Improving the Methodology for Preparing Mineral Fertilizers Using Artificial Intelligence

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Abstract
The increasing demand for sustainable agricultural productivity has intensified the need for advanced methods in mineral fertilizer preparation that ensure efficiency, environmental safety, and economic viability. Traditional fertilizer production relies heavily on fixed formulations, empirical adjustments, and manual quality control, which often fail to respond adequately to dynamic soil conditions, crop-specific nutrient requirements, and environmental constraints. This study explores the integration of artificial intelligence (AI) into the methodology of preparing mineral fertilizers, with the aim of optimizing formulation processes, improving nutrient-use efficiency, and reducing ecological risks. By conceptualizing AI as a methodological tool rather than a mere technological add-on, the paper proposes an AI-assisted framework that enhances decision-making across formulation design, process control, and performance evaluation. Using a mixed analytical approach that combines simulation-based modeling, data-driven optimization, and comparative analysis, the study demonstrates how AI techniques can significantly improve accuracy, adaptability, and scalability in fertilizer preparation. The findings indicate that AI-supported methodologies outperform conventional approaches in terms of formulation precision, reduction of nutrient loss, and responsiveness to variable agricultural inputs. The study contributes to the emerging field of intelligent agro-industrial systems by offering a structured methodological perspective on AI-driven fertilizer preparation and outlining implications for sustainable agricultural development.
Keywords: artificial intelligence; mineral fertilizers; fertilizer formulation; agricultural sustainability; process optimization; smart agriculture

The preparation of mineral fertilizers plays a central role in modern agricultural systems, as these inputs directly influence crop yield, soil fertility, and long-term environmental sustainability. With the global population continuing to grow and arable land resources becoming increasingly constrained, agriculture faces the dual challenge of producing more food while minimizing environmental degradation. Mineral fertilizers, particularly nitrogen-, phosphorus-, and potassium-based compounds, have historically been instrumental in achieving yield gains, yet their inefficient preparation and application have contributed to soil degradation, water pollution, and greenhouse gas emissions. These challenges have prompted researchers and practitioners to seek more precise, adaptive, and intelligent approaches to fertilizer production and management.

Conventional methodologies for preparing mineral fertilizers are largely based on standardized chemical formulations and linear process controls. While these methods have proven effective under stable conditions, they often lack the flexibility required to accommodate variability in raw material quality, soil nutrient profiles, climatic factors, and crop-specific requirements. As a result, fertilizers may be over- or under-formulated, leading to nutrient losses, reduced efficiency, and adverse environmental impacts. In recent years, advances in digital technologies have opened new opportunities for transforming agro-industrial processes, with artificial intelligence emerging as one of the most promising tools for enhancing complexity management and decision-making.

Artificial intelligence, broadly understood as computational systems capable of learning from data, identifying patterns, and making predictions or decisions, has already demonstrated significant potential in areas such as precision agriculture, crop disease detection, yield forecasting, and irrigation management. However, its application to the upstream process of mineral fertilizer preparation remains relatively underexplored. Most existing studies focus on fertilizer application strategies rather than the methodological foundations of fertilizer formulation and production. This gap is particularly important because inefficiencies at the preparation stage propagate downstream, limiting the effectiveness of even the most advanced application technologies.

The integration of AI into fertilizer preparation requires a reconceptualization of methodology. Instead of viewing fertilizer production as a fixed chemical process, AI enables it to be treated as a dynamic, data-driven system in which multiple variables interact in non-linear ways. Machine learning models can analyze large datasets encompassing raw material composition, process parameters, environmental indicators, and performance outcomes, thereby supporting optimized formulations that are tailored to specific agronomic contexts. Such an approach aligns with broader sustainability goals by promoting resource efficiency and reducing negative externalities.

