

Fertilizer Innovation and Practice in Sustainable Intensified Agriculture

Witold Grzebisz ¹  and Nevien Elhawat ^{2,3,*} 

¹ Department of Agricultural Chemistry and Environmental Biogeochemistry, Poznan University of Life Sciences, Wojska Polskiego 28, 60-637 Poznan, Poland; witold.grzebisz@up.poznan.pl

² Institute of Applied Plant Biology, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 4032 Debrecen, Hungary

³ Department of Food Biotechnology, Albert Kazmer Mosonmagyaróvár Faculty, Széchenyi István University, 9026 Győr, Hungary

* Correspondence: elhawat.nevien@agr.unideb.hu

1. Introduction

The thematic scope of this Special Issue, “Innovations and Fertilization Practice in Sustainable and Intensive Agriculture,” is broad. The topic concerns the introduction of fertilizer innovations into agricultural practices as a way of adapting current agricultural production systems in line with the assumptions of sustainable intensification. First, it is necessary to define the concept of a fertilization system, of which fertilizer innovations form a part. The fertilization system includes a set of agrotechnical elements, measures and tools selected to meet the nutritional requirements of the crop plant grown, as a condition for exploiting its yield potential [1]. Secondly, it is necessary to explain the meaning of the term sustainable intensification of agriculture (SIA), which appeared at the beginning of the 21st century. Pretty and Bharucha [2] defined SIA as a production process or system that increases crop yields without negatively impacting the environment and without using marginal, poor-quality soils. The essence of this concept is to increase production of high-quality food per unit of inputs used, taking into account, on the one hand, soil fertility, the use of fertilizers and pesticides, and on the other hand, the protection of existing natural ecosystems from destruction [3].

Crop production is determined by climate and inherent soil fertility. Under a precisely defined climatic region, plant growth and yields are determined by the soil, and more strictly by managing its fertility [4,5]. Once the natural production conditions, including constraints, have been determined, the farmer can begin to correct them. A farmer’s activity during the growing season focuses on a specific crop plant with a genetically defined growth pattern and yield formation [6,7]. This is the first key variable that must be taken into account in the validation of fertilizer innovations. The key to success (yield and environmental protection) is to synchronize the nutrient supply with the plant’s requirements, focusing on critical stages of yield formation [8]. The key to success is effective nitrogen (N) management, especially fertilizer N [8–10]. Therefore, N should be treated as a necessary production factor, while other nutrients and fertilization practices should be treated as conditional factors, aimed at the effective use of N for currently grown crops. N controls growth and yield patterns, provided that the fractional product of the conditioning factors is ≤ 1.0 , i.e., at optimum levels [11].

The primary goal of fertilizer innovations is to increase N efficiency, which should lead to a reduction in the N gap [12]. According to the SIA concept, these activities must be aimed at obtaining optimal yield of the currently grown crops, as well as crops in the



Received: 4 June 2026

Accepted: 10 June 2026

Published: 11 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

crop rotation. Innovative activities in crop fertilization must take into account both the growth and development of plant-critical phases and the vertical (soil profile) and spatial variability of soil fertility in the field. This applies to both mineral N resources and soil pH and nutrients, which primarily determine N uptake [13,14]. Therefore, alternative N sources and nutrients that support N uptake from the soil solution and their transformation in the plant require coordination with critical phases of the crop plant's N demand [6]. When introducing fertilizer innovations that actively affect nutrient resources in soil, farmers should not assume that these resources are infinite.

The aim of this article is to group the published articles into substantively homogeneous units, indicating (i) aspects of knowledge progress, as well as the practical significance of the developed fertilizer innovations.

2. Special Issue—General Issues

2.1. Increasing Nitrogen Use Efficiency

Improving nitrogen use efficiency (NUE) is one of the major objectives of sustainable intensification because it simultaneously determines crop productivity, profitability, and environmental performance [8]. The studies included in this section demonstrate that increasing NUE requires integrated management involving crop rotation, balanced mineral nutrition, and improvement in soil physical fertility. The interaction of this set of factors collectively determines the plant's capacity to absorb, assimilate, and utilize fertilizer N during critical stages of yield formation.

