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Impacts of Agricultural Chemicals (Chemical Fertilizers and Pesticides) on Human Health and Environmental Sustainability: An Illustrated Case Study of Nathupur and Seoli Village in Sonipat District, Haryana State

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ABSTRACT

The widespread use of Agricultural Chemicals (chemical fertilizers and pesticides) in modern agriculture has significantly increased crop yields, enabling farmers to meet the food demands of a growing population. However, these practices come with adverse effects on human health and environment sustainability, causing a major concern for sustainable farming practices. Fertilizers often contaminate water and air, leading to conditions such as cancer and respiratory disorders. Similarly, pesticides, designed to control pests, also impact human health, with potential links to neurological disorders, cancers and reproductive issues. This research study explores the effects of chemical fertilizers and pesticides on human health, illustrated through a case study of Nathupur Village, where industrial and agricultural practices have had a pronounced environmental impact and Seoli village in Haryana, where water scarcity and overuse of chemical inputs have further degraded soil health and agricultural sustainability.

Key words: Artificial intelligence, Chemical fertilizers, Cloud computing, Digital agriculture, Digital twin technology, Disruptive digital technology, Internet of things (IoT), Machine learning, Pesticides, Precision agriculture, Remote sensing, Sustainable agriculture.

India is one the largest producers of agricultural and horticultural crops worldwide (Sah *et al.*, 2022; Tiwari *et al.*, 2021). Endowed with diverse agro-climatic conditions, the Indian agriculture landscape is diversified in terms of structural aspects, from staple crops such as rice and wheat to cash crops like tea, coffee, spices *etc*. In India, agriculture is the most considerable sector of the country and it contributes around 17-20% to its gross domestic product (GDP) (Khan, 2021; Prakash, 2024). The livelihood of around 60% of the country's population is directly or indirectly dependent on agriculture, for centuries together (Prakash, 2024). Agriculture sustains the livelihood of farmers in about 127 agro climatic zones (ACZs) and 15 regions (ACRs) making it critical for India's economic sustainability and growth.

Chemical fertilizers are substances of natural or synthetic origin that aim to enhance crop growth by supplementing vital plant nutrients (Nadarajan, 2021). Typically, these fertilizers include three primary nutrients *i.e.* Nitrogen (N), Phosphorus (P) and Potassium (K), along with a few other macro nutrients (Jaswal *et al.*, 2021). Approximately 67% of all fertilizers utilized in the country are nitrogen-based (Abd Manan *et al.*, 2024), owing to its critical role in plant growth. An estimated 2.6 gigatons of carbon dioxide equivalent is produced by the production and application of fertilizers each year (Gao, 2023). Fertilizer application emits various anthropogenic greenhouse gasses into the atmosphere with approximately 80-90% of ammonia gas (NH3) emissions attributed to agricultural activities (Wyer *et al.*, 2022). Leaching of nitrates from erroneous application of fertilizers threatens the quality of groundwater sources (Hina, 2024). It is not easily treatable due to the slow dilution of groundwater and affects the water supply. Improper selection of fertilizers can also lead to acidification of soil, leading to a loss of agricultural land (Pahalvi *et al.*, 2021).

Pesticides are essential for protecting crops and improving productivity by managing a broad variety of pests that limit agricultural production. The targeted pests and

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functions of these substances, including both chemical and biological agents, fall into the classes: (a) Insecticides to fight the attack of insects that feed on crop plants or damage, for instance organophosphates and carbamates (Araujo, 2023), (b) Herbicides to kill or control plants that are considered weeds (Adams, 2022), (c) Fungicides to prevent and control fungal infections that lead to many plant diseases (Gikas *et al.*, 2022), (d) Rodenticides, which use active ingredients such as anticoagulants and neurotoxins, are made to control rodent populations that endanger growing crops as well as stored produce (Garud *et al.*, 2024) and (e) Nematicides to combat nematodes, which are microscopic worms that attack plant roots (Ahmad *et al.*, 2021). Since pesticides contaminate soil, water and air, they are particularly dangerous for various non-target species such as beneficial insects, wildlife and aquatic life due to environmental concerns (Punniyakotti *et al.*, 2024).

