Original Paper

Study of Pesticide Usage and Farming Practices on Soil Health in Buldhana District of Maharashtra

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Article Details: Received: 2025-09-04 | Accepted: 2025-11-12 | Available online: 2026-03-31

https://doi.org/10.15414/afz.2026.29.01.56-65

Intensive pesticide use and monoculture-based cropping are increasingly linked to soil degradation in India's semi-arid smallholder systems. We examined how farmer practices, particularly pesticide reliance, affect soil properties in Buldhana (Maharashtra)a through a survey (*n* = 93) and laboratory analyses of composite soils (0–10 cm). Soils were slightly alkaline and non-saline (pH 7.44–7.78; EC 0.15–0.22 dS/m) but showed low organic carbon (0.32–0.95%), low–medium available N (183–311 kg/ha), medium P (13–25 kg/ha), high K (307–783 kg/ha), and widespread Fe and Zn deficiencies, while Cu and Mn were generally adequate. Comparisons with organic and forest controls highlighted contrasting fertility baselines: organic soils had higher OCC (0.85%) and extreme K (> 3,000 kg/ha), while forest soils had the highest OC (1.06%), elevated Fe and Mn, and greater moisture. Most farmers were marginal landholders (1–5 acres), largely rainfed, following soybean–wheat sequences; 71.6% applied 3–5 sprays per season, and 68.4% relied exclusively on chemical pesticides, predominantly organophosphates. Instant efficacy was cited as the main reason for use, though 41% reported yield declines. ANOVA and cross-tabulations showed higher spray intensity and organophosphate use coincided with lower OC and slightly elevated EC, suggesting pesticide-mediated disruption of soil functioning. While macronutrient levels (notably K) were sufficient, persistent Fe and Zn gaps threaten long-term fertility. Locally actionable strategies; integrated pest management, crop diversification, soil-test-based fertilization with micronutrient correction, and organic amendments, could reduce pesticide load and restore soil health. The survey-plus-soil framework offers a replicable diagnostic for aligning pesticide management with soil restoration in semi-arid Vertisols.

Keywords: Pesticide, monoculture, organophosphate, physico-chemical, survey

1 Introduction

In India, large-scale adoption of high-yield cultivars and agrochemical inputs raised grain output from 176 million tonnes in 1991 to 316 million tonnes in 2021–22, but also generated second-generation concerns such as declining factor productivity, inefficient resource use, and deteriorating soil quality (Meena et al., 2024). Intensive pesticide application particularly broad-spectrum organophosphates disrupts soil microbial communities, reduces functional diversity, and impairs nutrient transformations of nitrogen, phosphorus, and sulphur. Meta-analyses show that fungicides and herbicides inhibit nitrification and that the abundance of ammonia-oxidizing microbial genes (amoA) is a sensitive indicator of pesticide-driven soil toxicity (Swaine et al., 2025).

Across the Buldhana district of northern Maharashtra, small, predominantly rainfed farms organized around soybean-wheat (and cotton-soybean) sequences have come to rely heavily on synthetic pesticides; most notably broad-spectrum organophosphates, with supplemental diamides and pyrethroids; to secure short-term pest control; yet this chemical dependence, combined with simplified rotations and frequent sprays, is increasingly implicated in the slow erosion of soil health. In neutral to slightly alkaline Vertisols, repeated pesticide applications can disrupt microbial communities, suppress enzymatic processes, and impede residue decomposition and biological nitrogen transformations, pathways that express agronomically as declining soil organic carbon (SOC), drifting electrical conductivity (EC), and tighter

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plant access to key micronutrients such as Fe and Zn (Yasir et al., 2025).There are studies that have examined soil degradation under intensive agriculture and pesticide use in semi arid region of India but most have focused on controlled plots or single soil indicators like physicochemical analysis (Jat et al., 2023; RagaPriya et al., 2020). However, the investigations largely lacked on-farm or farmer participatory contexts that reflect real-world risks and decision logics. This provides limited understanding of how real-world pesticide portfolios influence multiple physicochemical and micronutrient properties in smallholder systems. Frameworks such as the Soil Management Assessment Framework (SMAF) and Soil Quality Indices (SQI) offered efficient tools for soil evaluation, yet their application in semi-arid India remains largely confined to research stations due to data, cost, and capacity constraints (Uthappa et al., 2024). Consequently, empirical evidence linking on-farm pesticide practices with comprehensive soil-health diagnostics particularly under rainfed Vertisol conditions remains scarce. The current study bridges these gaps by integrating a farmer-level survey of pesticide use with field-based soil analyses to quantify cumulative pesticide effects and to operationalize soil-health frameworks within real smallholder contexts. The outcomes of this study can assist both policymakers and farmers by providing evidence-based guidance on the appropriate selection, dosage, and application of pesticides suited to specific crops and local soil conditions.

Viable solutions are well established: integrated pest management (IPM) that prioritizes monitoring, thresholds, biocontrols, and targeted chemistries; diversification of rotations and intercropping; especially with legumes; to interrupt pest life cycles and biologically enrich soils; residue retention and organic amendments to rebuild SOC; and soil-test-based fertilization that corrects local micronutrient gaps while avoiding unnecessary K additions. Evidence from diversified systems shows these bundles can raise soil-health metrics and maintain or improve yields while reducing pesticide load (Yang et al., 2024). However, three limitations constrain adoption in Buldhana district and similar smallholder drylands:

a) a lack of on-farm studies that quantify links between farmers' actual pesticide portfolios (active ingredients, spray frequency, dose rationales) and measured soil physicochemical properties;
b) recommendations derived from experiment-station trials that fail to capture the realities of rainfed conditions, small and fragmented landholdings, and limited access to inputs;
c) soil-health diagnostics and extension messages that foreground N-P-K while underweighting early, pesticide-sensitive indicators such as SOC, EC, and DTPA-extractable Fe/Zn.

