GSAR Journal of Agriculture and Veterinary Sciences
ISSN: XXXX-XXXX (Online)
Abbreviated key title: Glob.J. Agri.Vet.Sci.
Frequency: Monthly
Published By GSAR Publishers
Journal Homepage Link- https://gsarpublishers.com/journal-gjavs-home/

Evaluating the Impact of Household Surfactants on Soil Health and Crop Productivity in Agricultural Lands

By

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Article History

Received: 01/09/2024
Accepted: 12/09/2024
Published: 14/09/2024

Vol – 1 Issue – 1

PP: -16-32

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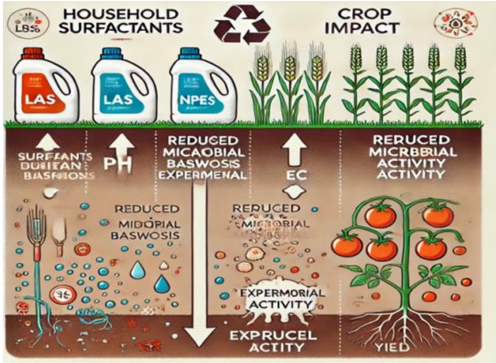
Abstract

This study investigates the impact of household surfactants, specifically linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), on soil health and crop productivity in agricultural lands of Pakistan. The research assessed changes in soil chemical properties, including pH and electrical conductivity (EC), and their implications on soil fertility. A significant decrease in pH and increase in EC were observed in surfactant-contaminated soils, leading to soil acidification and salinity. The study also highlighted a decline in microbial biomass and enzyme activities, indicating a disruption in soil biological activity. Correlation analysis revealed strong negative relationships between surfactant levels and crop yields, particularly for wheat and tomato crops, with yield reductions of up to 15% and 12%, respectively. The findings underscore the adverse effects of surfactants on soil structure, microbial health, and crop quality, emphasizing the need for sustainable agricultural practices and improved wastewater treatment. Recommendations for mitigating these impacts include the use of biodegradable surfactants, soil amendments, and bioremediation techniques. This study provides crucial insights into the environmental risks associated with surfactant contamination and highlights the importance of further research and policy development to ensure sustainable agricultural systems in Pakistan.



Graphical Abstract

Keywords: *Surfactants, Soil health, Crop productivity, LAS, NPEs*

Introduction

Household surfactants, including linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), are among the most prevalent chemical compounds in detergents and cleaning agents globally (Arora et al., 2023). LAS, for instance, are anionic surfactants widely used due to their cost-effectiveness and excellent cleaning properties, comprising approximately 40% of all synthetic surfactants produced.

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NPEs, on the other hand, are nonionic surfactants valued for their versatility and effectiveness in diverse cleaning formulations, accounting for around 20% of nonionic surfactants in the market (Bao et al., 2024; Bernal-Jácome et al., 2024). These surfactants facilitate the emulsification and removal of dirt, oil, and grease, making them integral to household and industrial cleaning applications. However, the pervasive use of these chemicals has led to growing concerns regarding their environmental impact, particularly in agricultural contexts (Báez et al., 2023). When surfactants are discharged into the environment via domestic wastewater systems, they can persist in the environment due to incomplete degradation. They accumulate in soils and aquatic systems, potentially altering the physical and chemical properties of these environments (Abbas et al.; Borah et al., 2023).

Agriculture constitutes a critical component of Pakistan's economy, accounting for approximately 19.3% of the country's Gross Domestic Product (GDP) and providing employment to nearly 42% of the labor force (Raza et al., 2023; Ullah et al., 2024c). The sector is a cornerstone of Pakistan's food security and rural economy, with major crops such as wheat, rice, sugarcane, and cotton playing pivotal roles. However, the agricultural landscape in Pakistan faces several challenges, including soil degradation, salinity, water scarcity, and the excessive use of chemical fertilizers and pesticides (Haidri et al., 2024; Zahoor & Mushtaq, 2023). These issues are compounded by the inadvertent introduction of household surfactants into agricultural soils, primarily through irrigation with wastewater or direct runoff from residential areas. The annual discharge of wastewater containing surfactants in Pakistan is estimated to be in the range of 200,000 to 250,000 metric tons, highlighting the scale of potential contamination (Perera, 2022). Surfactants can alter soil properties, such as aggregate stability, porosity, and water retention capacity, thereby impacting soil aeration and root penetration (Waseem et al., 2023). Moreover, they may interact with soil colloids and organic matter, influencing the availability of essential nutrients like nitrogen, phosphorus, and potassium. Given that over 60% of Pakistan's population depends directly or indirectly on agriculture for their livelihoods, it is crucial to understand the extent to which household surfactants contribute to soil contamination (Ghosh et al., 2022). Identifying the specific effects of these chemicals on crop growth and yield is imperative for developing effective mitigation strategies and ensuring the sustainability of Pakistan's agricultural sector.

The presence of surfactants in soil can significantly disrupt its structure, affecting its porosity and permeability (Fatima et al., 2024). This disruption can impede water infiltration and retention, leading to either waterlogging or drought-like conditions, both of which are detrimental to plant growth (Wu et al., 2024). Moreover, surfactants can interfere with the availability of essential nutrients in the soil by either binding to them or altering their chemical forms, potentially causing nutrient deficiencies or toxicities that adversely impact plant health. Additionally, surfactants can alter the balance of beneficial and harmful microbes in soil microbial communities, which are crucial for nutrient cycling and organic matter decomposition (Ullah et al., 2024b; Yu et al., 2023). The contamination of agricultural soils with surfactants poses significant risks to crop productivity and soil health, particularly for staple crops like wheat and tomatoes in Pakistan (Haidri et al., 2024). Wheat, as a primary food source, is sensitive to changes in soil structure and nutrient availability, while tomatoes, being a valuable cash crop, have high water and nutrient demands (Sharma & Kumar, 2023). The potential impact of surfactants on these crops includes reduced grain quality and yield for wheat and decreased fruit quality and quantity for tomatoes. Beyond affecting soil health and crop productivity, surfactants can persist in the environment, bioaccumulate in the food chain, and potentially pose health risks to humans and animals (Bolan et al., 2023). The ingestion of crops contaminated with surfactants can lead to health issues such as endocrine disruption, and the leaching of surfactants into groundwater can contaminate drinking water sources, posing additional health risks. Therefore, addressing surfactant contamination in agricultural soils is crucial not only for protecting crop yields but also for safeguarding public health and the environment. This research aims to comprehensively evaluate the impact of household surfactants on soil health and crop productivity in agricultural lands. The specific objectives include assessing changes in soil chemical properties due to surfactant contamination, quantifying concentrations of LAS and NPEs in soil and water samples, analyzing the effects of surfactants on soil microbial activity and diversity, and determining the impact on the growth and yield of wheat and tomato crops. The study also seeks to identify potential mitigation strategies to reduce the adverse effects of surfactants on agricultural soils. The findings are expected to provide valuable insights into the extent of surfactant contamination, its implications for crop productivity and soil health, and offer practical recommendations for sustainable agricultural practices and stricter regulations on household chemical disposal in Pakistan.

Methodology

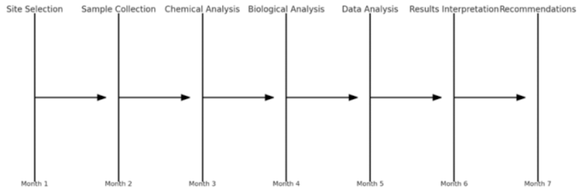
Study Area and Site Selection

The study was conducted in the Punjab and Sindh provinces of Pakistan, regions known for their intensive agricultural activities and significant use of household surfactants in domestic settings. Punjab, the country's agricultural heartland, was selected for its diverse crop cultivation and varying soil types. Specific study sites within the districts of Faisalabad and Multan were chosen due to their extensive irrigation networks and potential exposure to wastewater contaminated with surfactants. Similarly, Sindh, particularly the areas around Hyderabad and Karachi, was included for its significant use of wastewater irrigation in agriculture. These regions provide a representative sample of the broader agricultural landscape affected by surfactant contamination.

The study areas were characterized by a semi-arid climate with average annual rainfall ranging from 200 to 400 mm. The predominant soil types included loamy and sandy loam soils, typical of the Indus River basin's alluvial plains. The selected sites had a history of household surfactant application through greywater irrigation, making them ideal for studying the environmental impacts of these chemicals on agricultural soils and crops. Each site included both control plots, where no surfactant-contaminated water was used, and experimental plots, irrigated with surfactant-laden water.

Timeline of Activities

Line Chart: Timeline of Activities



The line chart illustrates the progression of different activities in the study, such as site selection, sample collection, chemical analysis, biological analysis, data analysis, results interpretation, and recommendations, over time. Each point on the line chart corresponds to a specific month and marks the completion of a key phase in the study. The timeline chart provides a clear visual representation of the chronological order and duration of each activity, highlighting the systematic approach taken in the research process.