A potential solution comes in the form of the application of Machine Learning (ML) to agriculture, specifically to crop prediction. ML allows systems to analyze enormous amounts of farm-specific data. It can predict yield out- comes in line with crop characteristics, weather patterns and quality of soil. Applications of ML in other domains, such as recruitment in higher education, have demonstrated its ability to identify key decision-making factors and process complex datasets effectively (Kawatra, 2021). Similarly, in agriculture, ML models which utilize both historical and current data outperform traditional methods (Kiran, 2023). It helps farmers decide the best planting schedules as well as the optimal management of resources for better yield outcomes. This research study findings emphasize the urgent need for sustainable practices to mitigate health risks while maintaining agricultural productivity and echoes the need for adoption of the Doubling Farmers Income by 2022 Committee Report (2018) recommendation: “digitalized integrated farm health management system and digitalized AgroMet advisories and comprehensive risk management solutions in villages”.

Nathupur and Seoli villages in Haryana are the focus of this research due to their distinct yet interconnected agricultural and environmental challenges, which exemplify broader issues faced by rural India. Nathupur has shifted from an agrarian base to an industrial hub, grappling with pollution and resource strain, while Seoli faces water scarcity and soil degradation from traditional farming practices. These contrasting yet linked issues make both villages key case studies for exploring machine learning and digital technologies to promote sustainable agriculture and address health risks.

This paper is structured into several sections, each addressing a specific aspect of the study. Section 2 discusses related works, summarizing key research in the field. Section 3 outlines the methodology employed to conduct the study. Section 4 examines the effects of agricultural chemicals on human health, with a focus on pesticides and fertilizers. Section 5 presents a case study of Nathupur Village, analyzing the local impact of pesticide and fertilizer use. Section 6 explores the situation in Seoli Village, highlighting its distinct yet complementary challenges. Finally, Section 7 concludes the paper with key insights and recommendations for promoting sustainable agricultural practices.

Literature review

Table 1 below summarizes the key findings from the related research conducted by combining machine learning with agriculture.

While previous research has highlighted various challenges in pesticide recommendation systems, such as interpretability issues, limited pest identification, data dependency and environmental variability, our approach aims to overcome these limitations. By leveraging real-time data collection, automation and robust ML models, we mitigate overfitting risks and enhance interpretability, making the system accessible to non-expert users.

Methodology

This study employs a mixed-methods approach to investigate environmental, agricultural and socioeconomic challenges in Nathupur and Seoli villages, Sonipat, Haryana. The methodology integrates field-based data collection, secondary data analysis and a proposed digital framework for real-time monitoring and predictive analytics to support sustainability interventions.

Primary data collection

Primary data was gathered through structured interviews, environmental sampling and field observations. Interviews with farmers, residents and industrial workers provided insights into local practices and challenges. In Nathupur, farmers reported misconceptions, such as assuming organic-labeled inputs are always safe and cited pressure from an “industrial mafia” encouraging excessive chemical use for higher yields. In Seoli, discussions revealed issues like outdated irrigation, pesticide dependence and limited awareness of alternatives such as integrated pest management (IPM). Soil and water samples were collected to assess contamination. In Nathupur, soil tests showed low organic carbon levels (0.032 mg ha^{-1} and water samples had TDS levels of 1200 mg/L, indicating significant pollution. In Seoli, soil testing focused on nutrient levels (NPK), pH and moisture, reflecting degradation from monocropping. Observations in Nathupur revealed open waste burning and unregulated effluent discharge. In Seoli, traditional irrigation systems and chemical overuse worsened water scarcity during dry spells. These findings established a clear picture of village-specific conditions.

Secondary data and analytical framework

Secondary data supported the primary findings and guided the analytical model. Reports, government records and environmental audits were reviewed for context. Nathupur is categorized as an Orange Zone with pockets nearing

Table 1: Literature review.