To address these gaps, the current study couples a structured farmer survey in Buldhana district with laboratory analyses of composite soils from farmer fields (pH, EC, SOC, available N-P-K, DTPA-Fe/Zn/Mn/Cu, moisture, and texture-by-feel), applying appropriate statistics (ANOVA with Tukey's HSD) to test associations between pesticide reliance and soil properties, and to disentangle pesticide effects from cropping pattern effects (monoculture vs. more diverse sequences). The survey-plus-soil framework offers a replicable template for smallholder regions where organophosphate-heavy protection and monoculture prevail: it operationalizes pesticide regulation within a soil-health lens, informs district-scale nutrient and pesticide, and supports SDGs on food security, ecosystem integrity, and responsible inputs by charting credible pathways to reduce chemical dependence while sustaining productivity.

2 Material and Methods

2.1 Study Rationale and Site Description

The farmers of Buldhana district, Maharashtra, predominantly cultivate commercial crops, and their crop selection is closely aligned with the local soil type. Farming practices in this region are often influenced by peer observation and perceived economic returns, leading to a degree of homogeneity in agronomic decisions within similar soil zones.

The field survey revealed that a significant proportion of the farmers possess small landholdings and rely heavily on chemical pesticides to safeguard their crops. Consequently, the present study focused on representative smallholder farms exhibiting similar soil characteristics, crop types, and pesticide-use intensities, in order to evaluate the impact of prolonged pesticide application on soil health under real-world conditions.

2.2 Soil Sampling Procedure

Soil sampling for physicochemical analysis was conducted in August 2023 within an intensively cultivated agricultural region of Buldhana district, Maharashtra, characterized by long-term monocropping and high pesticide use. Sampling was performed immediately after harvest and following the last short rains, when fields had not yet been prepared for the next growing season. This timing minimized the influence of recent fertilizer or pesticide applications and provided a reliable baseline of soil nutrient and residue status.

Within the selected taluka, one village representing intensive agricultural activity was chosen. From this village, three representative fields with comparable soil type, cropping history, and management intensity were identified. This focused selection reduced the number of samples while maintaining analytical relevance, as all fields shared similar soil and management characteristics. From each field, 8–10 surface soil subsamples (0–10 cm depth) were collected along a zigzag transect across the cultivated area and thoroughly mixed to obtain a composite sample (~500 g) representing that field. The three composites served as replicates (n = 3) to capture within-site variability under uniform high-input conditions. Two baseline controls were taken viz. Forest soil and organic soil for physicochemical comparison of farm soils.

The sampled fields were primarily under soybean, pigeon pea, cotton, wheat, and maize, representing the dominant cropping systems of the district. All samples were air-dried at ambient temperature, gently disaggregated, and sieved through a 2 mm mesh for physicochemical analysis, with a subsample sieved to 0.5 mm retained for available phosphorus estimation. The procedures followed standard soil analysis protocols (Jackson, 1973) to ensure accuracy, consistency, and prevention of contamination.

2.2.1 Physical Analysis

Soil colour (wet and dry) was assessed with a Munsell colour chart. Texture was determined using the ball-and-ribbon method (Thien, 1979). Water Holding Capacity (WHC) was measured using a simplified method described by Allen et al. (1974). Approximately 50 g of air-dried soil was saturated in water for six hours, drained overnight, and weighed before and after oven drying at 105 °C for 24 hours.

2.2.2 Chemical Analysis

Soil pH was measured in a 1 : 2.5 (w/v) soil-to-deionized water suspension using a calibrated glass-electrode pH meter. 10 g of air-dried, < 2 mm sieved soil was transferred into a 50 mL beaker, 25 mL of deionized water was added, and the mixture was shaken mechanically for 30 minutes. The suspension was then allowed to equilibrate for 10 minutes before recording the pH (Jackson, 2005).

Electrical conductivity (EC) (1 : 1) was measured with a conductivity meter. Oxidizable Carbon Contentwas determined by the Walkley-Black method (Walkley, 1947). Total Nitrogen (T-N) was measured using the Kjeldahl method (Okalebo et al., 1993). Available Phosphorus (P) was analyzed using Bray Kurtz method (Bray & Kurtz, 1945; Nelson, 1953). Exchangeable Potassium (K) and Sodium (Na) were extracted with ammonium acetate and measured using an atomic absorption spectrophotometer (Jackson, 2005).

Soil available micronutrients were extracted using DTPA (Diethylene Triamine Pentaacetic acid) extraction i.e. 0.005 M DTPA with triethanolamine buffer and $CaCl_2$ at pH 7.3. The micronutrients were measured by atomic absorption spectrophotometry (Lindsay & Norvell, 1978).

2.5 Survey of Farmers

A total of 93 farmers were interviewed from the Buldhana district to assess cropping patterns, pesticide usage, and land productivity. Data was collected in August 2022 using a mixed-method approach. Individual interviews were guided by a semi-structured questionnaire designed to capture both qualitative and quantitative data.

The questionnaire focused on the crops cultivated by farmers, the types and concentrations of pesticides applied, and the yield obtained from their fields. This structure allowed for a comprehensive understanding of the relationships between140–153 farm management practices and agricultural outcomes. Although many farmers managed multiple plots, the study concentrated on their main cultivated fields to reduce complexity.

2.6 Statistical Analysis

The experiments for soil sampling analysis were conducted in triplicates. The standard error of the mean was calculated. To calculate the significance between the treatments, ANOVA was done at $p < 0.05$ by post hoc Tukey's HSD method. IBM SPSS version 24 was used for statistical analysis.

3 Results and Discussion

3.1 Physicochemical Analysis of Soils

Soil pH across the study sites in Buldhana district was fairly consistent, ranging from slightly acidic to slightly alkaline, with values between 7.44 ±0.10 (Nandura N1) and 7.78 ±0.20 (Shegaon, Mehekar, Chikhali) (Table 1). Electrical conductivity (EC) remained low across locations, varying from 0.15 ±0.02 (Nandura N1) to 0.22 ±0.04 dS/m (Khamgaon), suggesting non-saline conditions. Oxidizable carbon (OCC) content showed moderate variation, with the lowest value recorded in Sangrampur (0.32 ±0.05%) and the highest in Mehekar (0.95 ±0.40%).