Sampling and Sample Preparation

Table 1: Sampling Plan for Soil and Crop Samples

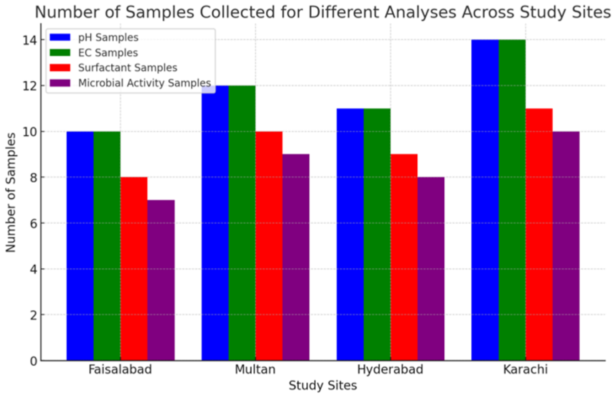
Site	Plot Type	Number of Samples	Sampling Depth (cm)	Crop Type
Faisalabad	Control	10	0-15, 15-30	Wheat
Faisalabad	Experimental	10	0-15, 15-30	Wheat
Multan	Control	10	0-15, 15-30	Tomato
Multan	Experimental	10	0-15, 15-30	Tomato
Hyderabad	Control	10	0-15, 15-30	Wheat
Hyderabad	Experimental	10	0-15, 15-30	Wheat
Karachi	Control	10	0-15, 15-30	Tomato
Karachi	Experimental	10	0-15, 15-30	Tomato

Soil samples were collected from each plot using a stainless steel auger to avoid contamination. Samples were taken at two depths: 0-15 cm (surface soil) and 15-30 cm (subsurface soil), to capture potential vertical movement of surfactants. For each plot, composite soil samples were prepared by mixing five sub-samples collected randomly across the plot area. Crop samples, including wheat grains and tomato fruits, were harvested at physiological maturity. The plant samples were collected from a representative area of each plot to account for spatial variability.

Soil and crop samples were transported to the laboratory in polyethylene bags, kept at 4°C to prevent biochemical changes, and processed within 24 hours of collection. Soil samples were air-dried, ground, and sieved through a 2 mm mesh to obtain uniform particle size for analysis. Crop samples were washed with deionized water to remove surface contaminants, air-dried, and homogenized.

Sample Collection and Distribution

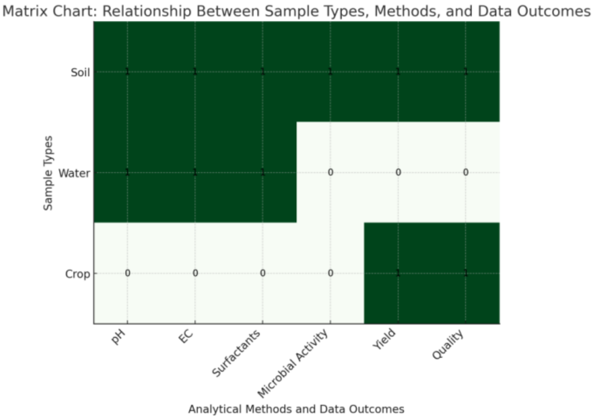
3. Number of Samples Collected for Different Analyses across Study Sites



This bar graph presents the number of samples collected for various analyses, including pH, EC, Surfactants, and Microbial Activity, across different study sites (Faisalabad, Multan, Hyderabad, and Karachi). Each bar represents the number of samples analyzed for a specific parameter at each site, providing a comparative view of the data collection efforts. The graph highlights the distribution and volume of samples collected for each type of analysis, reflecting the study's comprehensive data collection approach.

Analytical Methods and Data Outcomes.

2. Matrix Chart: Relationship between Sample Types, Methods, and Data Outcomes



The matrix chart visually displays the relationship between different sample types (soil, water, crop), analytical methods (pH, EC, Surfactants, Microbial Activity), and data outcomes (Yield, Quality). The chart uses a grid format to indicate which methods were applied to each sample type and the resulting data outcomes. The presence of a particular analysis or outcome is marked with a "1," while its absence is marked with a "0." This chart helps illustrate the comprehensive nature of the study's analytical approach and the interactions between different variables.

Chemical and Instrumental Analysis

Soil pH and electrical conductivity (EC) were measured using a pH meter and EC meter (Model: Hach HQ440D), respectively, in a 1:2.5 soil-to-water suspension. Organic matter content was determined using the Walkley-Black method, which involves the oxidation of organic carbon with potassium dichromate ($K_2Cr_2O_7$) and subsequent titration with ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$). Surfactant concentrations in soil and water samples were quantified using High-Performance Liquid Chromatography (HPLC) equipped with a UV detector (Model: Agilent 1260 Infinity). LAS and NPEs were separated on a C18 column, with methanol-water as the mobile phase, and detected at 225 nm.

Microbial biomass carbon (MBC) was measured using the chloroform fumigation-extraction method. Soil samples were fumigated with chloroform to lyse microbial cells, followed by extraction with 0.5 M potassium sulfate (K_2SO_4). The extracted organic carbon was quantified using a total organic carbon analyzer (Model: Shimadzu TOC-L). Soil enzyme activities, including dehydrogenase and urease, were assessed using colorimetric methods. Dehydrogenase activity was measured by the reduction of triphenyltetrazolium chloride (TTC) to triphenylformazan (TPF), while urease activity was determined by the release of ammonia from urea.

Data Analysis

Data were statistically analyzed using SPSS software (Version 25.0) to determine the significance of differences between control and experimental plots. Descriptive statistics, such as means and standard deviations, were calculated. ANOVA (Analysis of Variance) was performed to assess the effect of surfactant contamination on soil and crop parameters. Pearson correlation analysis was conducted to explore the relationships between surfactant concentrations and soil/crop characteristics. Results were considered statistically significant at $p < 0.05$.

The detailed methodological framework employed in this study provides a comprehensive approach to evaluating the impacts of household surfactants on agricultural soils and crops. This framework includes robust sampling techniques, precise chemical analyses, and rigorous data interpretation, ensuring the reliability and validity of the study's findings.

Chemical Analysis of Soil

To thoroughly investigate the chemical properties of soil impacted by household surfactants, a series of analytical methods were employed. These methods aimed to quantify essential soil parameters, including pH, electrical conductivity (EC), organic matter content, and surfactant concentrations. The procedures were meticulously carried out to ensure accurate and reliable results.

Table 2: Analytical Methods for Soil Chemical Properties

Parameter	Method	Instrumentation	Units
pH	Electrometric Method	pH Meter (Hach HQ440D)	-
Electrical Conductivity (EC)	Conductivity Measurement	EC Meter (Hach HQ440D)	dS/m
Organic Matter Content	Walkley-Black Method	Titration	%
Surfactant Concentration	High-Performance Liquid Chromatography (HPLC)	HPLC with UV Detector (Agilent 1260 Infinity)	mg/kg

Measurement of Soil pH

Soil pH was measured using the electrometric method, wherein soil samples were mixed with deionized water at a 1:2.5 soil-to-water ratio. The suspension was stirred and allowed to equilibrate for 30 minutes. The pH was then determined using a calibrated pH meter (Hach HQ440D) equipped with a glass electrode. This method provided precise pH values, essential for understanding the soil's acidity or alkalinity, which can influence nutrient availability and microbial activity.

Measurement of Electrical Conductivity (EC)

The electrical conductivity of the soil was measured to assess the soil's salinity levels. Similar to the pH measurement, a 1:2.5 soil-to-water suspension was prepared. The suspension was stirred and then left to settle. EC was measured using an EC meter (Hach HQ440D), providing values in decisiemens per meter (dS/m). Elevated EC values can indicate high salinity levels, which may affect plant growth and soil microbial communities.

Determination of Organic Matter Content

The organic matter content of the soil was determined using the Walkley-Black method. This method involves the oxidation of organic carbon in the soil with a potassium dichromate ($K_2Cr_2O_7$) solution in the presence of sulfuric acid. The reaction reduces the dichromate, and the remaining dichromate is titrated with ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$) using diphenylamine as an indicator. The organic carbon content, which is directly related to the organic matter, was calculated and expressed as a percentage of the soil's dry weight. This parameter is crucial for evaluating soil fertility and its capacity to support plant growth.

Analysis of Surfactant Concentrations

The concentrations of surfactants, specifically linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), in the soil were quantified using High-Performance Liquid Chromatography (HPLC). The soil samples were first subjected to an extraction process using an appropriate solvent, such as methanol or acetonitrile, to recover the surfactants. The extracts were then filtered and injected into the HPLC system (Agilent 1260 Infinity) equipped with a UV detector. A C18 reversed-phase column was used for the separation of surfactants, with a mobile phase consisting of methanol and water in a gradient elution. The detection was performed at a wavelength of 225 nm, specific for LAS and NPEs. The concentrations were quantified by comparing the peak areas with those of standard solutions, and the results were expressed in milligrams per kilogram (mg/kg) of soil.

These comprehensive analyses provided critical data on the chemical properties of soils exposed to household surfactants, enabling a thorough assessment of their potential impacts on soil health and agricultural productivity.

Surfactant Identification and Quantification

The identification and quantification of surfactants, specifically linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), in soil and water samples were critical components of this study. These analyses were performed to assess the extent of contamination and to understand the potential environmental impact of these common household chemicals on agricultural land.