References	Tools and techniques	Objectives	Features	Remarks
(Bhanumathi *et al.*, 2019)	• Transition Probability Function (TPF) • Convolutional Neural Net-work (CNN) • Soil NPK Sensor	Recommends insecticides and fertilizers through pest identification nutrient analysis using image processing sensor input.	• Speed: Pest identification within 10 seconds, fertilizer recommendation within 60-80 seconds. • High Accuracy: Achieved over 90 accuracy in pest identification. • Efficiency: Outperforms ANN, KNN and SVM in accuracy and time.	• Limited pest identification: Limited pest database may result in over/under pesticide use No data storage: No historical data storage affects long-term strategy
(Wickramasinghe *et al.*, 2019)	• Support vector machine (SVM) • Neural Net-works • IoT Sensors	Guides crop and fertilizer selection based on real-time soil monitoring.	• Personalized crop and fertilizer suggestions based on soil data • Real-time monitoring and response via IoT • Automation reduces manual input.	• Unstable networks may delay recommendations • Faulty sensors can lead to incorrect dosing • High setup costs hinder small farmer adoption
(Thorat *et al.*, 2023)	• Artificial Neural Network (ANN) • K-Nearest neighbour (KNN) • Support vector machine (SVM)	To predict pesticide toxicity to identify hazardous chemicals and support safer usage.	• Accurate yield prediction using random forest • Optimized fertilizer usage through precise recommendations • Compares models to select the most accurate (*e.g.*, TPF-CNN)	• Requires large, high-quality pesticide data • Poor adaptability to sudden environmental changes • Complex for non-expert farmers to adjust or apply
(Kanuru *et al.*, 2021)	• IoT Devices • Machine learning algorithms (Naive bayes, KNN, SVM)	Predict the type and amount of pesticides and fertilizers required for specific crops and regions using IoT and ML.	• Efficient resource use reduces costs • Real-time monitoring enables timely decisions • Accurate predictions via ML models (e.g., KNN)	• Relies on quality training data • High system cost limits small farmer access • Network delays can affect recommendation timing
(Anandhi and Iyapparaja, 2024)	• Random forest • Artificial neural networks • Support vector regression • Probabilistic neural networks (PNN)	Predicts pesticide toxicity to identify hazardous compounds and promote safer agricultural practices.	• High accuracy (up to 96.65%) with RF and PNN • Versatile across large and varied pesticide datasets	• Requires large historical toxicity datasets • Complex models may be hard for non-experts to interpret

Table 1: Continue...

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	• General Regression Neural Networks	.	• Supports safer farming by identifying and reducing toxic pesticide use	• Incomplete data can lead to unsafe recommendations
(Peshin *et al.*, 2020)	• Data collection and field surveys • GIS Mapping for hazard hotspot Identification	Identify pesticide misuse hotspots in North India to guide better pesticide management.	• Provides real-world usage data • Enables targeted interventions in high-risk areas	•Field surveys are time-consuming • Region-specific focus may overlook broader trends No predictive capability for real-time action
(Swain *et al.*, 2020)	• Support Vec- tor Machine • CAN Protocol • Raspberry Pi	Predict crop suitability and yield using sensor data and ML in embedded systems.	• Real-time, accurate decisions *via* SVM • Scalable sensor integration with CAN • Reliable data flow using embedded platforms	• High setup costs limit adoption • Technical complexity may hinder farmer usability
(Shahana *et al.*, 2022)	• k-Nearest Neighbor • Naive bayes • Decision tree • Random forest • Support vector machine	Predicts the most suitable crop for a region using environmental factors (soil, temperature, rainfall, topography).	• High accuracy with Decision Tree and RF • Uses diverse inputs for precise predictions • Scalable across regions /crops with dataset updates	• Relies heavily on data quality • High computational cost may limit real-time use
(Patil *et al.*, 2021)	• IoT • RGB color sensor • Arduino Mi- crocontroller	Real-time, portable soil nutrient and environment monitoring for efficient crop production.	• Instant, lab-free soil analysis • Remote data access *via* cloud • Portable and user-friendly system	• RGB sensors may affect pesticide accuracy • Internet dependency delays real-time decisions • Requires regular hardware maintenance
(Attwal and Dhiman, 2020)	• Decision Tree • Support vector machines • Random forest • Neural networks	Compares data mining techniques to predict crop yield using climatic, geographic and management data.	• High yield prediction accuracy with RF and NN • Versatile across crops and regions • Evaluates performance using multiple metrics	• Model complexity creates challenges for use by non-experts • Incomplete data lowers accuracy
(Issad, Aoudjit and Rodrigues, 2019)	• Decision trees • Support vector machines • Random forest • Neural Net-works	Review of data mining techniques for smart agriculture: Crop production, pest control, soil and resource management.	• Versatile techniques for diverse agri-problems • Efficient input use (*e.g.*, water, fertilizer) *via* models like SVM and Decision Trees • Supports precision agriculture with data-driven decisions	• Integrating heterogeneous data may cause errors • High infrastructure cost limits scalability • Complex models like NN are hard for farmers to interpret