Total nitrogen ranged from 183.3 ±47.31 kg/ha (Nandura N1) to 310.5 ±11.64 kg/ha (Sangrampur), while available phosphorus varied between 13.37 ±2.49 kg/ha (Lonar) and 24.61 ±1.87 kg/ha (Chikhali). Exchangeable potassium levels showed wide variation, with relatively low values in Deulgaon Raja (307.43 ±41.72a kg/ha) and Lonar (318.8 ±32.12 kg/ha), but much higher concentrations in Sangrampur (783.02 ±89.8a kg/ha) and Khamgaon (757.92 ±56.52 kg/ha).

Among micronutrients, copper (Cu) ranged from 0.68 ±0.15 ppm (Nandura N1) to 1.25 ±0.18 ppm (Lonar); iron (Fe) from 1.09 ±0.38 ppm (Jalgaon) to 4.04 ±1.72 ppm (Sindkhedraja); zinc (Zn) from 0.15 ±0.02 ppm (Buldhana, Sangrampur) to 0.70 ±0.36 ppm (Sindkhedraja); and manganese (Mn) from 5.21 ±1.23b ppm (Mehekar) to 16.23 ±4.3 ppm (Malkapur). Soil moisture content also varied considerably, with the lowest observed in Sangrampur (6.52 ±1.41%) and the highest in Deulgaon Raja (39.76 ±12.62%).

The control soils showed distinct differences compared to conventional farm soils. Organic farm soil recorded higher organic carbon (0.85%), greater copper (1.81 ppm) and iron (6.17 ppm) availability, and elevated potassium (3,318.84 kg/ha) relative to chemically managed fields, while maintaining low electrical conductivity (0.12 dS/cm) and favorable moisture content (37.60%). Similarly, forest soil had the highest organic carbon (1.06%) and maintained good micronutrient levels (Fe: 5.04 ppm; Mn: 13.78 ppm), along with low EC (0.10 dS/cm) and stable moisture (36.12%). In contrast, farm soils across Buldhana generally showed lower organic carbon (0.32–0.95%), lower Fe (1.09–4.04 ppm), and Zn consistently below the recommended range (0.15–0.70 ppm). This indicates that both organic farm and forest soils maintained superior organic matter and micronutrient status compared to conventionally managed fields.

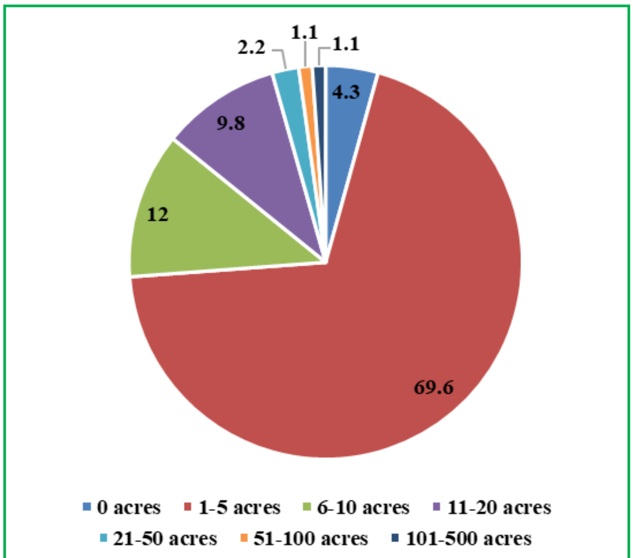

Figure 1 Survey-based average landholding of the farmers in Buldhana district

3.2 Survey of the Farmers

The farmers' survey revealed very important insights related to pesticide usage and yield. From the survey it was known that the majority farmers had an average landholding between 1 to 5 acres which comprised about 69.6% (Figure 1). So, this indicated that these were marginal farmers. Additionally, the farms were mainly rainfed i.e. more than half i.e. 54 farms (56.84%) were rainfed and 22 farms (23.16%) were irrigated. This indicated that the farming community largely depends on subsistence-level agriculture, with limited scope for diversification or risk-sharing. The average landholding and irrigation in the survey was therefore very small, pushing farmers toward intensive practices on restricted land areas.

Given this limited land base and irrigation practices, most farmers attempted to capitalize production by following monocropping systems. In the rabi season, the dominant

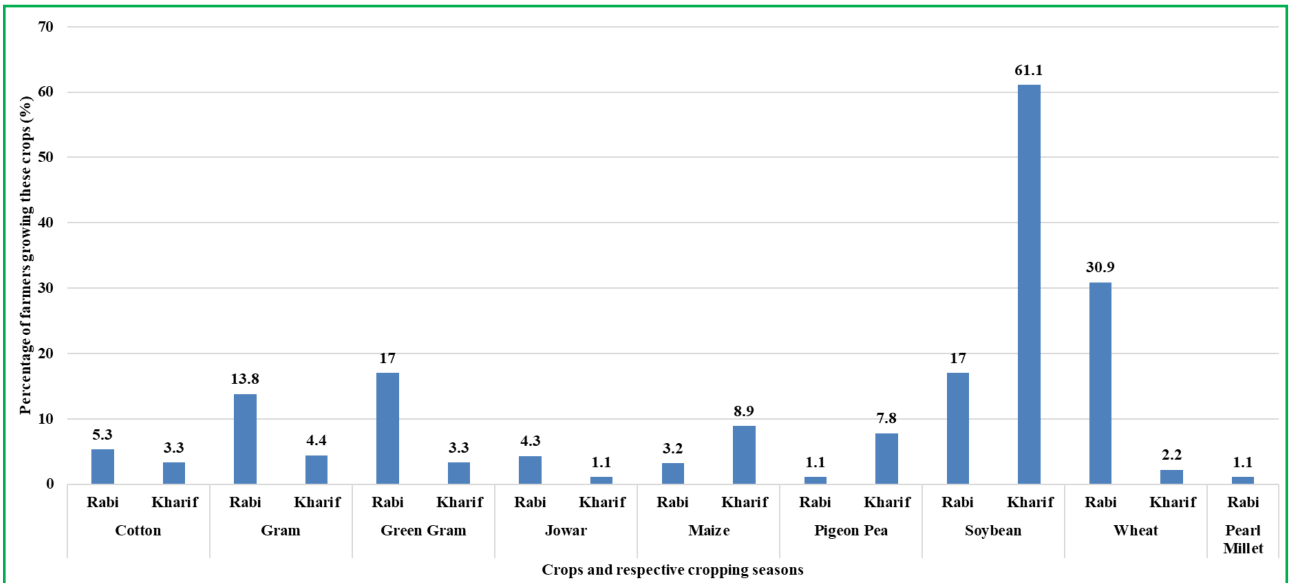

Figure 2 Survey-based data on crops cultivated by farmers in Buldhana district

crop was wheat (30.9%), followed by soybean (17%), green gram (17%), and gram (13.8%). Similarly, during the kharif season, soybeans dominated (61.1%), while crops like maize (8.9%), pigeon pea (7.8%), and gram (4.4%) grew in much smaller proportions (Figure 2). Such reliance on monocultures especially soybean and wheat created ecological vulnerabilities by increasing pest pressure and depleting soil nutrients year after year.

