake (Xu *et al.* 2020). According to the Food and Agriculture Organization (2022), sustainable intensification of rice systems requires combined management of soil fertility and crop protection. The rice-rice cropping system is a vital agricultural practice in India and makes a significant contribution to the country's food security. Rice-based cropping systems, including continuous rice sequences, are among the predominant cropping patterns practiced across major rice -growing regions of India, helping to sustain high levels of food grain production for the growing population

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(Deep *et al.* 2018). Increased nutrient availability with fertilization has been linked to higher soil organic carbon through greater crop residue inputs and rhizodeposition, and many studies report corresponding increases in microbial activity and soil biochemical indicators under improved crop growth conditions (Jing *et al.* 2025).

Weed infestation further aggravates productivity losses, often causing 30-50% yield reduction under unmanaged conditions (Walia *et al.* 2021). Integrating weed control with nutrient management helps to maintain soil enzymatic activity, organic matter, and nutrient cycling, ensuring long-term sustainability. Although manual weeding remains prevalent in many developing and underdeveloped nations, it is becoming increasingly unsustainable due to its time-consuming nature, high costs, physical demands, and the challenge of worker availability. Consequently, herbicides have emerged as a vital tool for weed management, offering economic, efficient, and timely weed control solutions. The weed flora present in rice ecosystems is diverse and tends to emerge in multiple flushes throughout the growing season, necessitating the sequential application of various herbicides to achieve effective weed control. Herbicide behaviour is strongly influenced by soil pH, organic matter, and nutrient status. In acidic soils, certain herbicides are prone to faster degradation, higher leaching losses, and reduced bioavailability. Verma *et al.* (2020) showed that nutrient-induced changes in soil chemistry can modify herbicide adsorption and persistence. Commonly used herbicides for the selective management of annual weeds in rice from chloro-acetanilide group include Butachlor and Pretilachlor. The application of such herbicides, whether used individually or in rotation, has the potential to modify the weed flora and their prevalence, contribute to the development of herbicide resistance, accumulate residues in the soil, and impact soil microbial and enzyme activities, as well as overall soil quality. Numerous soil enzymes serve as indicators of soil quality due to their sensitivity to ecological stress and land management practices (Hu *et al.* 2026). Existing studies suggest that prolonged use of both suboptimal and super optimal fertilizer, with or without the addition of organic manure, may result in deficiencies of various micro-nutrients, a decrease in soil organic carbon, and a decline in the physical and biological properties of the soil, in addition to directly impairing crop productivity. The aims of this study were to evaluate the long-term effects of herbicides and fertilizers, with or without organic manure, on soil quality parameters, nutrient availability, herbicide residue accumulation, nutrient uptake, and the productivity of the rice-rice system.

Materials and Methods

A long-term field experiment commenced in 2000 at the Research Farm of Assam Agricultural University, located in Jorhat, Assam, India. The current study was conducted in 2020 as part of an investigation to assess the effects of integrated nutrient management (INM) practices and herbicides on soil and rice crops across summer and winter. The experiment was designed using a randomized block design and the five treatments were T₁ - Farmers' practice (one hand weeding), T₂ - Butachlor + 2,4-D with 100% RDF, T₃ - Butachlor + 2,4-D with 75% RDF + 25% N from organic sources, T₄ - Butachlor + 2,4-D rotated with pretilachlor with 100% RDF, and T₅ - Butachlor + 2,4-D rotated with pretilachlor with 75% RDF + 25% N from organic sources. A recommended dose of fertilizer (RDF) of 40: 20: 20 and 60: 20: 40 kg/ha NPK was applied to summer and winter rice, respectively. The organic source used was vermicompost (VC), which contained total nitrogen (N) of 1.4-1.5%, phosphorus (P) of 1.0-1.1%, and potassium (K) of 1.5-1.8%, to provide 25% N. Soil samples were collected from two depths: (0-15 and 15-30 cm), air-dried, and sieved (<2 mm) for further analysis at the harvest of each rice crop. Periodic samples were also taken (0-15 cm) for herbicide residue analysis and enzyme activity assessment. The soil samples underwent analysis for physical, chemical, biological properties, and herbicide residues in various matrices, adhering to standard protocols. The analysis of variance outlined by Panse and

Sukhatme (1967), was employed in the randomized block design for statistical data analysis. To determine statistical significance, the differences between treatment means were evaluated using the Duncan Multiple Range Test (DMRT).