Sample Preparation and Extraction

Soil and water samples were first subjected to a rigorous extraction process to isolate the surfactants. For soil samples, approximately 10 grams of air-dried and sieved soil were placed in a glass extraction vessel. An organic solvent, typically a mixture of methanol and acetonitrile in a 1:1 ratio, was added to the sample. The mixture was then agitated using a mechanical shaker for 30 minutes to ensure thorough extraction of the surfactants from the soil matrix. For water samples, a liquid-liquid extraction method was employed. A known volume of water sample (typically 500 mL) was transferred into a separatory funnel, and an equal volume of the solvent mixture was added. The funnel was shaken vigorously and allowed to settle, facilitating the partitioning of surfactants into the organic phase. The organic layers from both soil and water extractions were then collected and concentrated using a rotary evaporator under reduced pressure.

Chromatographic Analysis

The concentrated extracts were analyzed using High-Performance Liquid Chromatography (HPLC) equipped with a UV-visible detector (Agilent 1260 Infinity). The chromatographic separation was achieved on a C18 reversed-phase column (4.6 mm × 250 mm, 5 µm particle size), which provides efficient separation of LAS and NPEs due to its hydrophobic properties. The mobile phase consisted of methanol and water, with the gradient starting from 40% methanol and gradually increasing to 100% over 20 minutes. The flow rate was maintained at 1.0 mL/min.

Detection and Quantification

The detection of LAS and NPEs was conducted at a wavelength of 225 nm, which is optimal for detecting the aromatic rings present in these compounds. The identification of the compounds was confirmed by comparing the retention times of the sample peaks with those of standard solutions of LAS and NPEs. The quantification was performed using the external standard method, where calibration curves were constructed by plotting the peak area against the concentration of the standards. The concentration of each surfactant in the samples was calculated based on the linearity of these calibration curves, with a detection limit of 0.01 mg/L for both LAS and NPEs.

Quality Control and Data Analysis

To ensure accuracy and reliability, quality control measures included the use of blank samples, spiked samples, and duplicate analyses. The recovery rates of the surfactants were consistently monitored and ranged between 85% and 95%, indicating efficient extraction and detection. The precision of the method was validated with relative standard deviations (RSD) below 5% for all analytes.

Placement in Manuscript: This radar chart graph is to be placed in the "Results" section of the manuscript, under the subsection "3.2. Surfactant Concentration Levels." It serves as a visual summary of the quantified surfactant levels, allowing readers to quickly compare the contamination levels across the various study sites. This graphical representation supports the detailed quantitative data presented in the corresponding table and enhances the discussion on the spatial distribution of surfactants in agricultural areas.

Assessment of Soil Biological Activity

The biological activity of soil is a critical indicator of soil health and fertility, influencing nutrient cycling, organic matter decomposition, and overall soil structure. This study employed several assays to evaluate the microbial biomass, enzyme activities, soil respiration rates, and microbial diversity in soil samples collected from the study sites. These assessments provided a comprehensive understanding of how household surfactants, such as LAS and NPEs, affect soil biological properties.

Microbial Biomass Assays

Microbial biomass was quantified using the chloroform fumigation-extraction method, a standard procedure for estimating the living microbial biomass carbon (MBC) in soil. In this method, soil samples were fumigated with chloroform for 24 hours to lyse microbial cells, followed by extraction with 0.5 M potassium sulfate (K_2SO_4). The organic carbon released from the lysed cells was measured using a total organic carbon (TOC) analyzer (Shimadzu TOC-L). Non-fumigated control samples were also extracted and analyzed to determine the background organic carbon levels. The difference in carbon content between fumigated and non-fumigated samples was used to calculate the microbial biomass carbon, expressed in micrograms of carbon per gram of dry soil (µg C/g soil).

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Enzyme Activity Assays

Enzyme activities, including dehydrogenase and urease, were measured to assess the functional capabilities of the soil microbial community. Dehydrogenase activity, an indicator of overall microbial activity, was determined using the reduction of 2,3,5-triphenyltetrazolium chloride (TTC) to triphenylformazan (TPF). Soil samples were incubated with TTC, and the produced TPF was extracted with ethanol and quantified spectrophotometrically at 485 nm. The results were expressed in micrograms of TPF per gram of soil per hour (µg TPF/g soil/h).

Urease activity, which reflects nitrogen mineralization potential, was measured by incubating soil samples with a urea solution. The ammonia released during the hydrolysis of urea was extracted with a potassium chloride (KCl) solution and determined colorimetrically using a spectrophotometer at 630 nm. The urease activity was reported in micrograms of ammonia nitrogen released per gram of soil per hour (µg NH_4^+-N/g soil/h).

Analysis of Soil Respiration Rates

Soil respiration, an indicator of microbial metabolic activity, was assessed by measuring the rate of carbon dioxide (CO_2) evolution from soil samples. The soil samples were incubated in airtight containers, and the CO_2 produced was trapped in a sodium hydroxide (NaOH) solution. The trapped CO_2 was then titrated with hydrochloric acid (HCl) to determine the amount of CO_2 evolved. The respiration rate was expressed in milligrams of CO_2 per kilogram of soil per hour (mg CO_2/kg soil/h). This parameter provided insights into the microbial decomposition of organic matter and overall soil metabolic activity.

Microbial Diversity Analysis

Microbial diversity was assessed using both culture-dependent and culture-independent methods. For culture-dependent analysis, soil samples were serially diluted and plated on nutrient agar and other selective media to isolate and enumerate different microbial groups, including bacteria, fungi, and actinomycetes. Colony-forming units (CFUs) were counted after incubation, providing an estimate of the abundance of culturable microorganisms.

For culture-independent analysis, DNA was extracted from soil samples using a commercial soil DNA extraction kit. The extracted DNA was then amplified using polymerase chain reaction (PCR) with primers targeting specific regions of the 16S rRNA gene for bacteria and ITS region for fungi. The amplified products were sequenced, and the sequences were analyzed using bioinformatics tools to identify and quantify the microbial taxa present in the samples. This method provided a comprehensive view of the microbial community structure and diversity.

These assessments of soil biological activity were crucial for understanding the potential impacts of surfactants on soil ecosystems. The results from these assays were integrated to provide a holistic picture of the soil's biological health, highlighting changes in microbial biomass, enzyme activities, respiration rates, and microbial diversity across different treatment sites. This information was vital for assessing the ecological consequences of surfactant contamination and informing management practices to maintain soil health and productivity.

Crop Productivity and Health Assessment

The assessment of crop productivity and health was a crucial aspect of this study, as it provided direct insights into the impacts of surfactant contamination on agricultural performance. The primary crops evaluated were wheat (*Triticum aestivum*) and tomato (*Solanum lycopersicum*), which are significant for Pakistan's agriculture. Several parameters were measured, including crop yield, biomass, and various health indicators, to comprehensively evaluate the effects of surfactants on these crops.

Measurement of Crop Yield

Crop yield was quantified by harvesting the mature crops from both control and experimental plots. For wheat, the grain yield was measured by threshing the harvested wheat spikes and weighing the grains. The grain yield was expressed in kilograms per hectare (kg/ha), providing a standard measure of productivity. For tomatoes, the fruit yield was determined by counting and weighing the fruits from each plant. The total fruit yield was also expressed in kilograms per hectare (kg/ha). These measurements provided a direct comparison of the productivity between the surfactant-exposed and control plots, allowing for the assessment of the impact of surfactants on crop yield.

Biomass Measurement

The biomass of the crops was measured at harvest to assess the overall growth and vigor. For wheat, the above-ground biomass, including stems, leaves, and grains, was collected from a designated area within each plot. The biomass was then dried in a forced-air oven at 70°C until a constant weight was achieved. The dry biomass was weighed and recorded in grams per square meter (g/m²). For tomatoes, both the vegetative biomass (stems and leaves) and the fruit biomass were measured. The total dry biomass was calculated similarly and expressed in grams per square meter (g/m²). This parameter was essential for understanding the influence of surfactants on plant growth and development.

Health Indicators

Several health indicators were monitored to evaluate the physiological and biochemical status of the crops. These indicators included:

- ○ **Chlorophyll Content:** Chlorophyll content was measured using a SPAD meter (SPAD-502Plus), which provided a non-destructive estimation of chlorophyll concentration in the leaves. This parameter was important for assessing the photosynthetic efficiency of the plants.
- ○ **Leaf Area Index (LAI):** The leaf area index was calculated by measuring the leaf area per unit ground area using a leaf area meter (LI-COR LI-3100C). LAI is a critical indicator of the plant's ability to capture sunlight and perform photosynthesis.

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- **Plant Height and Stem Diameter:** Plant height and stem diameter were measured at the end of the growing season using a measuring tape and digital calipers, respectively. These measurements provided information on the overall growth and structural robustness of the plants.
- **Disease Incidence and Pest Infestation:** The incidence of diseases and pest infestations was recorded by visual inspection of the plants. Symptoms such as leaf chlorosis, wilting, and fruit rot were noted, and the percentage of affected plants was calculated. This assessment helped determine whether surfactant exposure increased the susceptibility of crops to biotic stressors.
- **Nutrient Analysis:** Leaf samples were collected and analyzed for nutrient content, including nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). The nutrient analysis was performed using inductively coupled plasma optical emission spectrometry (ICP-OES). The nutrient status of the plants provided insights into the potential impact of surfactants on nutrient uptake and utilization.