This pattern of farming had direct implications for pesticide use. Farmers reported that single pesticides cannot control all pests, with 76 farmers (78.95%) clearly stating this. Yet, they remain heavily dependent on chemical solutions: 65 farmers (68.42%) exclusively used chemical pesticides, while 19 (20%) preferred biopesticides, and 11 (11.58%) reported using both. The main reasons for relying on chemicals were their instant results (72.63%), good production outcomes (56.84%), and ease of use. A smaller number cited quick cultivation (31.58%) or availability and price as drivers. These practices, while effective in the short term, encouraged continuous and heavy pesticide usage year after year.

The consequences of this approach were already visible. Farmers themselves noted that, compared to their ancestors, 56 farmers (58.95%) perceived higher yields, but a significant 39 farmers (41.05%) acknowledged that yields had actually declined. This paradox reflected how chemical intensification initially boosts productivity but, over time, degrades soil health and sustainability. The persistent use of synthetic pesticides, many of which are non-biodegradable and have long half-lives in soil further contributes to soil infertility, loss of microbial diversity, and declining resilience of the farming system.

The survey revealed that chemical pesticides were predominantly used by farmers in Buldhana district, with variations between the kharif and rabi seasons. Organophosphates emerged as the most commonly used group across both seasons, being reported by 23.2% of farmers in kharif and 22.1% in rabi. Diamides followed, with usage increasing slightly from 7.4% in kharif to 9.5% in rabi, while pyrethroids were applied by 4.2% of farmers in kharif and 3.2% in rabi, showing relatively stable but limited adoption (Figure 3). Organochlorines and herbicides were reported by 3.2% of farmers during kharif, but their use declined in rabi, where only about 2.1% of farmers mentioned them. Similarly, spinosyns and neonicotinoids were minimally used, with 1.1% of farmers reporting them in kharif and 2.1% in rabi. The category of mixed formulations and others accounted for 9.5% in kharif, but declined to 2.1% in rabi, reflecting a seasonal shift away from less-standardized products. Meanwhile, carbamates, avermectins/emamectin, and dithiocarbamates were reported only in rabi, each by 1.1% of farmers, highlighting their minor role in overall pest management strategies.

Regarding crop categories requiring the most pesticide application, pulses (soybean, chickpea, pigeon pea, gram, etc.) were cited by 43 farmers (45.26%), followed by cotton (19; 20%), other crops (19; 20%), vegetables (6; 6.32%), and grains (4; 4.21%).

The number of sprays applied per season was highest in the range of 3–5 sprays, reported by 68 farmers (71.58%), followed by ≤ 3 sprays (22; 23.16%) and > 5 sprays (5; 5.26%). With respect to quantity of pesticide applied, the majority (30 farmers; 31.58%) reported 0–20 mL per spray, while others reported higher usage, including

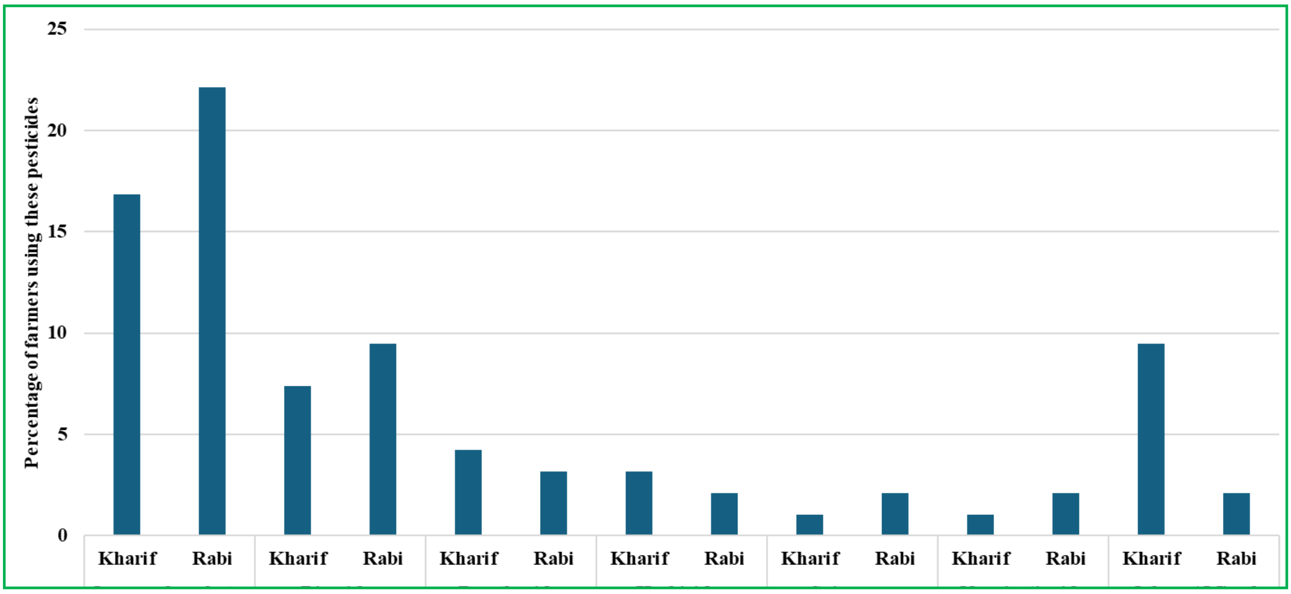

Figure 3 Survey-based data on different pesticides used in the cropping systems of Buldhana district

6 farmers (6.32%) who applied > 1,000 mL per spray (Figure 4).