Results and Discussion

The impact of fertilizer and herbicide application on various soil properties was prominent after 14 years of research (Table 1). The study results significant increase in the soil organic carbon (SOC) levels at soil depths of 0-15 cm (5.8-8.8 g/kg) and 15-30 cm (4.7-7.5 g/kg) compared to the control (FP) and higher carbon stock of 16.63 and 17.76 Mg/ha, respectively, in surface and subsurface soil, in contrast to FP, recorded 12.01 and 11.77 Mg/ha. Soils with higher organic matter and greater porosity (lower bulk density) generally have a higher WHC. The text correctly links the improvements in water holding capacity (WHC) and mean weight diameter (MWD) to increased organic carbon and porosity, which would lead to a decrease in bulk density. So, the lower bulk density (BD) value (1.23 g/cc) should be associated with the treated surface soil, and the higher BD value (1.67 g/cc) with a less-treated or compacted soil, not with the different depths as stated. Ketena *et al.* (2025) explained that increased in BD with soil depth in subsurface layers arise from less organic matter, reduced aggregation, and limited root penetration, directed to decrease pore space. The soil pH measuring between 4.55 and 4.63 across the various treatments. The concentration of available N in the FP was diminished owing to nutrient depletion resulting from continuous cropping without the supplementation of plant nutrients (Xia *et al.* 2025). Furthermore, the augmentation of P₂O₅ and K₂O attributed to the long-term application of balanced fertilizers or the integrated use of fertilizers alongside organic manure, as documented by Meshram *et al.* (2016). The decomposition of organic manure releases low-molecular-weight organic acids that promote the solubilization of native and mineral-bound phosphates, thereby improving phosphorus availability in soil through enhanced chelation, acidification, and microbial activity (Chen *et al.* 2022). The greater biomass production brought about improved nutrient absorption in the subsequent rice crop, making sustained and sufficient availability of nutrients in the soil from both applied and indigenous sources, as observed by Bhattacharya *et al.* (2025). The effective management of weeds and the prolonged availability of N, P₂O₅, and K₂O in the trial led to an increase in plant biomass production and enhanced N uptake (47.53-55.62 Kg/ha) in treated plots as compared to control (40.50 kg/ha). Meshram *et al.* (2016) indicated that the combination of fertilizer and organic manure may have facilitated initial plant growth and the development of a robust root system, contributing to increased plant biomass production.

Table 1. Physical and chemical properties of soil and nutrient uptake as affected by long term application of integrated nutrients and herbicides in rice.

Treatments	SOC (g/kg)		Carbon stock (Mg/ha)		Porosity (%)	WHC (%)	MWD (mm)	BD (g/cc)		Soil pH	Nutrient uptake (kg/ha)		
	0-15 cm	15-30 cm	0-15 cm	15-30 cm				0-15 cm	15-30 cm		0-15 cm	N	P
T1	5.8 ^c	4.7 ^b	12.01 ^b	11.77 ^b	4.82 ^c	45.77 ^b	43.58 ^d	1.38 ^a	1.67 ^a	4.55 ^a	40.50 ^d	15.77 ^d	53.48 ^d
T2	6.5 ^{bc}	5.9 ^a	12.87 ^{bc}	14.24 ^{ab}	4.85 ^{bc}	44.76 ^b	45.53 ^c	1.32 ^{ab}	1.61 ^{ab}	4.55 ^a	47.53 ^c	18.24 ^c	60.50 ^c
T3	8.8 ^a	7.5 ^a	16.63 ^a	17.76 ^a	5.05 ^a	47.56 ^a	51.25 ^b	1.26 ^{bc}	1.5 ^{ab}	4.57 ^a	51.12 ^b	21.46 ^b	67.25 ^b
T4	7.4 ^{ab}	6.8 ^a	15.09 ^{ab}	16.73 ^a	4.86 ^b	45.27 ^b	44.82 ^{cd}	1.36 ^a	1.64 ^{ab}	4.63 ^a	48.56 ^{bc}	21.35 ^{bc}	62.45 ^b
T5	8.5 ^a	7.3 ^a	15.68 ^{ab}	16.86 ^a	5.03 ^a	48.15 ^a	52.89 ^a	1.23 ^c	1.54 ^b	4.56 ^a	55.62 ^a	25.43 ^a	72.61 ^a