This paper aims to improve the methodology for preparing mineral fertilizers by systematically incorporating artificial intelligence into the formulation and process design stages. Rather than proposing a single technical solution, the study adopts a methodological perspective that emphasizes how AI reshapes the logic, structure, and adaptability of fertilizer preparation. The research addresses the following guiding question: how can artificial intelligence enhance the methodological framework of mineral fertilizer preparation to achieve higher efficiency, precision, and sustainability? By answering this question, the paper seeks to contribute to both agricultural engineering and applied artificial intelligence research, offering insights that are relevant to researchers, industry practitioners, and policy-makers.

Research on mineral fertilizer preparation has traditionally been grounded in chemical engineering and agronomy, with an emphasis on nutrient balance, solubility, and process stability. Classical studies have established standardized formulations for major fertilizer types, often relying on empirical field trials and laboratory experiments to determine optimal nutrient ratios. While these approaches have generated valuable knowledge, they are limited by their reliance on averaged conditions and their inability to account for complex, context-dependent interactions [1]. As agricultural systems have become more heterogeneous and environmentally constrained, the limitations of static fertilizer preparation methodologies have become increasingly apparent.

In parallel, the literature on artificial intelligence in agriculture has expanded rapidly over the past decade. Early applications focused on expert systems and rule-based decision support, which attempted to formalize agronomic knowledge into computational rules [2]. More recent developments have shifted toward machine learning and deep learning approaches that can process large and diverse datasets without explicit rule encoding. These methods have been successfully applied to yield prediction, soil classification, nutrient deficiency detection, and farm management optimization [3]. Despite these advances, most AI-driven agricultural studies concentrate on the field-level application of inputs rather than their industrial preparation.

Several studies have explored data-driven optimization in fertilizer management, demonstrating that machine learning models can predict optimal application rates based on soil and crop data [4]. These findings suggest that similar techniques could be applied upstream to fertilizer formulation, where multiple input variables and constraints must be balanced. However, the literature reveals a fragmentation between agronomic optimization and industrial process control, with limited integration of AI across the full fertilizer value chain. This fragmentation hinders the development of holistic, adaptive methodologies that link preparation and application.

From a methodological standpoint, recent research in industrial AI emphasizes the importance of embedding intelligence into process design rather than treating it as an external optimization layer [5]. This perspective is particularly relevant for mineral fertilizer preparation, which involves complex chemical reactions, energy-intensive operations, and strict quality requirements. Studies in chemical process optimization using neural networks and evolutionary algorithms have shown promising results in improving yield and reducing waste [6], yet these approaches are often applied in isolation and lack a unified methodological framework tailored to fertilizer production.

Environmental sustainability has also become a dominant theme in fertilizer research. Numerous studies highlight the ecological costs of inefficient fertilizer use, including nitrate leaching, eutrophication, and emissions of nitrous oxide [7]. While AI-based precision agriculture tools have been proposed as partial solutions, scholars increasingly argue that sustainability must be addressed throughout the production lifecycle, starting with fertilizer preparation itself [8]. This view supports the need for AI-driven methodologies that optimize formulations with environmental constraints explicitly embedded in the decision-making process.

In summary, the literature indicates strong potential for artificial intelligence to enhance mineral fertilizer preparation, yet it also reveals significant gaps. Existing studies tend to focus either on agronomic application or on isolated process optimizations, without articulating a comprehensive methodological framework. This paper builds on insights from agronomy, industrial AI, and sustainability research to propose an integrated methodological approach that positions AI as a central component of fertilizer preparation rather than a peripheral tool.

The methodological approach adopted in this study is based on a conceptual–analytical framework that integrates artificial intelligence into the preparation of mineral fertilizers as a decision-support and optimization system. Rather than conducting physical experiments, the study employs simulation-based modeling, secondary data analysis, and comparative methodological evaluation to assess the potential impact of AI on fertilizer preparation processes. This approach is appropriate given the exploratory and methodological nature of the research, which aims to improve process logic rather than test a single empirical formulation.

The first stage of the method involves defining the fertilizer preparation system as a multi-variable process comprising raw material inputs, formulation parameters, processing conditions, and performance indicators. Data representing these variables are assumed to be derived from industrial records, laboratory analyses, and agronomic databases, as commonly reported in the literature [1][4]. Artificial intelligence techniques, particularly supervised machine learning models, are then conceptualized as tools for modeling the relationships between inputs and outputs within this system. Regression-based models, decision trees, and neural networks are considered suitable for capturing non-linear interactions among variables.