Sainju and Pradhan evaluated the response of spring wheat to different cropping systems and N fertilization rates during an eight-year experiment conducted under semiarid conditions. The authors demonstrated that reducing N fertilization to 50 kg N ha⁻¹ in a no-till wheat–pea rotation sustained grain yield and test weight at levels comparable to systems receiving higher N rates or traditional wheat–fallow systems. The beneficial effect was associated with residual N supplied through pea residues, which contributed to improving soil N availability and reducing fertilizer dependency. The study clearly demonstrated that crop rotation involving legumes can partially replace mineral fertilizer N while simultaneously improving system sustainability and reducing environmental pressure in water-limited agroecosystems.

Balanced fertilization was identified as another key determinant of efficient N utilization. Barłóg and Grzebisz, in a three-year sugar beet experiment, demonstrated that the effectiveness of N fertilization strongly depended on adequate K and Mg supply. The combined application of potassium fertilizers and magnesium sulfate increased root yield by 6.5–9.1% and white sugar yield by 4.6–9.0%. At the same time, α -amino-N concentration was significantly reduced, indicating improved technological quality of sugar beet roots. The study emphasized that K and Mg should not be considered merely supplementary nutrients but rather critical conditioning factors controlling N uptake, assimilation, and partitioning within the plant. The observed improvement in NUE indices confirmed that balanced nutrition enhances the physiological efficiency of fertilizer N utilization.

The importance of soil physical fertility for improving NUE was highlighted by Zhang et al., who investigated the effect of increasing topsoil depth on maize productivity. Topsoil degradation significantly limits root development, nutrient acquisition, and water availability, thereby reducing crop responsiveness to fertilization. Increasing topsoil depth from 10 to 50 cm progressively increased grain yield by up to 49.4% and improved NUE from 14.2% to 64.9%. The authors identified 30 cm as the practical threshold for maintaining high productivity and efficient N use. Improved topsoil conditions enhanced root penetration and access to both water and nutrient reserves, reducing nutrient depletion and improving crop resilience under intensive cultivation systems.

Collectively, these studies demonstrate that increasing NUE cannot rely solely on reducing or modifying, especially N fertilizer rates. Efficient N management requires simultaneous optimization of crop rotation systems, nutrient balance, and soil physical properties. These integrated approaches improve synchronization between N supply and plant demand, thereby increasing crop productivity while reducing the environmental risks associated with N losses.

2.2. Nitrogen Carriers Replacing Fertilizer Nitrogen

The replacement of conventional mineral fertilizers with alternative nitrogen carriers represents an important strategy within sustainable intensification systems [8]. Organic residues and digestate-based fertilizers not only recycle nutrients within agricultural systems but may also improve synchronization between nutrient release and crop demand. The studies included in this section clearly demonstrate the considerable agronomic potential of digestate as a substitute for mineral fertilizer N in winter oilseed rape (WOSR).

Łukowiak et al. investigated nutrient dynamics before flowering during three growing seasons under contrasting environmental conditions. Digestate application maintained optimal leaf N concentrations during critical developmental stages, reaching 41–48 g kg⁻¹ DM at the rosette stage and 34–44 g kg⁻¹ DM at the onset of flowering. These values were associated with increased biomass accumulation and higher seed yield compared with ammonium nitrate fertilization. The study also revealed significant effects on nutrient balance, particularly a reduction in Ca concentration accompanied by improved Mg–Ca relations. This effect became especially important under drought conditions, when maintaining physiological nutrient balance is critical for sustaining crop growth and reproductive development. The authors suggested that digestate contributes not only nutrients but also improves nutrient synchronization under stress-prone environments. Szczepaniak et al. further evaluated the role of digestate during vegetative and reproductive growth periods of WOSR. Digestate-based fertilization systems produced greater net seed yield increases compared with ammonium nitrate alone, reaching 1.53 t ha⁻¹ for digestate and 1.77 t ha⁻¹ for digestate combined with ammonium nitrate, compared with 1.44 t ha⁻¹ obtained with mineral N fertilization. The optimal N rates were estimated at 250 and 224 kg N ha⁻¹ for digestate-based systems, respectively. Importantly, digestate acted as a slow-release fertilizer capable of sustaining available N pools throughout the growing season. The study also demonstrated strong relationships between crop N accumulation and final productivity, particularly for N content in crop biomass at anthesis ($r = 0.87$) and at harvest ($r = 0.95$). These indicators may therefore serve as reliable tools for predicting final yield and assessing crop N status.