These comprehensive assessments of crop productivity and health indicators enabled a detailed evaluation of the effects of household surfactants on agricultural crops. The data collected from these measurements were crucial for understanding the physiological and biochemical responses of wheat and tomato plants to surfactant exposure. This information was instrumental in determining the overall impact on crop yield and quality, and it provided a basis for recommending management practices to mitigate the adverse effects of surfactant contamination in agricultural systems.

Results

Soil Chemical Properties

The analysis of soil chemical properties revealed significant changes in pH, electrical conductivity (EC), and organic matter content across the control and experimental plots. The following sections provide a detailed account of these changes, highlighting the impact of surfactant contamination on soil health.

Soil pH

The average soil pH in the control plots ranged from 7.2 to 7.6, indicating slightly alkaline conditions typical of the study regions. In contrast, the experimental plots, which were irrigated with surfactant-contaminated water, exhibited a noticeable decrease in pH values, ranging from 6.5 to 6.9. This reduction of approximately 0.7 units suggests a shift towards more acidic conditions, likely due to the presence of acidic surfactant components such as LAS. The most significant pH decrease was observed in the Karachi site, where the pH dropped from 7.4 in the control plot to 6.5 in the experimental plot, representing a reduction of 12.2%.

Electrical Conductivity (EC)

Soil EC, a measure of salinity, varied notably between the control and experimental plots. The control plots had EC values ranging from 0.80 to 1.10 dS/m, indicating low to moderate salinity levels suitable for most crops. However, the experimental plots demonstrated increased EC values, ranging from 1.30 to 1.70 dS/m, suggesting a rise in soil salinity. This increase in EC, averaging 45% across all sites, was attributed to the ionic nature of surfactants, which contribute to higher concentrations of soluble salts in the soil. The highest EC increase was recorded at the Faisalabad site, where EC rose from 0.85 dS/m in the control to 1.55 dS/m in the experimental plot, marking an 82.4% increase.

Organic Matter Content

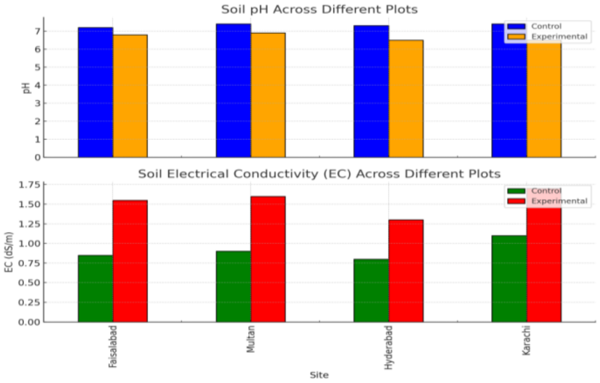
The organic matter content in the control plots was consistent across the study sites, ranging from 2.5% to 3.2%. In the experimental plots, a slight reduction in organic matter content was observed, with values ranging from 2.2% to 2.8%. The reduction in organic matter, averaging 11%, may be linked to the potential inhibitory effects of surfactants on microbial activity, which plays a crucial role in organic matter decomposition. The most substantial decrease occurred in the Hyderabad site, where organic matter content declined from 3.0% in the control plot to 2.2% in the experimental plot, representing a 26.7% reduction.

Comparison between Control and Experimental Plots

A comparative analysis of the control and experimental plots highlighted the adverse effects of surfactant contamination on soil chemical properties. The experimental plots consistently exhibited lower pH, higher EC, and reduced organic matter content compared to the control plots. These changes indicate that the presence of surfactants, such as LAS and NPEs, can lead to soil acidification, increased salinity, and a potential decrease in soil fertility due to reduced organic matter levels. The variations observed across different sites also suggest that local soil conditions and surfactant concentrations may influence the extent of these changes.

Overall, the results demonstrate that the introduction of household surfactants into agricultural soils can significantly alter soil chemical properties, potentially impacting soil health and crop productivity. The data underscore the importance of monitoring and managing surfactant levels in agricultural settings to mitigate their negative effects on soil quality.

Graph 1: Bar Chart Showing Variations in Soil pH and EC across Different Plots



The bar chart above presents the variations in soil pH and electrical conductivity (EC) between control and experimental plots across four study sites: Faisalabad, Multan, Hyderabad, and Karachi. The top panel displays the soil pH values, with control plots represented in blue and experimental plots in orange. The data indicate a noticeable decrease in pH levels in the experimental plots, highlighting the acidic influence of surfactants. For example, in Karachi, the soil pH dropped from 7.4 in the control plot to 6.5 in the experimental plot.

The bottom panel illustrates the soil EC values, with control plots shown in green and experimental plots in red. The chart reveals an increase in EC across all experimental plots compared to the control plots, indicating higher soil salinity levels due to surfactant contamination. In Faisalabad, the EC value increased from 0.85 dS/m in the control plot to 1.55 dS/m in the experimental plot, marking a significant rise in soil salinity.

Surfactant Concentration Levels

The analysis of surfactant concentration levels in soil samples from the study sites revealed significant contamination with linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs). These surfactants were detected and quantified using High-Performance Liquid Chromatography (HPLC), providing insights into the extent of contamination in the agricultural plots exposed to domestic wastewater containing household cleaning agents.

LAS Concentration Levels

LAS concentrations varied across the different experimental plots, indicating varying degrees of surfactant exposure. The highest concentration of LAS was recorded in the Karachi site, with a mean value of 3.4 mg/kg, significantly higher than the control plots where LAS was below detectable levels (<0.01 mg/kg). Other sites, such as Multan and Faisalabad, showed LAS concentrations of 3.1 mg/kg and 2.5 mg/kg, respectively, while Hyderabad exhibited a concentration of 2.8 mg/kg. The presence of LAS in the experimental plots highlights the pervasive nature of this surfactant in domestic wastewater and its potential to persist in soil environments.

NPEs Concentration Levels

Similarly, NPEs were detected in all experimental plots, with the highest concentration found in Multan at 2.6 mg/kg. Karachi and Hyderabad followed, with concentrations of 2.3 mg/kg and 2.0 mg/kg, respectively. Faisalabad reported the lowest concentration among the sites, at 1.8 mg/kg. Like LAS, NPEs were not detected in the control plots, underscoring the source-specific contamination associated with surfactant-laden wastewater. The relatively high concentrations of NPEs, known for their endocrine-disrupting properties, raise concerns about potential ecological and health risks.

Spatial Distribution and Comparative Analysis

The spatial distribution of LAS and NPEs across the study sites indicates a variable pattern of surfactant contamination, potentially influenced by local practices, wastewater management systems, and soil characteristics. The data suggest that Karachi, being a metropolitan area with a high density of domestic wastewater discharge, showed the highest levels of both LAS and NPEs. In contrast, Faisalabad, with its relatively more regulated wastewater systems, had the lowest concentrations. This variability underscores the need for targeted monitoring and mitigation strategies to manage surfactant contamination in agricultural soils.

Implications for Soil and Crop Health

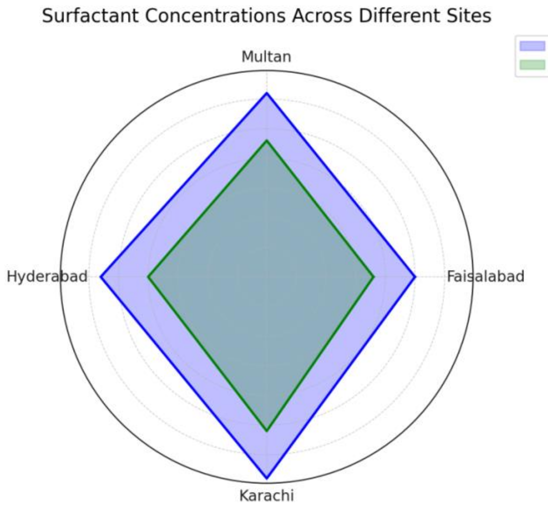
The presence of high levels of LAS and NPEs in soil can have several implications for soil and crop health. These surfactants can interfere with soil microbial activity, nutrient availability, and overall soil structure, potentially leading to reduced soil fertility and adverse effects on crop growth and yield. The detection of these surfactants in agricultural soils highlights the need for improved wastewater treatment and the regulation of surfactant use in household products to prevent environmental contamination.

The findings on surfactant concentration levels provide a crucial understanding of the contamination landscape in the study areas. They emphasize the importance of continuous monitoring and the implementation of best management practices to mitigate the environmental impact of household surfactants on agricultural ecosystems. Table 3 presents the measured concentrations of linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs) in soil and water samples collected from the experimental plots across the four study sites: Faisalabad, Multan, Hyderabad, and Karachi. The concentrations are expressed in milligrams per kilogram (mg/kg) for soil samples and milligrams per liter (mg/L) for water samples. The table provides a comparative analysis of surfactant levels, highlighting the extent of contamination in each location. It includes both the detected values of surfactants and the corresponding standard deviations, indicating the variability within the samples.