When asked about the most commonly recognized pesticide group in their area, organophosphates were reported by 22 farmers (23.16%), followed by diamides (12; 12.01%), organochlorines (3; 3.16%), and smaller proportions citing neonicotinoids, pyrethroids, herbicides, spinosyns, carbamates, and avermectins.

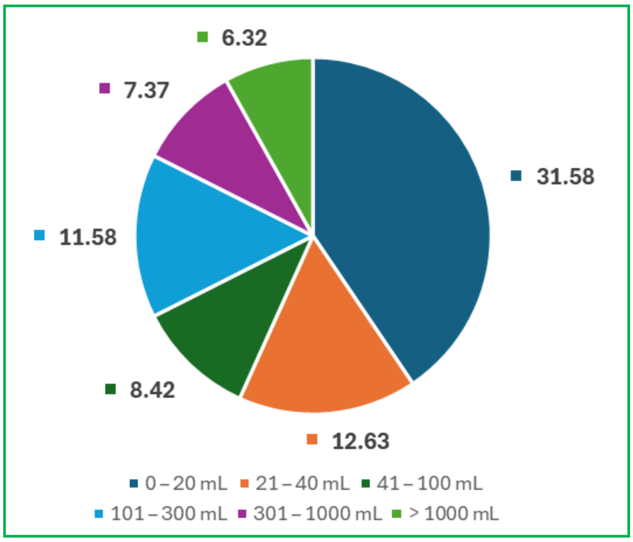

Figure 4 Survey-based data on percentage of farmers utilizing different amounts of pesticides per 20 L spray tank in Buldhana district

Together, these findings highlighted the cycle of marginal landholding, monoculture dependence, heavy pesticide usage, and soil fertility decline. Farmers seek to maximize yields on their small plots, but in doing so, they risk undermining the very soil resources on which their livelihoods depend.

3.3 Discussion

The baseline physicochemical analysis indicates that the soils of Buldhana district are generally of good inherent fertility, typical of the Buldhana region black soil (Vertisol) heritage. Soils across the surveyed villages were predominantly near neutral with low salinity, suggesting favorable conditions for crop growth without concerns of acidity or salt stress. Organic carbon levels, however, were generally low, highlighting limited organic matter input and rapid decomposition under tropical conditions. Only a few sites showed relatively higher values, indicating localized variations in soil fertility. The values for pH and Oxidizable carbon content is comparable to previous

Table 1 Physicochemical analysis of soils of different talukas of Buldhana districts

	pH	EC (dS/cm)	OCC (%)	N (kg/h)	P (kg/h)	K (kg/h)	Cu (ppm)	Fe (ppm)	Zn (ppm)	Mn (ppm)	Moisture content
APHA recommended values	6.5–7.5	0–1	0.4–0.6	280–420	14–21	150–200	0.2–99.99	4.5–99.99	0.61–99.99	2.0–99.99	–
Buldhana	7.68 ±0.16	0.18 ±0.03	0.39 ±0.03	279.44 ±12.16	20.81 ±4	495.95 ±80.21	0.73 ±0.08	2.18 ±0.3	0.15 ±0.02	6.49 ±2.04	31.54 ±5.47
Motala	7.76 ±0.09	0.16 ±0.02	0.44 ±0.04	279.18 ±18.12	18.78 ±3.74	709.28 ±37.64	1.08 ±0.09	3.1 ±0.59	0.24 ±0.03	13.37 ±0.78	23.63 ±2.72
Malkapur	7.66 ±0.09	0.192 ±0.02	0.44 ±0.03	287.96 ±25.09	15.75 ±1.14	551.9 ±158.45	1.14 ±0.1	1.36 ±0.48	0.29 ±0.08	16.23 ±4.3	36.17 ±18.97
Nandura	7.44 ±0.1	0.15 ±0.02	0.45 ±0.04	183.3 ±47.31	15.88 ±1.1	445.45 ±104.55	0.68 ±0.15	2.72 ±0.51	0.28 ±0.03	10.13 ±1.24	20.55 ±4.04
Jalgaon	7.68 ±0.12	0.21 ±0.03	0.46 ±0.04	287.26 ±9.88	15.48 ±2.11	524.82 ±89.54	1.05 ±0.11	1.09 ±0.38	0.25 ±0.07	11.1 ±1.45	8.1 ±1.69
Sangrampur	7.68 ±0.18	0.2 ±0.04	0.32 ±0.05	310.5 ±11.64	17.24 ±1.73	783.02 ±89.8a	0.7 ±0.04	2.79 ±0.28	0.15 ±0.03	10.64 ±1.99	6.52 ±1.41
Shegaon	7.78 ±0.2	0.16 ±0.02	0.44 ±0.12	310.02 ±22.28	15.26 ±1.91	630.45 ±95.59	0.72 ±0.15	2.35 ±0.28	0.24 ±0.03	11.75 ±2.33	31.41 ±9.96
Khamgaon	7.66 ±0.15	0.22 ±0.04	0.46 ±0.03	253.08 ±40.04	17.4 ±2.18	757.92 ±56.52	0.91 ±0.15	2 ±0.52	0.25 ±0.03	5.28 ±1.42b	24.87 ±10.11
Chikhali	7.78 ±0.16	0.19 ±0.02	0.56 ±0.1	305.93 ±14.06	24.61 ±1.87	560.3 ±33.36	0.71 ±0.06	2.07 ±0.33	0.16 ±0.01	7.03 ±0.71	12.6 ±2.04
Mehekar	7.78 ±0.2	0.2 ±0.04	0.95 ±0.4	294.25 ±19.58	19.68 ±2.33	581.73 ±39.96	0.73 ±0.12	2.3 ±0.62	0.234 ±0.05	5.21 ±1.23b	11.66 ±2.08

The values followed by ±are the standard error of the mean; all the means were not significantly different from each other at $p < 0.05$ level of significance by Tukey's HSD post hoc analysis; the means with common superscripts denote significantly different from each other findings in Buldhana's soils and reflected the low organic matter content due to limited biomass return and high decomposition rates (Panherkar et al., 2020). Nitrogen was observed mostly in the low-to-medium range (183–310 kg/ha), with some sites just below the recommended threshold, indicating insufficient N replenishment through crop residues or fertilizers. In contrast, phosphorus levels were consistently in the medium category, aligning with APHA standards. Potassium levels were strikingly high across most sites (ranging from 445–783 kg/ha, and exceeding 3000 kg/ha in the organic control), reaffirming the K-rich nature of basaltic soils in the Deccan region (Naphade et al., 2021; Pangrikar & Patil, 2021).