Red Zone status and is located in Seismic Zone 4, increasing its vulnerability. Under the change in land use (CLU) scheme, much of the agricultural land (now limited to 70-80 acres) has been converted for industrial use, particularly for plastics and pesticide-related production. Seoli's secondary data confirmed wheat and paddy dominance, which, while market-driven, contributes to soil nutrient depletion and pest outbreaks. Studies also highlighted the region's minimal uptake of organic practices and modern irrigation.

These findings formed the basis for a data analysis framework. IoT sensor and drone data would be transmitted to a cloud-based platform for storage and processing. In Nathupur, analysis would focus on pollution monitoring, while in Seoli, it would assess soil health, irrigation and crop yields. Machine learning algorithms are proposed to identify environmental and agricultural trends. These include forecasting pollution risks, modeling crop performance and predicting pest outbreaks. Data mining would uncover relationships between land use, emissions and soil degradation. A digital twin system is proposed to simulate various scenarios, such as pollution spread in Nathupur or water-efficient cropping strategies in Seoli. Although full deployment is pending, pilot tests of drones and sensors in both villages demonstrated the feasibility of this approach.

Technological deployment

To address the limitations of manual data collection, a multi-tiered digital architecture is proposed. In Nathupur, NPK sensors, pH meters and air quality monitors would be installed near farms and industrial areas to detect soil contamination and emissions. In Seoli, IoT devices would track soil moisture and automate irrigation for efficient water use. Drones equipped with high-resolution and multispectral cameras would be used in both villages. In Nathupur, they would monitor pollution hotspots and water contamination; in Seoli, they would assess crop health and pest stress to support precision agriculture. Edge devices, such as Raspberry Pi or Arduino boards, would handle real-time data processing before uploading to the cloud for deeper analysis.

Effect of agricultural chemicals on human health

Agricultural chemicals such as pesticides and fertilizers have played a critical role in enhancing crop productivity and reducing losses due to pests and nutrient deficiencies. However, their widespread and often unregulated use has raised serious concerns about environmental degradation and adverse effects on human health. This section explores the health impacts of these chemicals, focusing on exposure pathways, associated diseases and potential solutions for sustainable and safe agricultural practices.

Pesticides (including herbicides, insecticides and fungicides) are extensively used in modern farming, with herbicides accounting for nearly 50% of all usage. They are broadly classified into inorganic and organic types. Inorganic pesticides, derived from mineral or metal compounds, are often non-selective and persistent in the environment, leading to bioaccumulation and unintended ecological damage (Tudi *et al.*, 2021). Organic pesticides, such as pyrethrin and Bacillus thuringiensis (Bt), are derived from natural sources and degrade more rapidly, making them comparatively safer for both the environment and human health (Bose *et al.*, 2021).

Despite their benefits, pesticides pose significant risks to human health through direct contact, inhalation, or ingestion. Human are directly exposed to pesticide by missing personal protective equipment (gloves, goggles, respirator, long pant, cap) (Kumar *et al.*, 2024). Farmers and agricultural workers face the highest exposure, but residues on food, water contamination and air pollution can affect the general population as well. Acute pesticide poisoning can cause symptoms such as dizziness, nausea and respiratory distress, while chronic exposure has been linked to cancer (*e.g.*, leukemia, lymphoma), neurological disorders and endocrine disruption (Tripathi *et al.*, 2020; Daraban, 2023). Children are especially vulnerable due to their developing organs and higher intake of contaminated resources per body weight. Pesticides like chlorpyrifos have been linked to developmental delays and reduced IQ in children, prompting regulatory bans in the U.S. and EU (Lallas, 2001). Runoff from pesticides also contaminates water sources, creating indirect exposure pathways and spreading toxicity into surrounding ecosystems (Otorkpa *et al.*, 2024).