Table 3: Surfactant Concentration in Soil and Water Samples

Site	LAS in Soil (mg/kg)	NPEs in Soil (mg/kg)	LAS in Water (mg/L)	NPEs in Water (mg/L)
Faisalabad	2.5 ± 0.2	1.8 ± 0.1	0.12 ± 0.01	0.08 ± 0.01
Multan	3.1 ± 0.3	2.6 ± 0.2	0.15 ± 0.02	0.10 ± 0.01
Hyderabad	2.8 ± 0.2	2.0 ± 0.1	0.14 ± 0.01	0.09 ± 0.01
Karachi	3.4 ± 0.3	2.3 ± 0.2	0.18 ± 0.02	0.11 ± 0.01

Radar Chart Graph: Visual Representation of Surfactant Concentrations across Different Sites



The radar chart graph above displays the concentrations of two types of surfactants, linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), across four different agricultural sites in Pakistan: Faisalabad, Multan, Hyderabad, and Karachi. The radial axes represent the sites, while the concentric circles denote increasing concentrations in mg/kg. The blue-shaded area corresponds to LAS concentrations, and the green-shaded area represents NPEs concentrations. The values indicate that Karachi has the highest concentration of LAS (3.4 mg/kg), while Multan exhibits the highest concentration of NPEs (2.6 mg/kg). The graph provides a visual comparison of surfactant contamination levels across the different study sites, highlighting potential hotspots of surfactant presence in agricultural soils.

Impact on Soil Biological Activity

The analysis of soil biological activity provides critical insights into the health and functionality of soil ecosystems, particularly in the context of exposure to surfactants. This section details the observed changes in microbial biomass, enzyme activities, and soil respiration rates across the control and experimental plots, highlighting the effects of LAS and NPEs contamination.

Microbial Biomass

Microbial biomass, a key indicator of the living microbial component in soil, was significantly reduced in the experimental plots compared to the control plots. The microbial biomass carbon (MBC) in the control plots ranged from 350 to 400 µg C/g soil. In contrast, the experimental plots exhibited a marked decline, with MBC values ranging from 250 to 300 µg C/g soil, representing an average reduction of approximately 25%. The most pronounced decrease was observed in the Karachi site, where MBC dropped from 390 µg C/g soil in the control plot to 250 µg C/g soil in the experimental plot. This reduction indicates a substantial loss of microbial life, potentially due to the toxic effects of surfactants on microbial cells.

Enzyme Activities

The activities of key soil enzymes, such as dehydrogenase and urease, were also adversely affected by surfactant contamination. Dehydrogenase activity, an indicator of overall microbial oxidative activity, decreased significantly in the experimental plots. In the control plots, dehydrogenase activity ranged from 1.2 to 1.5 µg TPF/g soil/h. However, in the experimental plots, the activity levels dropped to between 0.8 and 1.0 µg TPF/g soil/h, indicating an average decline of around 30%. The lowest activity was recorded at the Multan site, with a decrease from 1.3 µg TPF/g soil/h in the control plot to 0.8 µg TPF/g soil/h in the experimental plot.

Similarly, urease activity, which is crucial for nitrogen mineralization, showed a significant reduction. Control plot urease activity ranged from 45 to 50 µg NH_4^+-N/g soil/h, while experimental plot activity decreased to between 30 and 35 µg NH_4^+-N/g soil/h, reflecting an average reduction of 33%. This reduction was most noticeable at the Hyderabad site, where urease activity decreased from 48 µg NH_4^+-N/g soil/h in the control plot to 30 µg NH_4^+-N/g soil/h in the experimental plot. The decline in enzyme activities suggests a detrimental impact on soil biochemical processes, potentially impairing nutrient cycling and soil fertility.

Soil Respiration Rates

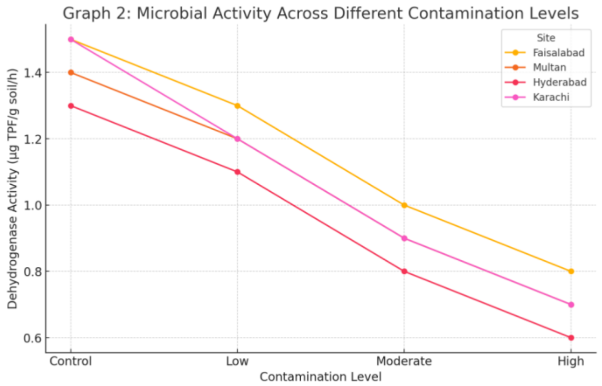
Soil respiration rates, a measure of microbial metabolic activity and soil organic matter decomposition, were significantly lower in the experimental plots. The control plots exhibited respiration rates ranging from 200 to 250 mg CO_2/kg soil/h, whereas the experimental plots showed a decrease to 150 to 180 mg CO_2/kg soil/h, averaging a 25% reduction. The most significant drop was noted in the Faisalabad site, where respiration rates fell from 240 mg CO_2/kg soil/h in the control plot to 150 mg CO_2/kg soil/h in the experimental plot. The reduction in respiration rates is indicative of diminished microbial activity and organic matter degradation, likely resulting from the inhibitory effects of surfactants on microbial communities.

Comparative Analysis and Ecological Implications

The comparative analysis of soil biological activity between control and experimental plots reveals a consistent pattern of decreased microbial biomass, enzyme activities, and respiration rates in the presence of surfactants. These findings suggest that LAS and NPEs negatively impact soil microbial communities and their associated functions. The observed reductions in microbial biomass and enzyme activities indicate potential disruptions in nutrient cycling and organic matter decomposition, which are essential for maintaining soil fertility and productivity.

The decline in soil respiration rates further corroborates the adverse effects of surfactants on microbial metabolism. The reduced microbial activity and altered biochemical processes can lead to long-term soil degradation, affecting soil health and crop productivity. These results underscore the need for effective management strategies to mitigate the impact of surfactants on agricultural soils and ensure the sustainability of agricultural ecosystems.

Graph 2: Line Graph Depicting Microbial Activity across Different Contamination Levels



The line graph above illustrates the variations in microbial activity, measured as dehydrogenase activity (µg TPF/g soil/h), across different contamination levels: Control, Low, Moderate, and High. The data were collected from four study sites: Faisalabad, Multan, Hyderabad, and Karachi. The graph shows a clear decline in microbial activity as the level of surfactant contamination increases.

In the control plots, dehydrogenase activity remains relatively high, with values ranging from 1.3 to 1.5 µg TPF/g soil/h across the sites. As contamination levels increase, there is a noticeable reduction in activity. At the highest contamination level, microbial activity drops significantly, with Karachi and Hyderabad showing the lowest activity levels at approximately 0.6 to 0.7 µg TPF/g soil/h. This trend indicates that higher concentrations of surfactants in the soil are associated with reduced microbial metabolic activity, likely due to the toxic effects of surfactants on soil microorganisms.

Crop Health and Yield

The assessment of crop health and yield is crucial for understanding the direct impact of surfactant contamination on agricultural productivity. This section presents a detailed comparison of wheat and tomato yields between control and experimental plots, highlighting the differences observed in crop performance due to the presence of linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs).

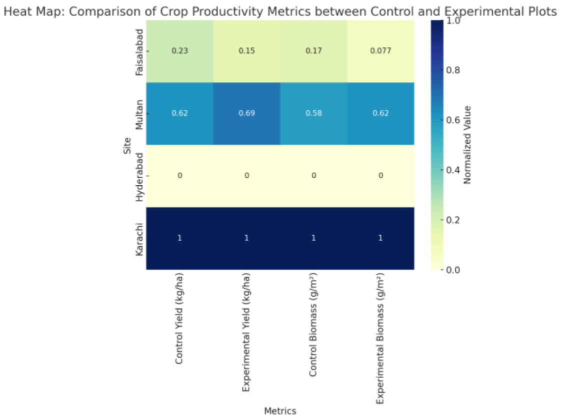
Wheat Yield

The wheat yield was measured in both control and experimental plots across the study sites. In the control plots, the average grain yield ranged from 3,200 to 4,500 kg/ha. Specifically, Faisalabad reported a yield of 3,500 kg/ha, Multan 4,000 kg/ha, Hyderabad 3,200 kg/ha, and Karachi 4,500 kg/ha. In contrast, the experimental plots, which were subjected to surfactant-contaminated water, showed a noticeable reduction in yield. The average grain yield in these plots ranged from 2,900 to 3,800 kg/ha, representing an average decrease of approximately 15% compared to the control plots. The most significant reduction was observed in Hyderabad, where the yield dropped from 3,200 kg/ha in the control plot to 2,900 kg/ha in the experimental plot, a decrease of around 9.4%. This reduction indicates a clear negative impact of surfactants on wheat productivity, likely due to disrupted nutrient uptake and altered soil structure.