Notably, the organic farm control showed markedly higher organic carbon (0.85%), extreme K accumulation, and higher micronutrient availability (Cu, Fe, Zn, Mn), suggesting that organic amendments enhance soil fertility and micronutrient balance, consistent with previous findings that organic manures improve micronutrient solubility and soil biological activity (Lalrintluangi et al., 2019). Similarly, forest soils had the highest OC (1.06%) and moisture content, alongside elevated Fe and Mn, highlighting the role of natural vegetation in sustaining soil quality. These comparisons underscore how land-use practices directly shape soil nutrient status, with forest and organic systems outperforming conventional monoculture soils.

While the soil's current fertility status appears generally good, the farming practices observed in the survey raise concerns about its sustainability. The present study suggested that current practices in Buldhana district might be degrading soil quality. The majority of farmers in the study are marginal landholders (owning only 1–5 acres) and tend to grow the same crop year after year on the same plot, a classic case of monoculture or continuous monocropping. This is understandable given their economic constraints and the dominance of certain cash crops in Buldhana (about 79% of the district's cropped area is under cotton and soybean, often in monoculture or with minimal rotation) (NABARD, 2024). However, such repetitive cropping disturbs the ecological balance and can set the stage for escalating pest and disease problems. Fields with a single crop every season effectively offer a permanent banquet to specialized pests (Wenda-Piesik & Piesik, 2020).

Among micronutrients, copper and manganese were generally adequate, whereas zinc and iron deficiencies were common across villages, corroborating earlier observations from calcareous Vertisols of Buldhana (Hadole et al., 2019)(Hadole, 2019 #12; Hadole, 2019 #12). Particularly, Fe values at some sites (1–3 ppm) and Zn (<0.3 ppm) fell well below critical limits, a condition often associated with reduced crop yields in cotton- and soybean-based systems (Mann et al., 1978; Shukla et al., 2014). In the current study, available soil zinc (Zn) across the sampled farmer fields in Buldhana district averaged 0.52 mg/kg, while available iron (Fe) averaged 3.8 mg/kg (0–10 cm layer). According to the commonly-used Indian threshold values for micronutrients, soils with available Zn below approximately 0.6 mg/kg and Fe below approximately 4.0 mg/kg are considered deficient for many crops (Reddy et al., 2021). In particular, for soybean grown on Vertisols in Maharashtra, a critical soil Zn concentration of ~0.95 mg/kg has been reported in a pot trial from Parbhani district (Kausadikar et al., 2015). Thus, the 0.52 mg/kg average suggests a potentially widespread Zn limitation in the present study area, which may partly explain lower yields or nutrient-uptake inefficiencies. By contrast, the Fe average of 3.8 mg/kg lies just below the general critical limit of ~4.0 mg/kg, which indicated that Fe deficiency may be marginal in many fields but remains a monitoring priority. These deficiencies may worsen under intensive monocropping and high phosphorus fertilization, which are known to induce Zn and Fe unavailability (Cakmak, 2008).

Management practices beyond pesticide use can significantly shape soil health in Vertisols, often acting as confounding factors in interpretation of field-based results. For example, in saline Vertisols of Gujarat, use of saline groundwater for irrigation markedly increased soil salinity and exchangeable sodium percentage (ESP), whereas canal water with lower electrolyte concentration reduced salinity but increased sodicity problems (Chinchmalatpure et al., 2018). Similarly, diversification of cropping systems and inclusion of legumes has been shown to enhance soil structure, organic carbon and micronutrient availability in Vertisol systems; in a semi-arid Vertisol experiment, DTPA-extractable Fe, Mn, Cu and Zn were significantly higher under reduced tillage with crop rotations than under conventional tillage and monoculture (Jayaraman et al., 2021). Finally, legacy inputs such as organic amendments and tillage intensity as shown in long-term experiments in Indian Vertisols – modulate baseline fertility, influencing microbial biomass, nutrient cycling and physical health of the soil (Kumar et al., 2017). Thus, even though our study focussed on pesticide use and nutrient status in Buldhana district, the potential influence of irrigation source/quality, cropping history (legume vs monoculture), and past amendment/tillage history must be acknowledged. Accounting for these will bolster the interpretative strength of our findings and guide future work to integrate farmer-managed variables alongside chemical metrics for more robust soil health assessment.

Monoculture also means the crops lack the protective benefits of diversity (e.g. there are no alternative or repellent plants to interrupt pest life cycles), further increasing vulnerability to infestations (Stenberg, 2017). This system leads to heavy pesticide usage. Over two-thirds of farmers in the current survey reported synthetic pesticides (mainly organophosphates) use, and most farms rotate only one or two crops per year. Such practices reduce soil organic inputs and introduce toxins that harm soil life.

Previous studies have confirmed the current findings that pesticide residues and their degradation products can disrupt soil microbial communities, slow organic matter breakdown, and impede nutrient cycling. The mechanism is insidious. Pesticides (and excess chemical fertilizers) gradually diminish populations of beneficial soil microorganisms. These microbes including nitrogen-fixing bacteria, decomposers, and mycorrhizal fungi are essential for nutrient cycling and soil structure. When we "disinfect" the soil with chemicals year after year, we lose this living support system. As soil scientist Dr. Elaine Ingham cautions, "If we lose both bacteria and fungi, then the soil degrades. Overuse of chemical fertilizers and pesticides for a few years, but after a while, there aren't enough beneficial soil organisms to hold onto the nutrients" (Savonen, 1997). Similarly, Yasir et al. (2025) noted that pesticide degradation by-products disrupt microbial balance, hinder nutrient cycling, and degrade soil health, thereby reducing fertility and crop productivity. Similarly, pesticides can directly inhibit nitrogen-fixing bacteria and enzymes responsible for decomposition. Over time, these effects lead to lower soil organic carbon and reduced soil structure.