To ensure sufficient crop yield, farmers normally apply NPK, urea and super phosphate fertilizers (Ri Neog, 2019) based on perceived soil requirements. However, this widespread use has raised concerns, chemical fertilizers particularly (nitrogen-based ones) pose considerable health risks when misused. While essential for increasing agricultural yields, they contribute to water and air pollution, which can lead to respiratory issues, reproductive problems and chronic diseases. There is an apprehension that the use of chemical fertilizers over the years might may impaired soil fertility. In fact, studies have shown that the application of nitrogen or rhizobium fertilizers does not always result in significant increases in plant biomass, which raises concerns about their long-term efficacy (Budiastuti *et al.*, 2025). Nitrate leaching into groundwater is a significant concern, particularly in rural areas dependent on shallow wells. High nitrate levels have been associated with methemoglobinemia, or "blue baby syndrome," where the blood's ability to carry oxygen is reduced, particularly dangerous for infants (De Graaf *et al.*, 2022). Long-term exposure is also linked to higher risks of stomach and bladder cancers. Fertilizer-related emissions, such as ammonia and nitrogen oxides, contribute to smog and fine particulate matter (PM2.5), worsening asthma and other respiratory illnesses (Foong *et al.*, 2020).

To mitigate these risks, sustainable land-use systems are necessary. Fig 1 outlines a sustainable framework where

system productivity exceeds input value while maintaining long-term resource viability. It balances biophysical and socio-economic components to reduce environmental and health impacts.

In addition, Fig 2 presents a proposed Health Informatics Network Value Chain, emphasizing the integration of AI, data analytics and blockchain technologies to monitor soil nutrient levels, crop quality and potential human health impacts. This digital framework supports early warning systems, precision farming and community-level interventions.

Promoting integrated pest management (IPM), educating farmers on safe chemical usage and adopting precision agriculture can significantly reduce human exposure. Policymakers must play a central role by enforcing stricter limits on nitrate levels in water, regulating pesticide residues and encouraging organic alternatives. A shift toward digital, data-driven and health-conscious agricultural practices is essential to ensure both food security and long-term public health.

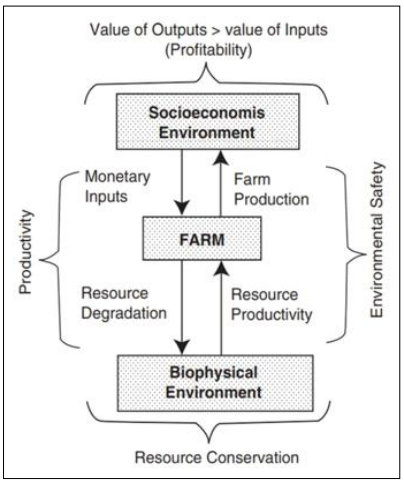


Fig 1: Sustainable land use practices (Adapted from (Sustainable Land Use Systems Research, 1992).

Nathupur village: A case study

Nathupur Village (situated at latitude 28.497287, longitude 77.0902281) in Sonipat tehsil of Haryana State, is a small rural community. It faces significant challenges as it grapples with industrial expansion, environmental degra- dation and resource scarcity. The village's resident population of 4,000 to 4,500 people supports a migrant population that far exceeds its capacity (an estimated 20,000 to 25,000 people). The key industries in the area include plastic manufacturing, pesticides, rubber production, bearings and tobacco processing and occupy approximately 700 acres of land. Pollution levels range from Orange to red zone due to unchecked industrial activity. The village also lies within seismic zone 4 reflecting a higher risk of seismic activity. This geological vulnerability, combined with the pollution levels, exacerbates the risks faced by the village's residents.

A 2018 incident highlighted the hazards: A transportation truck carrying hazardous chemicals leaked its contents en route to Nathupur, causing 40-50 girls from a local school to faint from toxic fumes emitted by the leaked chemical. Emergency measures, including the sprinkling of water, were required to contain the hazardous effects of the leak. Waste management in Nathupur Village remains poorly regulated-solid waste is openly burned and industrial liquid waste is discharged into groundwater or nearby water bodies, raising TDS to 1200 mg/L, double safe limits.

Agriculture, once a primary source of livelihood for the village's residents, has been severely impacted by industrial development. Only 70 to 80 acres of land remain available for cultivation due to land sales under Change in Land Use (CLU) scheme. Crops like wheat, paddy, cabbage and radish are still grown, but soil health has deteriorated, with organic carbon at 0.032 mg ha^{-1}. Proximity of fields to industrial units leads to further contamination *via* pesticide fumes and burning for pottery, polluting air and soil.