The weed population under different treatments increased progressively up to 60 DAT and thereafter declined gradually until crop maturity, primarily due to intensified crop-weed competition and canopy closure Yadav *et al.* (2023). The weed density at 30 and 60 DAT varied

between 16 to 46 and 20 to 62.3 individuals per square meter, respectively (Fig.1) and weed dry matter accumulation was between 7.8-17.7, 10.7-35.7, and 14.7-20.7 (g/m²) at 30 DAT, 60 DAT, and at harvest, respectively. Moreover, Mishra *et al.* (2023) observed a significantly lower weed dry matter accumulation in the treatments as compared to FP. The lowest rice productivity was recorded in the FP, where only 50% RDF was utilized with one hand weeding (HW) over the other treatments (Fig. 2) and the data suggested that straw yield followed a similar pattern to that of grain productivity. The productivity data indicated an increase in summer and winter rice yields by 49.92 and 42.80 % over FP. The enhanced and sustained availability of nutrients from both native and applied sources, along with improvements in soil physico-chemical properties and microbial activity, positively influenced the crop growing environment, ultimately leading to increased productivity (Rajkhowa 2011). The enhanced and sustained availability of nutrients from both native and applied sources, together with improvements in soil physico-chemical properties and microbial activity, created a favorable crop-growing environment, which ultimately resulted in increased productivity (Lal 2020).

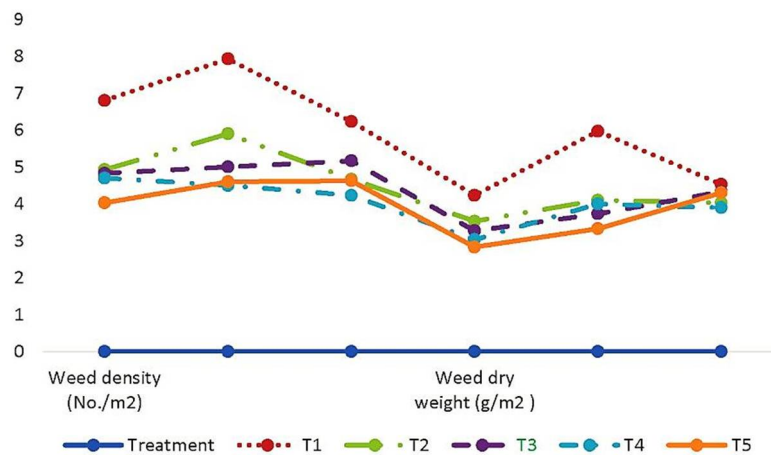


Fig. 1. Weed density and dry weight as affected by long term application of integrated nutrients and herbicides in rice.

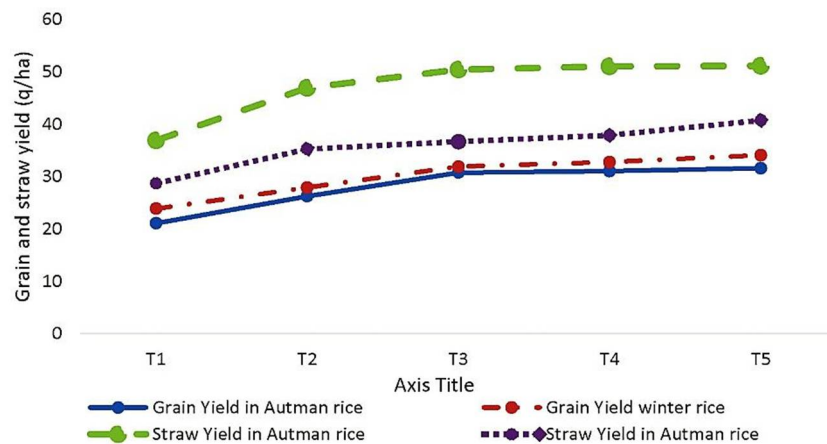


Fig. 2. Grain and straw yield as affected by long term application of integrated nutrients and herbicides in rice.