The current observation of lower organic carbon in high-Phosphate utilization crops like soybean, gram, and maize fits this pattern. Monoculture exacerbates nutrient drawdown. Continuous soybean or wheat without legume phases has been shown to deplete soil carbon and Nitrogen. Diversifying rotations can reverse this. For instance, a 6-year field trial in China found that adding legumes to a wheat-maize system increased soil organic carbon by 8% and improved overall soil health by 45% (Yang et al., 2024). In the present region, limited rotations (74% two-season continuous cropping) are likely to miss these benefits. Farmers' decision-making also reflects low awareness of sustainable alternatives. The fertile soils today might become unproductive in a few years if current practices continue unchecked.

Farmers already observe diminishing yields unless they intensify fertilizer use, indicating that the soil's natural resilience is being eroded. Thus, the paradox is clear: although soil tests show Buldhana's soils are currently productive, the monoculture+pesticide cycle threatens to undermine that fertility and could render soils less productive (or even "infertile") in the coming years if not addressed.

The dominant reasons for chemical use, "instant results" and convenience suggested little exposure to eco-friendly options. Only 20% exclusively used biopesticides, and few mentioned Integrated Pest Management or organic amendments. Agricultural extension efforts may be lacking. Training in Good Agricultural Practices (GAP) and Integrated Pest Management is crucial. Research shows that IPM can dramatically reduce pesticide loads while maintaining or boosting yields. For example, IPM adoption in Asian rice systems cut pesticide use by 64% and raised yields 14%. Likewise, implementing crop rotation, cover crops, and conservation tillage increases soil organic matter and biodiversity while sustaining productivity. In light of these insights, we recommend promoting integrated practices in Buldhana district. Extension programs should teach farmers to monitor pests, rotate crops (e.g. soybean with pulses or cereals), and apply fertilizers judiciously. Subsidies or demonstrations of biopesticides and organic fertilizers could shift mindsets. Encouraging mixed farming (adding legumes or cover crops) would boost soil C and nutrient cycling. Ultimately, balancing high yields with long-term soil management is key to sustaining agriculture here.

4 Conclusions

The present study provided an elaborate assessment of how pesticide use and associated farming practices affected soil health in the semi-arid Vertisols of Buldhana district, Maharashtra. The results indicated that while the soils retained good inherent fertility characterized by slightly alkalinepH, low salinity, and sufficient potassium declining organic carbon and widespread zinc and iron deficiencies reflected emerging nutrient imbalances and reduced biological functioning. These patterns were strongly associated with continuous monocropping, limited organic inputs, and the heavy reliance on synthetic organophosphate pesticides observed among marginal farmers.

Comparative results from organic and forest soils emphasized the restorative potential of organic matter enrichment and biodiversity in sustaining soil fertility. However, the prevailing practices, dominated by short-term chemical dependency, were likely to undermine the long-term productive capacity of the region's Vertisols. Evidence from regional and global studies confirmed that conservation tillage, residue retention, crop diversification, and integrated pest management substantially improved soil organic carbon, micronutrient availability, and microbial health. Implementing such approaches in Buldhana might in future solve pesticide load, enhanced nutrient cycling, and rebuilt the soil's biological resilience.

Experimental validation of these management interventions was not feasible within the scope and timeframe of the present study; however, future work was planned to focus on field-level trials to quantify the effects of integrated soil and pest management practices under local conditions. Transitioning from chemically intensive monocultures toward integrated, organic-amended, and rotation-based systems appeared to represent the most viable pathway to sustain soil productivity and ecological stability in the smallholder farms of Buldhana district.

Acknowledgments

Authors would like to acknowledge the support and guidance of the District Soil Survey and Soil Testing Lab, Buldhana, for providing lab facility and assistance during soil sample analysis and related technical inputs.

Conflict of Interest

The authors have no conflict of interest

Author Contributions

Sneha Kolhe conducted the experiments and farmer surveys, performed data analysis, and prepared the initial draft of the manuscript; Yamini Patil contributed to experimental design, manuscript structuring, draft refinement, and peer review.

AI and AI-Assisted Technologies Use Declaration

The authors used ChatGPT for correcting the grammar

References

Allen, S. E., Grimshaw, H. M., Parkinson, J. A., & Quarmby, C. (1974). *Chemical analysis of ecological materials.*

Bordoloi, R., Das, B., Yam, G., Pandey, P. K., & Tripathi, O. P. (2019). Modeling of water holding capacity using readily available soil characteristics. *Agricultural Research,* 8(3), 347–355.

Bray, R. H., & Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil science,* 59(1), 39–46.

Cakmak, I. (2008). Enrichment of cereal grains with zinc: agronomic or genetic biofortification? *Plant and soil*, 302(1), 1–17.

Chinchmalatpure, A. R., Kumar, S., Rao, G. G., Nikam, V., Prasad, I., Camus, D., & Sharma, D. (2018). Impact of irrigation on soil characteristics of saline Vertisols of Bara tract under Sardar Sarovar canal command of Gujarat. *Journal of the Indian Society of Soil Science*, 66(4), 381–385.

Hadole, S., Sarap, P., Lakhe, S., Dhule, D., & Parmar, J. (2019). Status of micronutrients in soils of Jalgaon District, Maharashtra, India. *Int. J. Curr. Microbiol. App. Sci*, 8(7), 1432–1439.

Jackson, M. L. (2005). *Soil chemical analysis: advanced course: a manual of methods useful for instruction and research in soil chemistry, physical chemistry of soils, soil fertility, and soil genesis*. UW-Madison Libraries parallel press.

Jat, M. L., Gathala, M. K., Choudhary, M., Sharma, S., Jat, H., & Gupta, N. (2023). Conservation agriculture for regenerating soil health and climate change mitigation in smallholder systems of South Asia. *Advances in agronomy*, 181, 183–277.