The industrial influence on Nathupur Village has not only affected its environment but also its socioeconomic fabric. Only 10 to 15% of the village's resident population, excluding migrants, now relies on farming. The majority of

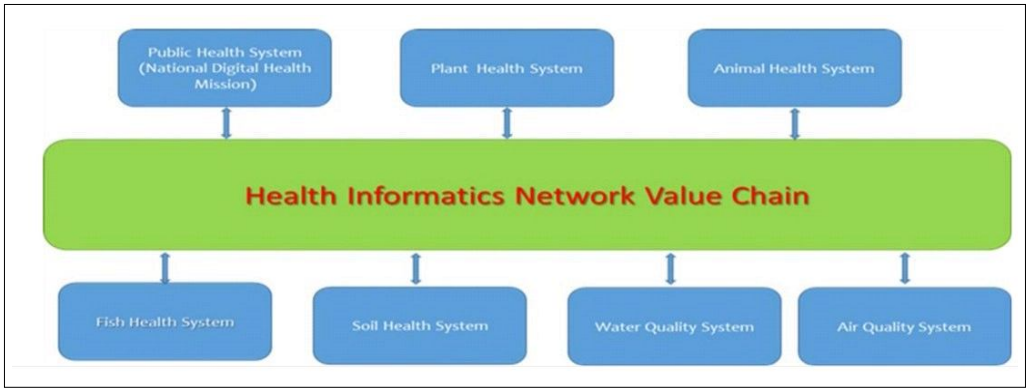


Fig 2: Health informatics network value chain adapted from (Moni, 2019).

residents have turned to industrial jobs or other forms of labor to sustain themselves. Overcrowding and pollution from the migrant population worsen sanitation and resource access.

Table 2 provides a concise summary of the key environmental, socioeconomic and industrial challenges faced by Nathupur Village, along with the primary data points discussed in this study.

To address these pressing issues, advanced technological interventions can play a pivotal role in monitoring and mitigating pollution. Fig 3 contains a proposed system for monitoring industrial and environmental pollution.

It integrates a multi-layered approach to data collection, processing and analysis. Soil NPK and IoT sensors deployed in the field detect soil contamination, nutrient levels, pH, conductivity, temperature and humidity, while drones with aerial imaging monitor air and water pollution in real time. Data from sensors is processed on edge devices (*e.g.*, Raspberry Pi or Arduino), which handle contamination and fertility data before sending it to a cloud server. The server stores and processes industrial pollution data, using machine learning to identify patterns and trends. An AI model forecasts future environmental risks and health impacts, enabling data mining for actionable insights. These insights support comprehensive reports for policymakers to guide mitigation strategies and public health protection.

This system ensures real-time monitoring, efficient processing and predictive analysis to tackle industrial pollution in areas like Nathupur. Implementation, along with stricter regulations, better waste management and industrial practice reform, can ease the environmental burden. CSR funding is essential to expand network studies and establish a Digital Twin System promptly.

Seoli village: A case study

Seoli village (situated at latitude 28.02205, longitude 77.35085), located in Sonipat district of Haryana, presents a microcosm of the agricultural challenges faced by many rural areas in India. The village's agricultural yields are

Table 2: Summary of findings from Nathupur village.

Category	Findings
Population	Resident population: 4,000-4,500; Migrant population: 20,000-25,000.
Industrial activities	Plastic manufacturing, pesticides, rubber, bearings and tobacco processing
Pollution classification	Orange Zone (moderate pollution), Red Zone (severe pollution in some areas).
Seismic classification	Located in Seismic Zone 4 (high earthquake risk).
Environmental issues	Unregulated waste disposal, air and water pollution, high TDS (1200 mg/L) in water sources.
Agriculture stats	Only 70-80 acres of land remain for farming; soil organic carbon: 0.032 mg ha^{-1}.
Air pollution sources	Industrial emissions, open waste burning, pesticide packaging near fields, wood burning.
Water contamination	Liquid industrial waste dumped into groundwater and local water bodies.
Socioeconomic impact	Only 10-15% of the local population remains in agriculture; most have shifted to industrial jobs.
Data collection issues	Reliance on manual surveys, outdated methods, lack of real-time monitoring.
Proposed solution	IoT sensors, drones, AI-driven analysis, predictive modeling and a digital twin system.
Implementation challenges	Resistance from industry, lack of funding, weak environmental law enforcement.