The accelerated rate of enzyme activity during the summer season in comparison to the winter season, ascribed to the faster breakdown of herbicide compounds (Table 2). A significant enhancement in enzyme activity was observed with the application of butachlor or pretilachlor, with or without organic manure, peaking at 14 days after application (DAA) and gradually declining until 60 DAA (Singh and Singh 2019). The partial substitution of mineral nitrogen fertilizer with organic manure has been shown to significantly enhance soil dehydrogenase activity (DHA) by stimulating microbial growth and metabolic processes (Saha *et al.* 2025). The increase in acid phosphatase activity (APA) can be attributed to the higher input of organic matter, which serves as a source of organic carbon and nitrogen and stimulates microbial activity in soil. Recent studies have confirmed that organic amendments significantly enhance phosphatase activity through improved substrate availability and microbial proliferation (Bhaduri *et al.* 2020). Similarly, the application of butachlor has been reported to exert minimal long-term effects on urease activity (UA), although a temporary increase is often observed during the early stages after application, irrespective of season (Singh *et al.* 2022). The rise in microbial biomass carbon (MBC) in certain herbicide-treated soils may be recognized to the presence of specific herbicides that serve as nutrient sources (Mahanta *et al.* 2017a) significantly influence microbial growth and development. Conversely, excessive application of chemical fertilizers has been reported to suppress microbial survival and activity by inducing osmotic and salt stress in the soil environment, thereby adversely affecting soil biological health (Prakash *et al.* 2024).

Table 2. Seasonal variation of soil bio chemical properties as affected by long term application of integrated nutrients and herbicides in rice.