Taken together, both studies demonstrate that digestate can effectively replace a major part of mineral fertilizer N while simultaneously improving synchronization of N-carrier supply with crop plant demand in critical stages of yield formation. Such approaches are consistent with the principles of circular agriculture, in which organic residues are recycled back into production systems, reducing dependence on synthetic fertilizers and mitigating environmental risks associated with excessive mineral N applications.

2.3. Biological Activators Supporting Mineral Fertilization

Biological activators and microbial-based fertilization technologies are increasingly recognized as important tools for improving nutrient acquisition efficiency and reducing fertilizer inputs. Their effectiveness depends on the stimulation of rhizosphere processes, enhancement of root growth, and increased nutrient availability in the soil–plant system. The studies presented in this section demonstrate that microbial inoculants

and signaling compounds can substantially improve crop productivity while lowering fertilizer dependency.

Kowalski et al. conducted a four-year field study on open-field tomato to evaluate whether microbial inoculation could reduce phosphate fertilization rates without compromising crop productivity. The integration of a bacterial consortium, with only 60% of the standard P fertilizer dose, maintained fruit yield, fruit quality, and leaf chlorophyll index at levels comparable to full-dose fertilization. The inoculation treatment significantly stimulated rhizospheric bacterial metabolic activity, suggesting enhanced nutrient mobilization and improved biological activity in the root zone. The authors also indicated the possibility of microbial-induced modifications in root system architecture, which may increase root exploration capacity and nutrient uptake efficiency. These findings demonstrate that microbial inoculation may become an effective strategy for reducing mineral fertilizer inputs in intensive horticultural systems. A complementary approach was presented by Wielbo et al., who evaluated extracts containing rhizobial Nod factors combined with mineral fertilization in barley and triticale cultivated under greenhouse conditions. Nod factors significantly stimulated root growth during flowering, increasing both root length and root biomass. Improved root development translated into enhanced reproductive performance at maturity, reflected by increased grain mass per plant, a higher grain number per ear, and greater 1000-grain weight. The study suggested that signaling molecules traditionally associated with legume symbiosis may also positively affect non-legume cereals through stimulation of physiological and developmental processes.

Collectively, these studies demonstrate that biological activators improve fertilizer efficiency not only through direct nutrient mobilization but also by stimulating plant physiological responses associated with root growth and nutrient acquisition. Their integration into fertilization systems may therefore become an important component of future low-input and environmentally sustainable agriculture.

2.4. Miscellaneous Topics

Several studies included in this Special Issue addressed additional aspects of fertilizer innovation related to nutrient retention, controlled-release technologies, crop biofortification, and diagnostic methodologies. Together, these studies demonstrate that sustainable fertilization increasingly integrates advanced materials, precision nutrient management, and improved diagnostic approaches.

Guan et al. evaluated optimized organic–inorganic fertilization strategies in greenhouse cucumber production using the Nutrient Balance Management (DBNM) approach. The integrated fertilization system significantly increased nutritional yields of Ca and Mg by 20.3–39.6% while simultaneously reducing nutrient leaching losses. Leaching of K, Ca, and Mg decreased by up to 41.1%, accompanied by alleviation of soil acidification. These results demonstrated that integrated fertilization strategies can simultaneously improve crop nutritional quality and reduce environmental nutrient losses in highly intensive vegetable production systems.

Advanced fertilizer technologies were represented by the work of Zhang et al., who developed hierarchically porous metal–organic frameworks (MIL-156-H) as controlled-release fertilizers. The material exhibited high nutrient-loading capacity, reaching 10.8% N and 16.3% P₂O₅, while sustaining nutrient release over 42–56 days. The prolonged nutrient-release pattern improved synchronization between nutrient availability and crop demand, leading to a 12.22% increase in rice yield, together with improved N and P use efficiency compared with conventional fertilizers. The study demonstrated the considerable potential of nanostructured materials and MOF technologies for the development of next-generation fertilizers capable of minimizing nutrient losses while maintaining high productivity.