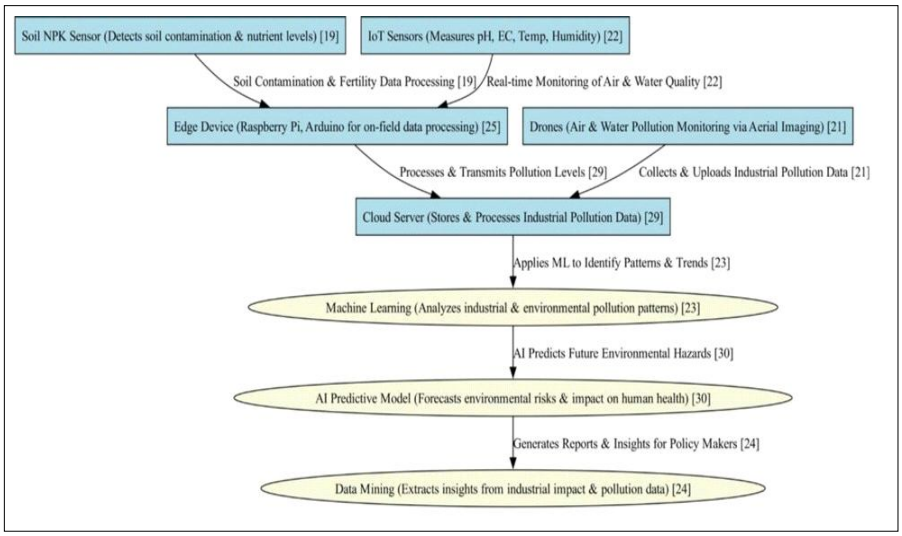


Fig 3: Architecture for monitoring industrial pollution in Nathupur.

influenced by irrigation issues, crop selection, pest control, economic challenges and soil health. One of the primary challenges faced by farmers in Seoli village is limited access to water, especially during dry seasons. It is worsened by unpredictable rainfall and a lack of modern irrigation systems, such as drip and sprinkler irrigation.

Farmers in the village primarily grow wheat and rice, driven by market demand. However, this lack of crop diversification has negative consequences, including reduced soil fertility. Vulnerability to pest outbreaks and depletion of specific nutrients from the soil. Pest damage is widespread, with farmers relying heavily on chemical pesticides due to limited awareness of alternatives like integrated pest management. Organic farming practices, which can offer sustainable solutions, are not widely adopted due to a lack of understanding about their benefits. Economic constraints significantly impact farmers' ability to improve agricultural productivity.

Despite these challenges, there are numerous opportunities to enhance agricultural productivity and sustainability in Seoli village. Introducing efficient irrigation, promoting crop diversification and encouraging farmers to grow a mix of high-value and traditional crops can help improve soil quality.

Adopting organic farming methods is another viable solution. Organic farming enhances soil fertility through the use of natural compost, crop residues and biofertilizers. It also reduces the dependency on chemical inputs, promoting long-term environmental and agricultural sustainability. Training programs for farmers can raise awareness and community initiatives can further address economic challenges. Encouraging farmer cooperatives can enhance collective bargaining power and improve access to markets and resources.

Table 3 presents a concise overview of the agricultural challenges and potential solutions for improving sustainability in Seoli Village.

Leveraging technology can provide a transformative solution to Seoli's agricultural challenges. Fig 4 showcases the proposed system for enhancing precision agriculture in Seoli Village.

It integrates a multi-tiered approach to monitor soil health, crop growth and irrigation needs. Soil NPK and IoT sensors collect real-time data on nutrients, moisture, pH

Table 3: Summary of findings from Nathupur village.