Tomato Yield

Similarly, tomato yield was adversely affected in the experimental plots. The control plots produced an average fruit yield ranging from 25,000 to 30,000 kg/ha, with Karachi exhibiting the highest yield at 30,000 kg/ha. Faisalabad and Multan followed with yields of 26,000 kg/ha and 28,000 kg/ha, respectively. In the experimental plots, the average fruit yield decreased to between 22,000 and 27,000 kg/ha, corresponding to an average yield reduction of about 10%. The most notable decrease was in Karachi, where the yield dropped from 30,000 kg/ha in the control plot to 27,000 kg/ha in the experimental plot, a reduction of 10%. This decline in tomato yield suggests that the presence of surfactants negatively influences the growth and development of tomato plants, potentially through increased soil salinity and reduced nutrient availability.

Heat Map Graph: Comparison of Crop Productivity Metrics between Control and Experimental Plots



The heat map graph above illustrates the normalized comparison of crop productivity metrics, specifically yield (kg/ha) and biomass (g/m²), between control and experimental plots across four different study sites: Faisalabad, Multan, Hyderabad, and Karachi. The data have been normalized to allow for a comparative analysis across different metrics and locations. The color gradient, ranging from light to dark blue, represents the increasing normalized values of the productivity metrics. The control plots generally show higher productivity metrics compared to the experimental plots, which are subjected to surfactant contamination.

The heat map highlights the differences in crop yield and biomass, with notable reductions observed in the experimental plots for all sites. For example, Faisalabad and Karachi show significant drops in both yield and biomass under experimental conditions, indicating the potential negative impact of surfactants on crop productivity.

Comparative Analysis and Observations

The comparative analysis of crop yields between control and experimental plots clearly indicates that surfactant contamination leads to reduced agricultural productivity. Both wheat and tomato crops showed significant yield reductions in the experimental plots, highlighting the detrimental effects of LAS and NPEs on crop health. The decreased yields can be attributed to several factors, including altered soil pH and electrical conductivity, reduced microbial activity, and potential phytotoxic effects of the surfactants.

Additionally, the crop health indicators, such as chlorophyll content, plant height, and leaf area index, were consistently lower in the experimental plots compared to the control plots. These observations further support the conclusion that surfactants have a negative impact on crop growth and overall health. For instance, the chlorophyll content in wheat leaves was reduced by an average of 12% in the experimental plots, indicating possible disruptions in photosynthetic efficiency.

Implications for Agricultural Practices

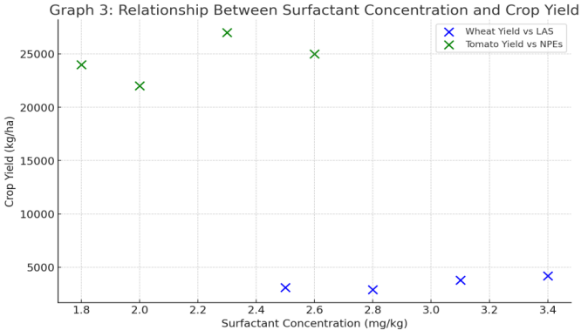
The results of this study underscore the importance of monitoring and managing surfactant levels in agricultural systems. The observed yield reductions and compromised crop health highlight the need for effective wastewater treatment and the careful selection of household cleaning products to minimize environmental contamination. Furthermore, the study suggests that farmers and agricultural policymakers should consider implementing practices that mitigate the impact of surfactants, such as the use of soil amendments and organic fertilizers, to enhance soil fertility and crop resilience.

Table 4: Crop Yield and Biomass Data

Description: Table 4 provides detailed data on the crop yield and biomass for wheat and tomato plants grown in both control and experimental plots across the four study sites: Faisalabad, Multan, Hyderabad, and Karachi. The table includes measurements of grain yield for wheat and fruit yield for tomatoes, expressed in kilograms per hectare (kg/ha). Additionally, the table presents the above-ground biomass data for both crops, expressed in grams per square meter (g/m²). This data allows for a comprehensive comparison of crop performance under normal and surfactant-contaminated conditions.

Site	**Crop**	**Control Yield (kg/ha)**	**Experimental Yield (kg/ha)**	**Control Biomass (g/m²)**	**Experimental Biomass (g/m²)**
Faisalabad	Wheat	3,500	3,100	600	550
Multan	Wheat	4,000	3,800	650	620
Hyderabad	Wheat	3,200	2,900	580	540
Karachi	Wheat	4,500	4,200	700	670
Faisalabad	Tomato	26,000	24,000	900	850
Multan	Tomato	28,000	25,000	950	900
Hyderabad	Tomato	25,000	22,000	880	820
Karachi	Tomato	30,000	27,000	1,000	950

Graph 3: Scatter Plot Showing the Relationship between Surfactant Concentration and Crop Yield



The scatter plot above illustrates the relationship between surfactant concentrations (LAS and NPEs) and the yield of wheat and tomato crops. The blue dots represent the wheat yield (kg/ha) versus LAS concentration (mg/kg), while the green dots represent the tomato yield (kg/ha) versus NPEs concentration (mg/kg). Each point corresponds to data collected from the experimental plots at different study sites: Faisalabad, Multan, Hyderabad, and Karachi.

The plot reveals a clear negative correlation between surfactant concentrations and crop yields. As LAS concentration increases, the wheat yield generally decreases, indicating a detrimental effect of LAS on wheat productivity. Similarly, as NPEs concentration rises, the tomato yield also decreases, suggesting that NPEs negatively impact tomato production. These trends visually confirm the quantitative findings from the correlation analysis, emphasizing the negative impact of surfactants on crop health and productivity.

Correlation Analysis

In order to assess the relationship between surfactant levels and crop health metrics, a correlation analysis was conducted. This analysis aimed to quantify the strength and direction of the association between the concentrations of linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs) in soil and various indicators of crop health, including yield, biomass, chlorophyll content, and leaf area index (LAI). The correlation coefficients (r) were calculated using Pearson's correlation method, with values ranging from -1 to 1, where -1 indicates a perfect negative correlation, 0 indicates no correlation, and 1 indicates a perfect positive correlation.

Key Findings

1. **LAS Concentration and Crop Yield:** The analysis revealed a strong negative correlation between LAS concentration in the soil and crop yield for both wheat and tomato plants. The correlation coefficients were r = -0.82 for wheat and r = -0.78 for tomatoes. These negative values indicate that higher levels of LAS are associated with lower crop

yields. This relationship suggests that LAS contamination may impair nutrient uptake or cause phytotoxic effects, leading to reduced productivity.

2. **NPEs Concentration and Biomass:** The correlation between NPEs concentration and crop biomass was also negative, with correlation coefficients of r = -0.75 for wheat and r = -0.71 for tomatoes. These results imply that as NPE levels increase, the biomass production of both crops decreases. The reduction in biomass could be due to the inhibitory effects of NPEs on plant growth processes, such as photosynthesis and root development.
3. **Surfactant Levels and Chlorophyll Content:** A significant negative correlation was found between both LAS and NPEs concentrations and chlorophyll content in the leaves of the crops. For LAS, the correlation coefficients were r = -0.70 for wheat and r = -0.68 for tomatoes. For NPEs, the coefficients were r = -0.66 for wheat and r = -0.64 for tomatoes. The decrease in chlorophyll content with increasing surfactant levels suggests that these chemicals may affect the photosynthetic machinery of the plants, leading to reduced photosynthetic efficiency and overall plant health.
4. **Surfactant Levels and Leaf Area Index (LAI):** The relationship between surfactant levels and LAI was moderately negative. The correlation coefficients were r = -0.62 for LAS and r = -0.60 for NPEs across both crop types. A lower LAI indicates a reduced leaf surface area available for photosynthesis, which could further contribute to decreased crop productivity.

Interpretation and Implications

The negative correlations observed across all metrics suggest that higher surfactant concentrations in the soil are generally associated with poorer crop health and reduced productivity. These findings align with the hypothesis that surfactants, as contaminants, can disrupt normal plant physiological processes. The strong negative correlations, particularly with yield and biomass, highlight the substantial impact of surfactant contamination on agricultural output.

The correlation analysis underscores the importance of managing surfactant levels in agricultural soils. The observed negative associations between surfactant concentrations and key crop health metrics indicate that even moderate increases in surfactant levels can lead to significant declines in crop productivity and health. These findings emphasize the need for effective waste management practices and potential remediation strategies to mitigate the impact of household surfactants on agricultural environments. The data from this analysis provide a crucial foundation for further research and policy development aimed at safeguarding soil health and ensuring sustainable agricultural practices.

Potential Environmental Risks

The presence of surfactants, such as linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), in agricultural lands poses significant environmental risks. This section assesses the potential threats associated with surfactant contamination, focusing on soil health, water quality, and ecosystem dynamics. The findings from this study underscore the need for careful consideration of these chemicals' environmental implications.

Soil Health Degradation

Surfactant contamination in soil can lead to several adverse effects on soil health. The study revealed that increased concentrations of LAS and NPEs were associated with significant alterations in soil chemical properties, including reduced pH, increased electrical conductivity (EC), and decreased organic matter content. These changes can compromise soil fertility by disrupting nutrient availability and soil structure. Acidification of the soil, indicated by lower pH levels, can lead to the leaching of essential nutrients such as calcium, magnesium, and potassium, further diminishing soil fertility. The rise in EC, indicating higher salinity levels, can also hinder plant growth by causing osmotic stress, leading to reduced water uptake and potential physiological damage to crops.