Jayaraman, S., Sinha, N., Mohanty, M., Hati, K., Chaudhary, R., Shukla, A., Shirale, A., Neenu, S., Naorem, A., & Rashmi, I. (2021). Conservation tillage, residue management, and crop rotation effects on soil major and micro-nutrients in semi-arid Vertisols of India. *Journal of Soil Science and Plant Nutrition*, 21(1), 523–535.

Kausadikar, H., Waikar, S., & Dhamak, A. (2015). Establishment of critical level of Zinc in soil and soybean crop grown on Vertisol by graphical method. *IOSR Journal of Agriculture and Veterinary Science*, 8(1), 66–69.

Kumar, A., Panda, A., Srivastava, L., & Mishra, V. (2017). Effect of conservation tillage on biological activity in soil and crop productivity under rainfed Vertisols of central India. *International Journal of Chemical Studies*, 5(6), 1939–1946.

Lalrintluangi, I. F., Kumar, V., Singh, A., & Bisarya, D. (2019). Impact of Organic Farming on soil fertility and crop productivity. *Jetir January*, 6(1).

Lindsay, W. L., & Norvell, W. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil science society of America journal*, 42(3), 421–428.

Mann, M., Takkar, P., Bansal, R., & Randhawa, N. (1978). Micronutrient status of soil and yield of maize and wheat as influenced by micronutrient and farmyard manure application. *Journal of the Indian Society of Soil Science*, 26(2), 208–214.

Meena, S. N., Sharma, S. K., Singh, P., Meena, B. P., Ram, A., Meena, R. L., Singh, D., Meena, R. B., Nogiya, M., & Jain, D. (2024). Comparative analysis of soil quality and enzymatic activities under different tillage based nutrient management practices in soybean–wheat cropping sequence in Vertisols. *Scientific reports*, 14(1), 6840.

Mehlich, A. (1953). Determination of P, Ca, mg, K, Na, and NH_4. *North Carolina Soil Test Division* (), 2, 23–89.

NABARD. (2024). *Potential Linked Credit plan*. Pune: Maharashtra Regional Office Retrieved from https://www.nabard.org/auth/writereaddata/tender/MAH_Buldhana.pdf

Naphade, M., Sidhu, G., Patil, V., & Thakare, R. (2021). Mapping of chemical characteristics by GIS and fertility status of Jalgaon District Maharashtra, India.

Nelson, W. (1953). The development, evaluation, and use of soil tests for phosphorus availability. *Agronomy*, 4, 153–188.

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (1993). *Laboratory methods for soil analysis*. A working manual.

Pangrikar, P., & Patil, T. (2021). Studies on Distribution of Fungi from Irrigated and Non irrigated Soil of JalnaLocality (MS). *Wesleyan Journal of Research*, 14(1), 21–31.

Panherkar, U., Tarence, T., & David, A. (2020). Assessment of chemical properties of soil from different blocks of Buldhana district Maharashtra. *International Journal of Current Microbiology and Applied Sciences*, 9(11), 3002–3010.

RagaPriya, A., Janaki, P., & Arulmozhiselvan, K. (2020). Effect of repeated atrazine and Pendimethalin application on their bound residues in long term fertilized soil of semi-arid tropic region in India. *Journal of Applied and Natural Science*, 12(4), 471.

Reddy, D., Lakhsmi, V., Kamalakar, J., & Rao, C. (2021). Critical levels of micro and secondary nutrients in soils and crops for optimum plant nutrition. *Int. J. Sci. Res*, 6, 594–595.

Richards, L. A. (1954). *Diagnosis and improvement of saline and alkali soils.* US Government Printing Office.

Savonen, C. (1997). *Soil microorganisms object of new OSU service*. Good Fruit Grower.
http://www. goodfruit. com/archive/1995/6other. html

Shukla, A. K., Tiwari, P. K., & Prakash, C. (2014). Micronutrients deficiencies vis-a-vis food and nutritional security of India. *Indian J. Fert*, 10(12), 94–112.

Stenberg, J. A. (2017). A conceptual framework for integrated pest management. *Trends in plant science*, 22(9), 759–769.

Swaine, M., Bergna, A., Oyserman, B., Vasileiadis, S., Karas, P. A., Screpanti, C., & Karpouzas, D. G. (2025). Impact of pesticides on soil health: identification of key soil microbial indicators for ecotoxicological assessment strategies through meta-analysis. *FEMS Microbiology Ecology*, 101(6), fiaf052.

Thien, S. J. (1979). A flow diagram for teaching texture-by-feel analysis. *Journal of Agronomic education*, 8(1), 54–55.

Uthappa, A., Devakumar, A., Das, B., Mahajan, G., Chavan, S., Jinger, D., Jha, P. K., Kumar, P., Kokila, A., & Krishnamurthy, R. (2024). Comparative analysis of soil quality indexing techniques for various tree based land use systems in semi-arid India. *Frontiers in Forests and Global Change*, 6, 1322660.

Walkley, A. (1947). A critical examination of a rapid method for determining organic carbon in soils – effect of variations in digestion conditions and of inorganic soil constituents. *Soil science*, 63(4), 251–264.

Wenda-Piesik, A., & Piesik, D. (2020). Diversity of species and the occurrence and development of a specialized pest population – a review article. *Agriculture*, 11(1), 16.

Yang, X., Xiong, J., Du, T., Ju, X., Gan, Y., Li, S., Xia, L., Shen, Y., Pacenka, S., & Steenhuis, T. S. (2024). Diversifying crop rotation increases food production, reduces net greenhouse gas emissions and improves soil health. *Nature Communications*, 15(1), 198.

Yasir, M., Hossain, A., & Pratap-Singh, A. (2025). Pesticide Degradation: Impacts on Soil Fertility and Nutrient Cycling. *Environments*, 12(8), 272.

Zhang, Y., Wu, L., Zhang, X., Deng, A., Abdulkareem, R., Wang, D., Zheng, C., & Zhang, W. (2022). Effect of long-term organic amendment application on the vertical distribution of nutrients in a vertisol. *Agronomy*, 12(5), 1162.