Category	Findings
Water scarcity	Limited irrigation water, unpredictable rainfall, lack of modern irrigation systems.
Crop selection	Predominantly wheat and rice; lack of crop diversification leading to soil depletion and pest outbreaks.
Pest management	Overreliance on chemical pesticides; lack of awareness of integrated pest management.
Soil health	Degraded soil fertility due to monocropping, excessive fertilizer use and lack of organic practices.
Economic constraints	Farmers struggle to afford quality seeds, fertilizers and modern equipment due to financial limitations.
Sustainable solutions	Adoption of organic farming, crop diversification, efficient irrigation and soil testing can improve sustainability.
Technological interventions	IoT-based sensors, AI-driven predictive models, automated irrigation and drone surveillance proposed.
Data collection issues	Reliance on periodic soil testing; lack of real-time monitoring and precision agriculture techniques.
Opportunities	Smart farming techniques, community cooperatives and precision agriculture for improved resource management.
Challenges to implementation	Financial constraints, technological resistance and inadequate rural infrastructure.

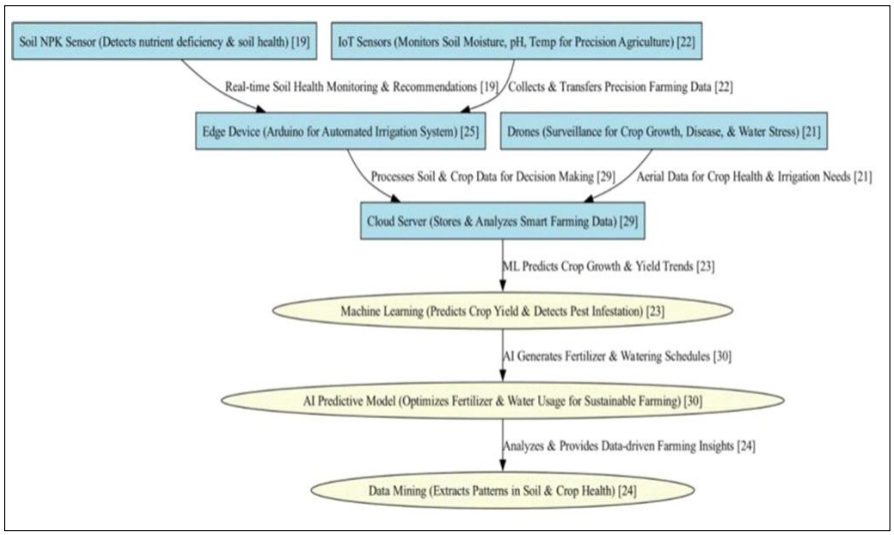


Fig 4: Architecture for monitoring industrial pollution in Seoli.

and temperature, while drones assess crop health and water stress. Edge devices like Arduino automate irrigation and send data to the cloud, where machine learning predicts yields and detects pests. AI models optimize fertilizer and water use, while data mining offers actionable insights to boost productivity and resource efficiency. This integrated, data-driven framework addresses Seoli Village's agricultural challenges. It requires CSR funding for undertaking intensified research and establishing a Digital Twin village to facilitate appropriate resolutions.

CONCLUSION

The cases of Nathupur and Seoli villages illustrate the complex interplay between industrial expansion, environmental sustainability and agricultural resilience in rural India. Nathupur has shifted from an agrarian base to an industrial hub, resulting in pollution, environmental degradation and resource scarcity. Industries like plastic and pesticide manufacturing have harmed both the ecosystem and public health. Poor waste disposal and reduced soil quality have diminished agriculture and made the village environmentally vulnerable. Seoli, meanwhile, faces sustainability issues due to water scarcity, lack of crop diversification and overuse of chemicals. Economic constraints and limited awareness of sustainable farming have worsened soil and water quality. Both villages illustrate the need for balanced rural development that safeguards the environment while supporting economic progress. Solutions include stricter environmental regulation, better waste management, sustainable agriculture and tech-driven interventions. Furthermore, the findings of this study highlight the urgent need to integrate sustainable practices with digital interventions, aligning with the recommendations of the Doubling Farmers Income by 2022 Committee Report (2018). The use of Machine Learning (ML) in crop yield forecasting and AgroMet advisories can enable farmers to make informed decisions, ensuring both economic and environmental sustainability in rapidly industrializing rural regions.

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Author's contribution

Ruchi Kawatra, Himakshi and Shivangi have done the paper writing work. All authors were involved in filed study Raghav has prepared the literature review table Prof Moni and Mr Bhanu shanker have done the final review.

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

The paper consists of case study done by us at different villages. Data has not been taken from any data source. Not applicable.

Conflict of interest

The authors have no competing interest.

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