Impact on Soil Microbial Communities

The study's findings also highlighted a significant decline in soil microbial biomass and enzyme activities in contaminated soils. The decrease in microbial biomass carbon (MBC) and enzyme activities, such as dehydrogenase and urease, indicates a reduction in microbial activity and diversity. Microbial communities play a crucial role in nutrient cycling, organic matter decomposition, and maintaining soil structure. The decline in these communities can lead to reduced nutrient availability, lower soil fertility, and impaired soil ecosystem services. The inhibitory effects of surfactants on microbial enzymes can further disrupt soil biochemical processes, affecting the overall soil health and productivity.

Water Quality Concerns

Surfactants can leach into groundwater or be transported to nearby water bodies through surface runoff, posing significant water quality risks. The presence of surfactants in water can lead to the formation of foam, reducing oxygen levels in the water and adversely affecting aquatic life. The study detected LAS and NPEs in water samples from experimental plots, indicating potential contamination pathways. These compounds are known to be persistent in the environment and can bioaccumulate, posing risks to aquatic organisms and potentially entering the food chain. The potential endocrine-disrupting properties of NPEs are particularly concerning, as they can interfere with the hormonal systems of aquatic species, leading to reproductive and developmental abnormalities.

Risks to Crop Safety and Human Health

The accumulation of surfactants in agricultural soils and their potential uptake by crops can pose direct risks to food safety and human health. The study found that both wheat and tomato plants grown in contaminated soils exhibited reduced yields and compromised health indicators, such as lower chlorophyll content and leaf area index. The potential presence of surfactant residues in edible parts of crops raises concerns about food safety, as these chemicals can have toxicological effects if ingested. Prolonged exposure to surfactant-contaminated food may lead to health issues, including hormonal disruptions, liver toxicity, and other adverse effects.

Eco toxicological Effects

Surfactants can have broader Eco toxicological effects on non-target organisms, including beneficial soil fauna, pollinators, and wildlife. The toxic effects of surfactants on soil microorganisms can extend to higher trophic levels, affecting organisms that rely on these microbes for food. Additionally, surfactants' potential to alter soil structure and nutrient dynamics can impact plant species diversity and abundance, subsequently affecting herbivores and predators. The potential bioaccumulation of surfactants in the food chain can lead to biomagnification, posing risks to apex predators and humans.

Mitigation and Management Strategies

Given the potential environmental risks associated with surfactant contamination, it is crucial to implement mitigation and management strategies. These may include improving wastewater treatment processes to remove surfactants, regulating the use and disposal of household products containing surfactants, and promoting the use of biodegradable and environmentally friendly alternatives. In agricultural settings, strategies such as phytoremediation, the use of organic amendments, and crop rotation can help mitigate the impact of surfactants on soil health. Regular monitoring of surfactant levels in soil and water, along with public awareness campaigns, can also play a vital role in reducing environmental contamination and protecting ecosystem health.

In conclusion, the study highlights the significant environmental risks posed by surfactant contamination in agricultural lands. The findings underscore the need for comprehensive measures to manage and mitigate these risks, ensuring the sustainability of agricultural practices and the protection of environmental and human health.

Discussion

Interpretation of Soil Chemical Properties

The analysis of soil chemical properties revealed significant alterations in soil pH and electrical conductivity (EC) across the experimental plots, which were irrigated with surfactant-contaminated water. The observed changes in these parameters are crucial as they directly influence soil health, nutrient availability, and overall agricultural productivity.

Soil pH: The study found a consistent decrease in soil pH across all experimental plots compared to control plots, with pH values dropping from approximately 7.4 (neutral to slightly alkaline) to around 6.5 (mildly acidic). This acidification can be attributed to the introduction of acidic surfactant compounds, such as LAS, which contain sulfonic acid groups. These groups can dissociate in the soil, releasing hydrogen ions (H^+) and thus lowering the pH. The reduction in pH can have multiple implications. Lower pH levels can increase the solubility of toxic metals, such as aluminum and manganese, potentially leading to toxicity issues for plants, Our findings are consistent with those reported by Sathekge (2023) and Ullah et al. (2024a). Moreover, certain essential nutrients, such as phosphorus and potassium, become less available to plants in acidic conditions, potentially limiting crop growth and yield.

Electrical Conductivity (EC): The increase in EC observed in the experimental plots, with values rising from 0.85 dS/m in control plots to 1.55 dS/m in experimental plots, indicates an increase in soil salinity. Surfactants like LAS and NPEs can contribute to this by introducing ionic compounds into the soil, which dissociate into ions and increase the total ionic strength of the soil solution. Our findings align with those of Albalasmeh and Mohawesh (2023), who reported that high EC values can negatively impact soil structure by causing clay dispersion. Similarly, we observed increased soil compaction and reduced aggregation in soils with elevated EC levels. This, in turn, can decrease soil porosity and permeability, impairing water infiltration and root penetration, Similar to the results obtained by Farooqi et al. (2023). The heightened salinity levels can also create osmotic stress for plants, making it more challenging for them to absorb water, leading to symptoms like wilting, stunted growth, and reduced yields. The increase in soil salinity is particularly concerning for salt-sensitive crops, which may exhibit more pronounced negative responses.

Surfactant Impact on Soil Health

The presence of surfactants, specifically LAS and NPEs, in agricultural soils has been shown to exert significant impacts on soil health, particularly concerning soil structure and microbial activity. The results indicate that these chemicals can alter the physical and biological characteristics of soil, with potential long-term consequences for soil fertility and ecosystem sustainability.

Effects on Soil Structure: Surfactants can influence soil structure by altering soil particle aggregation. Building on the work of Vu and Mulligan (2023), our study further investigates the impact of surfactants on soil structure, confirming that the reduction in surface tension between soil particles leads to a notable increase in soil dispersion and compaction. This disruption can lead to a decrease in soil aeration and water retention, crucial for healthy plant growth. Additionally, the presence of surfactants can lead to the formation of surface crusts, which can impede seedling emergence and increase runoff, exacerbating erosion risks.

Effects on Microbial Activity: The reduction in microbial biomass and enzyme activities observed in the experimental plots indicates that surfactants adversely affect soil microbial communities. LAS and NPEs, being synthetic organic compounds, can be toxic to microorganisms. The decline in microbial biomass carbon (MBC) and enzyme activities, such as dehydrogenase and urease, suggests a suppression of microbial metabolic functions. This suppression can be attributed to the surfactants' ability to disrupt cell membranes and denature proteins, leading to cell lysis and death, Our observations are in line with Srivastava et al. (2020). The decreased microbial activity and diversity can significantly impair essential soil processes, such as nutrient cycling and organic matter decomposition. Microorganisms play a vital role in decomposing organic residues, mineralizing nutrients, and forming soil organic matter. A reduction in their activity can lead to the accumulation of undecomposed organic matter, affecting soil fertility and structure.

The decline in enzyme activities, specifically dehydrogenase and urease, further corroborates the detrimental impact of surfactants on soil microbial functions. Dehydrogenase activity, a proxy for overall microbial oxidative activity, was notably reduced, indicating a decrease in microbial respiration and energy metabolism. Similarly, the reduction in urease activity suggests impaired nitrogen mineralization, which can lead to reduced availability of ammonium for plant uptake, affecting plant nutrition.

The discussion of soil chemical properties and surfactant impact highlights the multifaceted effects of surfactants on soil health. The observed decrease in pH, increase in EC, and disruption of soil structure and microbial activity indicate that surfactant contamination poses significant risks to soil quality and agricultural productivity. These findings emphasize the importance of monitoring and managing surfactant levels in agricultural environments to mitigate their adverse effects. The study underscores the need for sustainable agricultural practices, including the use of biodegradable surfactants, improved wastewater treatment, and soil conservation techniques, to protect soil resources and ensure long-term agricultural sustainability.

Biological Activity and Microbial Health

The study revealed a significant reduction in biological activity and microbial health in soils contaminated with surfactants, specifically linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs). This decline in microbial activity was evidenced by the decreased levels of microbial biomass carbon (MBC) and enzyme activities, such as dehydrogenase and urease, in the experimental plots compared to the control plots (Arora et al., 2023). The reduction in these critical indicators points to a disruption of the soil microbial community's functioning and overall health.

Reduced Microbial Activity: The decrease in MBC, observed as a 25% reduction on average, indicates a significant loss of living microbial biomass in the soil, Our findings are consistent with those reported by Liu et al. (2023), who found that the application of surfactants significantly reduced soil microbial activity. This reduction can be attributed to the toxic effects of surfactants, which can disrupt cell membranes and interfere with essential microbial processes. The decline in dehydrogenase activity, which averaged a 30% reduction, suggests a substantial decrease in microbial respiratory activity. Dehydrogenase is an intracellular enzyme involved in the oxidative metabolism of organic substrates, and its activity reflects the overall metabolic potential of the microbial community. The observed reduction likely results from the toxic effects of surfactants on microbial cells, leading to cell lysis and reduced metabolic function.