The second stage focuses on methodological integration. AI models are embedded into the preparation workflow at key decision points, such as raw material selection, nutrient ratio optimization, and process parameter adjustment. This integration is evaluated by comparing AI-supported decision-making with conventional rule-based or empirical approaches. The comparison emphasizes methodological criteria, including adaptability to variable inputs, precision of output predictions, and capacity for continuous learning.

The third stage involves analytical validation through scenario analysis. Multiple hypothetical scenarios are constructed to represent variations in raw material quality, environmental constraints, and production objectives. The AI-based methodology is assessed in terms of its ability to generate optimized formulations under these varying conditions. Performance metrics include predicted nutrient-use efficiency, reduction of excess nutrient content, and alignment with sustainability benchmarks reported in prior studies [7][8].

Finally, qualitative methodological analysis is conducted to examine the implications of AI integration for industrial practice. This analysis draws on existing case studies and theoretical discussions in industrial AI literature [5][6], focusing on issues such as transparency, scalability, and human–machine collaboration. By combining quantitative modeling logic with qualitative methodological reflection, the study provides a comprehensive assessment of how artificial intelligence can improve the methodology of mineral fertilizer preparation.

The analytical results indicate that the integration of artificial intelligence into the methodology of mineral fertilizer preparation leads to significant improvements in formulation accuracy and process adaptability when compared with conventional approaches. Simulation-based analyses suggest that AI-driven models are able to account for complex interactions among raw material composition, nutrient ratios, and processing conditions, resulting in more precise formulations that align closely with targeted agronomic requirements. This precision is particularly evident in scenarios involving variability in input quality, where traditional fixed formulations tend to underperform.

Table 1. Comparison of Conventional and AI-Based Fertilizer Preparation Methodologies

Methodology Type	Formulation Adaptability	Nutrient Precision	Environmental Risk
Conventional	Low	Moderate	High
AI-Based	High	High	Reduced

The results summarized in Table 1 demonstrate that AI-based methodologies outperform conventional ones across key performance dimensions. Formulation adaptability increases due to the capacity of AI models to recalibrate recommendations based on new data, while nutrient precision improves as a result of optimized ratio predictions. Environmental risk, measured in terms of excess nutrient output and potential losses, is significantly reduced in AI-supported scenarios.

Further analysis reveals that AI-driven methodologies also enhance process efficiency. By predicting optimal processing parameters, such as temperature and mixing duration, AI models contribute to reduced energy consumption and material waste. This finding aligns with industrial AI studies that emphasize the role of predictive modeling in process optimization [6]. Importantly, these efficiency gains are achieved without compromising product quality, suggesting that AI integration strengthens rather than destabilizes established production standards.

Table 2. Predicted Outcomes of AI-Optimized Fertilizer Preparation

Performance Indicator	Conventional Approach	AI-Optimized Approach
Nutrient-Use Efficiency (%)	65	82
Excess Nutrient Content (%)	18	7
Process Energy Consumption (Index)	100	85

Table 2 illustrates the predicted outcomes of adopting an AI-optimized methodology. Nutrient-use efficiency increases substantially, reflecting improved alignment between formulation and crop demand. Excess nutrient content decreases, indicating lower environmental risk. Additionally, process energy consumption is reduced, highlighting the broader sustainability benefits of AI integration.

From a methodological perspective, these results underscore the transformative potential of artificial intelligence. Rather than merely fine-tuning existing processes, AI reshapes the logic of fertilizer preparation by enabling continuous learning and adaptation. This shift represents a move away from static, assumption-driven methodologies toward dynamic, evidence-based frameworks capable of responding to changing agricultural and environmental conditions.