Treatment	Bio chemical properties	Autumn					Winter				
		0 DAA	7 DAA	14 DAA	30 DAA	60 DAA	0 DAA	7 DAA	14 DAA	30 DAA	60 DAA
T ₁ = Farmers' practice	DHA	118.30 ^e	123.10 ^e	128.41 ^e	125.82 ^d	121.82 ^d	108.52 ^e	115.12 ^e	103.81 ^e	106.71 ^d	110.60 ^c
	APA	288.20 ^a	285.60 ^a	290.40 ^a	287.60 ^a	294.74 ^a	245.81 ^a	242.32 ^a	249.92 ^a	250.72 ^a	246.81 ^a
	UA	270.73 ^e	276.77 ^e	288.48 ^d	295.76 ^c	281.55 ^d	234.55 ^d	243.76 ^d	225.39 ^e	242.76 ^c	251.72 ^e
	MBC	387.34 ^c	382.39 ^c	419.42 ^c	399.61 ^c	410.41 ^c	374.51 ^c	367.35 ^c	358.79 ^c	355.19 ^c	375.15 ^c
T ₂ = Butachlor + 2,4-D with 100% RDF	DHA	133.70 ^d	138.81 ^d	144.52 ^d	134.74 ^c	127.82 ^c	126.72 ^d	131.06 ^d	136.04 ^d	124.44 ^c	119.52 ^b
	APA	255.70 ^e	248.21 ^e	242.63 ^e	259.72 ^e	267.01 ^e	202.51 ^e	190.52 ^d	188.21 ^d	206.03 ^e	219.73 ^d
	UA	285.54 ^c	292.62 ^c	268.540 ^c	278.58 ^d	267.59 ^e	226.70 ^e	255.87 ^c	267.76 ^c	236.71 ^d	247.80 ^d
	MBC	332.66 ^c	319.49 ^e	313.61 ^e	330.26 ^c	339.76 ^c	299.57 ^e	280.67 ^c	270.57 ^e	289.44 ^e	304.21 ^e
T ₃ = Butachlor + 2,4-D with 75% RDF + 25% N from organic sources	DHA	142.70 ^b	149.70 ^b	152.50 ^b	139.72 ^b	135.84 ^b	136.54 ^b	143.62 ^b	147.23 ^b	134.82 ^b	128.74 ^a
	APA	265.00 ^c	255.30 ^c	252.32 ^c	268.70 ^c	275.73 ^c	210.42 ^c	204.50 ^c	202.04 ^c	222.32 ^c	234.41 ^b
	UA	315.40 ^a	329.39 ^a	340.49 ^a	311.43 ^b	303.46 ^b	290.63 ^a	281.89 ^b	296.75 ^a	276.69 ^b	287.75 ^a
	MBC	452.59 ^b	442.33 ^b	439.39 ^b	459.41 ^b	461.32 ^b	430.61 ^b	425.29 ^b	405.34 ^b	412.86 ^b	429.34 ^b
T ₄ = Butachlor + 2,4-D rotated with pretilachlor with 100% RDF	DHA	137.5 ^c	144.5 ^c	147.4 ^c	135.7 ^c	128.6 ^c	129.7 ^c	134.1 ^c	138.7 ^c	125.7 ^c	120.7 ^b
	APA	258.5 ^d	250.5 ^d	245.6 ^d	262.5 ^d	269.4 ^d	204.6 ^d	187.7 ^e	189.1 ^d	210.7 ^d	225.5 ^c
	UA	279.04 ^d	287.64 ^d	294.79 ^c	265.76 ^e	292.43 ^c	242.79 ^c	230.57 ^e	254.61 ^d	229.61 ^e	265.64 ^c
	MBC	365.47 ^d	359.21 ^d	350.47 ^d	368.53 ^d	379.38 ^d	337.62 ^d	328.63 ^d	318.45 ^d	340.38 ^d	322.49 ^d
T ₅ = Butachlor + 2,4-D rotated with pretilachlor with 75% RDF + 25% N from organic sources	DHA	145.7 ^a	154.5 ^a	156.7 ^a	143.7 ^a	139.7 ^a	140.7 ^a	147.6 ^a	151.1 ^a	138.5 ^a	130.2 ^a
	APA	269.3 ^b	258.4 ^b	256.7 ^b	272.5 ^b	280.6 ^b	212.2 ^b	210.4 ^b	205.6 ^b	225.0 ^b	237.6 ^b
	UA	309.65 ^b	301.62 ^b	317.03 ^b	331.65 ^a	336.82 ^a	280.83 ^b	289.50 ^a	280.62 ^b	295.83 ^a	281.50 ^b
	MBC	498.43 ^a	479.58 ^a	478.43 ^a	486.49 ^a	506.79 ^a	468.48 ^a	463.47 ^a	444.25 ^a	449.53 ^a	458.19 ^a

The mean half-life of butachlor (5 days) and pretilachlor (7 days) was observed, with dissociation coefficients ranging from 0.13 to 0.16 days and 0.06 to 0.07 days during the summer and winter seasons, respectively (Table 3). In terms of herbicide residue accumulation, butachlor residues are consistently lower than pretilachlor, regardless of whether continuous or rotational application was employed. The periodical butachlor residue in summer rice was 0.13 to 0.36 µg/g

on the day of application and below the detection limit (BDL) at 30 DAA in the soil. Conversely, in winter rice, butachlor residue was recorded 0.19 to 0.23 $\mu\text{g/g}$ on the day of application, and reaching BDL at 30 DAA in soil. The continuous or rotational application of butachlor with pretilachlor combined with 2,4-DEE as post emergence in each season did not indicate the presence of these herbicide residues in the soil at harvest within the rice-rice cropping system (Mahanta *et al.* 2017b). Similar findings regarding butachlor residue build up in soil, specifically BDL in soil at 30 DAA of the herbicide at post-harvest of the rice crop, were reported by Kaur *et al.* (2017).

Table 3. Half-life and K values for Butachlor and Pretilachlor in soil under rice-rice system.

Treatment	Autumn rice		Winter rice			
	Butachlor		Butachlor		Pretilachlor	
	Half-life (Days)	K (Days ⁻¹)	Half-life (Days)	K (Days ⁻¹)	Half-life (Days)	K (Days ⁻¹)
T ₁	-	-	-	-	-	-
T ₂	4.37	0.16	4.34	0.16	-	-
T ₃	5.19	0.13	4.33	0.16	-	-
T ₄	4.43	0.15	-	-	11.01	0.07
T ₅	4.44	0.16	-	-	10.53	0.06

The use of 75% inorganic and 25% organic sources is a good approach, but the text could benefit from a more detailed explanation of why this specific ratio is beneficial.