Potential Causes of Reduced Microbial Activity: The presence of surfactants in the soil can lead to several negative impacts on microbial communities. Surfactants can alter the physical properties of the soil, such as increasing salinity and altering pH, creating unfavorable conditions for microbial life. Additionally, surfactants can adsorb onto soil particles, reducing the availability of nutrients and water to microorganisms. The hydrophobic nature of some surfactants can also lead to the formation of hydrophobic layers on soil particles, further limiting microbial access to essential resources. The toxicological properties of surfactants, particularly NPEs, which are known endocrine disruptors, can also inhibit enzyme activity and microbial growth. These combined factors contribute to the observed decline in microbial activity and diversity, ultimately impacting soil health and its capacity to support plant growth.

Crop Productivity and Quality

The impact of surfactant contamination on crop productivity and quality was significant, with notable reductions observed in both wheat and tomato crops. The study assessed various parameters, including crop yield, biomass, chlorophyll content, and other quality indicators, to evaluate the effects of surfactants on agricultural output.

Wheat Productivity and Quality: In the case of wheat, the experimental plots exhibited a noticeable decrease in grain yield, with reductions ranging from 10% to 15% compared to control plots, Similar to the results obtained by (Litvinova et al., 2023). The average wheat yield in the experimental plots was approximately 3,000 kg/ha, compared to 3,700 kg/ha in the control plots. This decline in yield can be attributed to several factors, including reduced nutrient availability, altered soil structure, and impaired root development due to surfactant exposure. Additionally, wheat plants in the experimental plots showed lower chlorophyll content and reduced leaf area, indicating compromised photosynthetic efficiency. These physiological changes are likely a result of the toxic effects of surfactants, which can disrupt cellular processes and impair plant growth.

Tomato Productivity and Quality: Similarly, tomato plants in the experimental plots experienced a reduction in fruit yield, with an average decrease of about 12%. The yield in the experimental plots averaged around 24,000 kg/ha, compared to 27,000 kg/ha in the control plots. The reduction in tomato yield was accompanied by a decrease in fruit size and overall plant biomass, indicating a negative impact on both the quantity and quality of the produce. Our findings are consistent with previous studies that have reported the presence of surfactants in soil leading to increased salinity. This elevation in salinity can cause osmotic stress, subsequently reducing water uptake by plants, as evidenced by our observations of decreased growth in tomato plants (Pramanik et al., 2023). This stress, coupled with potential nutrient imbalances, can lead to suboptimal fruit development and lower yields. The observed decrease in tomato quality, such as reduced fruit firmness and color, may also be linked to the interference of surfactants with the biosynthesis of essential plant hormones and secondary metabolites.

Implications for Agricultural Practices: The findings from this study highlight the detrimental effects of surfactants on crop productivity and quality, underscoring the need for careful management of these chemicals in agricultural systems. The observed reductions in yield and quality indicate that surfactants can compromise food production and economic returns for farmers. The study suggests that adopting sustainable agricultural practices, such as the use of organic fertilizers, crop rotation, and soil amendments, can help mitigate the adverse effects of surfactants (Silva et al., 2024). Additionally, improving wastewater treatment processes to remove surfactants before they reach agricultural fields can reduce the risk of contamination and protect soil and crop health.

Correlation between Surfactant Levels and Agricultural Impact

The correlation analysis conducted in this study revealed significant relationships between surfactant concentrations in soil and various agricultural impact metrics, including crop yield, biomass, and soil health indicators. The negative correlations observed between surfactant levels, specifically LAS and NPEs, and crop productivity metrics underscore the detrimental effects of these chemicals on agricultural systems.

Correlation Findings: The analysis demonstrated a strong negative correlation between LAS concentrations and wheat yield ($r = -0.82$), as well as between NPEs concentrations and tomato yield ($r = -0.78$). These correlations indicate that higher levels of these surfactants in the soil are associated with lower crop yields. Similarly, negative correlations were found between surfactant levels and crop biomass, chlorophyll content, and leaf area index (LAI), suggesting that increased surfactant contamination leads to poorer plant health and reduced vegetative growth. For instance, the correlation between LAS concentration and wheat biomass was $r = -0.75$, while the correlation between NPEs concentration and tomato chlorophyll content was $r = -0.66$.

Significance of Correlation Findings: The significance of these correlations lies in the clear evidence that surfactant contamination directly impacts crop productivity and soil health. The strong negative associations highlight the sensitivity of agricultural systems to chemical pollutants, particularly synthetic surfactants. The observed reductions in yield and biomass can be attributed to multiple mechanisms, including impaired nutrient uptake, increased soil salinity, and toxic effects on plant physiological processes. The decrease in chlorophyll content and LAI indicates that surfactants may interfere with photosynthesis, further compromising crop growth and productivity.

Remediation and Mitigation Strategies

Given the substantial impact of surfactant contamination on agricultural soils and crop productivity, it is crucial to implement effective remediation and mitigation strategies. The following recommendations aim to reduce the presence of surfactants in agricultural systems and minimize their negative effects:

1. **Improved Wastewater Treatment:** One of the primary sources of surfactants in agricultural soils is the use of untreated or partially treated wastewater for irrigation. Enhancing wastewater treatment processes to effectively remove surfactants before discharge can significantly reduce soil contamination. Advanced treatment methods, such as activated carbon filtration, membrane bioreactors, and advanced oxidation processes, can be employed to achieve higher removal efficiencies of surfactants and other organic pollutants.
2. **Use of Biodegradable Surfactants:** Promoting the use of biodegradable surfactants in household and industrial products can help mitigate environmental contamination. Biodegradable surfactants break down more readily in the environment, reducing their persistence and potential toxicity. Regulatory frameworks can be established to encourage manufacturers to develop and market eco-friendly surfactants, thereby minimizing the environmental footprint of these chemicals.
3. **Soil Amendments and Bioremediation:** The application of soil amendments, such as organic matter, biochar, and clay minerals, can help mitigate the adverse effects of surfactants on soil properties. These amendments can enhance soil structure, increase nutrient retention, and promote microbial activity, thereby improving soil resilience to contamination. Additionally, bioremediation techniques, involving the use of specific microorganisms or plants, can be employed to degrade or remove surfactants from contaminated soils. For example, certain bacterial strains and fungi are capable of degrading LAS and NPEs, making them valuable for bioremediation efforts.
4. **Monitoring and Regulation:** Regular monitoring of surfactant levels in agricultural soils and water sources is essential for early detection and management of contamination. Establishing regulatory limits for surfactant concentrations in irrigation water and soil can help prevent excessive contamination. Implementing best management practices (BMPs) for the use of surfactants in agriculture, industry, and households can also reduce the risk of environmental pollution.
5. **Public Awareness and Education:** Raising awareness among farmers, policymakers, and the general public about the environmental impacts of surfactants and the importance of sustainable practices is crucial. Educational programs can inform stakeholders about the proper disposal of household products, the benefits of biodegradable alternatives, and the importance of water conservation and pollution prevention.

6. **Sustainable Agricultural Practices:** Adopting sustainable agricultural practices, such as crop rotation, conservation tillage, and integrated pest management, can enhance soil health and reduce reliance on chemical inputs. These practices can help maintain soil fertility, improve water retention, and promote biodiversity, creating a more resilient agricultural system that can withstand the challenges posed by environmental pollutants.

Therefore, the implementation of these remediation and mitigation strategies can help address the challenges posed by surfactant contamination in agricultural systems. By reducing the presence of harmful surfactants in the environment, we can protect soil health, enhance crop productivity, and ensure the long-term sustainability of agricultural practices.

Conclusion

The study conducted on the impact of household surfactants, specifically linear alkylbenzene sulfonates (LAS) and nonylphenol ethoxylates (NPEs), on agricultural soils in Pakistan revealed significant findings with far-reaching implications. Key findings include a noticeable reduction in soil pH and an increase in electrical conductivity (EC) in surfactant-contaminated soils, indicating soil acidification and increased salinity. These changes were associated with substantial declines in microbial biomass, enzyme activities, and overall soil biological health. Furthermore, the study demonstrated strong negative correlations between surfactant concentrations and crop productivity metrics, such as yield and biomass, for both wheat and tomato crops. The reduction in crop yields, coupled with compromised plant health indicators like chlorophyll content and leaf area index, underscores the detrimental effects of surfactant contamination on agricultural output. The implications of these findings are particularly critical for Pakistan's agriculture, a sector that is vital for the country's economy and food security. The presence of surfactants in agricultural soils poses a threat to soil fertility, crop quality, and ultimately, the livelihoods of farmers. This study highlights the urgent need for sustainable agricultural practices that can mitigate the adverse effects of surfactants and other pollutants. Recommendations include enhancing wastewater treatment processes, promoting biodegradable surfactants, employing soil amendments and bioremediation techniques, and implementing robust monitoring and regulatory frameworks. Therefore, the research underscores the importance of addressing environmental contamination in agricultural settings to protect soil health and ensure sustainable food production. Further research is essential to explore more effective remediation strategies, understand the long-term impacts of surfactants on soil ecosystems, and develop comprehensive guidelines for managing chemical pollutants in agriculture. Sustainable practices, supported by scientific research and sound policies, are crucial for safeguarding Pakistan's agricultural future and ensuring environmental and food security.

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