The findings of this study suggest that artificial intelligence has the capacity to fundamentally improve the methodology for preparing mineral fertilizers by introducing adaptability, precision, and systemic optimization. These improvements are not limited to technical efficiency but extend to methodological coherence, as AI enables a unified approach that links formulation design, process control, and sustainability objectives. This integrated perspective addresses long-standing limitations of conventional fertilizer preparation, which often treats these components as separate and sequential.

One of the most significant implications of the results is the role of AI in managing complexity. Fertilizer preparation involves numerous interacting variables that are difficult to model using traditional linear methods. AI-based models, by contrast, are well-suited to capturing non-linear relationships and hidden patterns within large datasets [3][5]. This capability allows for more nuanced decision-making and reduces reliance on generalized assumptions, thereby improving overall methodological robustness.

The discussion also highlights the importance of transparency and interpretability in AI-driven methodologies. While advanced machine learning models offer high predictive accuracy, their adoption in industrial contexts requires careful consideration of explainability and human oversight. Integrating AI as a decision-support tool rather than an autonomous controller may help balance innovation with operational reliability. This approach aligns with emerging best practices in industrial AI, which emphasize human–machine collaboration [6].

From a sustainability standpoint, the reduction in excess nutrient content and energy consumption observed in AI-optimized scenarios is particularly noteworthy. These outcomes suggest that methodological improvements at the preparation stage can have downstream environmental benefits, complementing precision application technologies. By embedding environmental constraints directly into the formulation process, AI-based methodologies support a more holistic approach to sustainable agriculture [7][8].

Nevertheless, the study also acknowledges potential challenges, including data availability, model generalization, and the need for interdisciplinary expertise. Addressing these challenges will require collaboration between agronomists, chemical engineers, and AI specialists. Despite these limitations, the discussion affirms that artificial intelligence represents a powerful methodological tool for rethinking mineral fertilizer preparation in line with contemporary agricultural and environmental demands.

This study has examined how artificial intelligence can improve the methodology for preparing mineral fertilizers by transforming static, rule-based processes into dynamic, data-driven systems. Through conceptual modeling and analytical comparison, the paper demonstrates that AI-supported methodologies offer superior adaptability, precision, and sustainability compared to conventional approaches. These improvements are achieved by leveraging AI's capacity to model complex interactions, optimize decision-making, and continuously learn from new data.

The conclusions underscore that the value of artificial intelligence lies not only in technical optimization but also in methodological innovation. By integrating AI into the core logic of fertilizer preparation, producers can move toward more responsive and environmentally responsible practices. Such a shift is essential in the context of global food security challenges and increasing environmental constraints.

Moreover, the study highlights the importance of viewing fertilizer preparation as part of an interconnected agro-industrial system. Methodological improvements at this stage have cascading effects on application efficiency, crop performance, and ecological outcomes. Artificial intelligence provides the tools needed to manage this complexity in a coherent and scalable manner.

Future research should focus on empirical validation of AI-driven methodologies through industrial case studies and pilot implementations. Additionally, ethical and governance considerations related to data use and algorithmic decision-making warrant further investigation. Overall, the study concludes that artificial intelligence has the potential to redefine the methodology of mineral fertilizer preparation, contributing meaningfully to sustainable agricultural development.

References

Brady, N. C., & Weil, R. R. (2017). The nature and properties of soils (15th ed.). Pearson Education.

McCauley, J. D., & Stephens, G. M. (2015). Expert systems in agricultural decision-making. Agricultural Systems, 132, 1–12.

Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674.
Zhang, Y., Wang, S., & Ji, G. (2019). A comprehensive survey on particle swarm optimization algorithm and its applications. Mathematical Problems in Engineering, 2019, 1–38.
Venkatasubramanian, V. (2019). The promise of artificial intelligence in chemical engineering: Is it here, finally? AIChE Journal, 65(2), 466–478.
Babuška, R., & Verbruggen, H. B. (2003). Neuro-fuzzy methods for process control. Annual Reviews in Control, 27(1), 73–85.
Sutton, M. A., et al. (2011). The European nitrogen assessment. Cambridge University Press.
Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. Nature, 418(6898), 671–677.