The rotational application of pre-emergence herbicides such as butachlor and pretilachlor, followed by the post-emergence application of 2, 4-D, in conjunction with integrated nutrient management that utilizes 75% of nutrients from inorganic fertilizers (NPK) and 25% from organic sources, is beneficial as a source of balanced and sustained nutrient supply, improvement in soil health, enhanced nutrient use efficiency, increased crop yield and quality, sustainability and environmental safety, improvement in soil biological activity and cost-effectiveness. Notably, there were no detectable levels of herbicide residues found in the soil or the rice crop. The sequential use of pre-emergence and post-emergence herbicides is crucial for the effective management of weeds that emerge in multiple flushes within a rain-fed lowland rice ecosystem.

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References

- Bhaduri D, Purakayastha TJ, Chakraborty K, Chakrabarti K and Singh 2020. Soil enzyme activities and microbial biomass under long-term organic and inorganic nutrient management. *Appl. Soil Ecol.* **152**: 103571.
- Bhattacharyya T, Ray SK, Gangopadhyaya SK and Wani SP 2025. Black soils and their carbon sequestration potential Indian examples. *Indian J. Fert.* **21**(8): 712-733.
- Chen Y, Zhang J, Li S and Wang X 2022. Organic amendments enhance phosphorus availability through microbial and biochemical processes in agricultural soils. *Sci. Total Environ.* **806**: 150700.
- Das A, Ghosh PK, Choudhury BU, Patel DP, Munda GC, Ngachan SV and Layek J 2021. Soil fertility management in acidic soils of Northeast India. *J. Soil Sci. Plant Nutr.* **21**.
- Deep M, Kumar R, Saha S and Singh A 2018. Rice-based cropping systems for enhancing productivity of food grains in India: decadal experience of AICRP. *Indian Farming* **68**(01): 27-30.

- Food and Agriculture Organization of the United Nations (FAO) 2022. World Food and Agriculture-Statistical Yearbook 2022. Rome: FAO. ISBN 978-92-5-136930-2.
- Hu Y, Zhang H, Cui L, Zhou W and Zhang M 2026. Responses of soil enzyme activities to increasing salinity: A quantitative meta-analysis. *J. Environ. Manag.* **398**. 128578.
- Jing Z, Zhang S, Sun Z, Liu Z, Liu S and Ding X 2025. Straw Incorporation and Nitrogen Fertilization Enhance Soil Organic Carbon Sequestration by Promoting Aggregate Stability and Iron Oxide Transformation. *Agronomy*. **15**: 871. <https://doi.org/10.3390/agronomy15040871>.
- Kaur P, Randhawa SK, Duhan A and Bhullar M S 2017. Influence of long-term application of butachlor on its dissipation and harvest residues in soil and rice. *Bull. Environ. Contam. Toxicol.* **98**(6): 874-880.
- Ketena S, Gebresenbet G, Kolhe KP, Dananto M, Seifu Y and Mathwos 2025. Impacts of soil physical and mechanical behaviors under different tillage depths for agrotechnical operation in Bukito, Sidama. *Ethiop. Sci. Rep.* **5**: 199511 <https://doi.org/10.1038/s41598-025-03130-4>
- Kumar A, Saini KS, Dasila H, Kumar R, Devi K, Bisht YS, Yadav M, Kothiyal S, Chilwal A and Maithani D 2023. Sustainable Intensification of Cropping Systems under Conservation Agriculture Practices: Impact on Yield, Productivity and Profitability of Wheat. *Sustain.* **15**. 7468. [CrossRef]
- Lal R 2020. Soil organic matter and crop productivity. *Soil Tillage Res.* **198**: 104523.
- Mahanta K and Deka J 2017b. Persistence and dissipation of pretilachlor in soil and rice plant under conservation agriculture system in Assam. *In proc. Biennial Conference of the Indian Society of Weed Science on "Doubling Farmers' Income by 2022: The Role of Weed Science*. MPUA and T, Udaipur, India.
- Mahanta K, Dutta P, Nath, Deka J, Barua IC, Deka NC and Sarma AK 2017a. Long term application of herbicides on soil microbial demography in rice - rice cropping sequence of North-East India. *Indian J. Weed Sci.* **49**(4): 317-323.
- Meshram NA, Ismail S, Shirale ST and Patil VD 2016. Impact of long-term fertilizer application on soil fertility, nutrient uptake, growth and productivity of soybean under soybean-safflower cropping sequence in Vertisol. *Legume Res.* **42**(2): 182-189.
- Mishra Ha, Tripathi A, Pal BR and Singh RS 2023. Effect of Fertility Levels and Weed Management Practices on Weed Species and Weed Dry Matter Accumulation. *Int. J. Plant. Soil.* **35**(16):342-51. <https://doi.org/10.9734/ijpss/2023/v35i163160>.
- Panse VG and Sukhatme PV 1967. Statistical method for Agricultural Workers. Indian Council of Agricultural Research, New Delhi, India.
- Prakash AD, Sheoran S, Yadav PK, Kumari M, Kumar S, Prajapat K, Alamri S, Siddiqui MH and Gupta RK 2024. Different cropping systems impact soil health by improving soil biological activities and total organic carbon content. *Arch. Agron. Soil Sci.* **70**(1): 1-24.
- Rajkhowa DJ 2011. Effect of rice straw management practices on yield of kharif rice and soil fertility under rice- rice cropping system. *J. Indian Soc. Soil Sci.* **60**(3): 208-212.
- Saha S, Kucher OD, Utkina AO and Rebouh NY 2025. Precision agriculture for improving crop yield predictions: a literature review. *Front. Agron.* **7**: 1566201.
- Singh V and Singh S 2019. Impact of herbicides and organic amendments on soil biological properties in rice ecosystems. *Environ. Monitor. Assess.* **191**: 312.
- Singh V, Kumar A, Sharma R and Patel R 2022. Constraints of acidic soils in Eastern India and their management strategies. *Geoderma Region.* **29**: e00512. <https://doi.org/10.1016/j.geodrs.e00512>.
- Verma A, Sharma B C, Nandan B, Kumar R and Banotra M 2020. Effect of weed management interventions on soil microbial count in wheat and direct seeded basmati rice in irrigated plains of Shivalik foothills of Jammu. *Int. J. Curr. Microbiol. App. Sci.* **9**(8): 821-831.
- Wang H, Ciais P, Yang H, Smith P, Grassi G, Schwingshack C, Panagos P, Bar-On Y, Sitch S, Chevallier F, Palmer PI, Li X, Hong S, Chang J, Albergel C, Fan L, Wang K, Liu L, Frappart F and Wigneron JP 2025. Land use-induced soil carbon loss in the dry tropics nearly offsets gains in northern lands. *Natr. Commun.* **16**: 10008 2 <https://doi.org/10.1038/s41467-025-64929-3>.

- Walia MK, Zanetti F, Gesch RW, Krzyżaniak M, Eynck C, Puttick D, Alexopoulou E, Royo-Esnal A, Stolarski MJ, Isbell T and Monti A 2021. Winter camelina seed quality in different growing environments across Northern America and Europe. *Ind. Crops Prod.* **169**(1): 113639.
- Jiang XC, Riaz M, Yu F, Dong Q, Yan Y, Zu C, Zhou C, Wang J and Shen J 2025. Impacts of continuous cropping on soil fertility, microbial communities, and crop growth under different tobacco varieties in a field study Hao PN 2-13. *Environ. Sci. Europe* **37**: 5 <https://doi.org/10.1186/s12302-024-01037-x>
- Xu J, Henry A and Sreenivasulu N 2020. Rice yield formation under high day and night temperatures-a prerequisite to ensure future food security. *Plant Cell Environ.* **43**(7): 1595-1608. <https://doi.org/10.1111/pce.13748>
- Yadav S, Kumar A and Jat ML 2023. Weed population dynamics under integrated weed management in field crops. *Indian J. Agron.* **68**(1): 78-84.

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