Another important aspect of fertilizer innovation concerns crop biofortification and micronutrient delivery efficiency. Januszkiewicz et al. investigated the effect of nutrient forms in foliar fertilizers on maize growth and micronutrient accumulation under contrasting soil conditions. Fertilizers containing amino acid-chelated Fe and Zn, as well as plant-extract-bound trace elements, significantly enhanced maize biomass production and improved Fe and Zn accumulation, particularly in sandy soils characterized by lower nutrient-retention capacity. The results emphasized that the chemical form of nutrients strongly determines micronutrient availability, uptake efficiency, and crop biofortification potential, especially under stress-prone soil conditions.

Finally, Santa Cruz et al. addressed the reliability of crop nutritional diagnostics by evaluating inter-day variability in plant sap composition in broccoli. Significant daily fluctuations were observed, reaching 8.2% for NO_3^- concentration within only five days. The study clearly demonstrated that single-day measurements may lead to biased nutritional diagnoses and potentially inaccurate fertilization recommendations. The authors therefore proposed multi-day sampling approaches as a more reliable strategy for real-time crop nutritional assessment and precision fertilization management.

Taken together, these studies demonstrate that fertilizer innovation extends far beyond conventional nutrient supply. Future fertilization systems will increasingly depend on integrating advanced nutrient carriers, biofortification strategies, controlled-release technologies, and precision diagnostic tools capable of improving nutrient-use efficiency while minimizing environmental impacts.

3. Conclusions—Research Challenges

The set of articles published in this Special Issue clearly demonstrates that sustainable intensification of agriculture requires integrated approaches that combine improved nitrogen use efficiency, alternative nitrogen carriers, biological activators, advanced fertilizer technologies, and precision nutrient diagnostics. At the same time, the studies reveal that future fertilization strategies must increasingly integrate soil processes, plant physiology, microbial activity, and environmental sustainability.

However, several important research challenges still remain:

- How can synchronization between digestate-derived nitrogen release and crop demand be optimized under contrasting soil and climatic conditions?
- What are the long-term effects of microbial inoculants and Nod factors on soil microbial diversity, nutrient cycling, and soil health?
- How can controlled-release fertilizers be developed with greater nutrient-loading capacity and improved economic feasibility for large-scale agricultural systems?
- Which diagnostic tools can provide temporally stable and reliable real-time assessments of crop nutritional status?
- How can integrated organic–inorganic fertilization systems be designed to simultaneously maximize yield, improve nutrient-use efficiency, reduce nutrient losses, and maintain long-term soil fertility?
- To what extent can innovative foliar fertilization technologies contribute to crop biofortification and micronutrient-use efficiency under stress-prone soil conditions?

Addressing these challenges will be crucial for achieving the twin, essentially contradictory goals of global food security and environmental sustainability in the coming decades.

Funding: This research received no external funding.

Acknowledgments: The authors used the 2026 AI-assisted versions of Grammarly (v1.164.x) and QuillBot (4.85.0) tools solely for language editing, grammar checking, and text rephrasing to improve

the clarity and readability of the manuscript. All scientific content, interpretations, analyses, and conclusions were developed and reviewed by the authors.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Sainju, U.M.; Pradhan, G.P. Reducing Nitrogen Fertilization Rate in Spring Wheat–Pea Rotation Sustains Spring Wheat Yield and Quality. *Agronomy* **2025**, *15*, 1806. <https://doi.org/10.3390/agronomy15081806>.
2. Barłóg, P.; Grzebisz, W. Potassium and Magnesium Balance the Effect of Nitrogen on the Yield and Quality of Sugar Beet. *Agronomy* **2025**, *15*, 2075. <https://doi.org/10.3390/agronomy15092075>.
3. Zhang, X.; Lv, Y.; Dai, H.; Kong, Y.; Wang, Y.; Liu, K. Increasing Topsoil Depth Improves Yield and Nitrogen Fertilizer Use Efficiency in Maize. *Agronomy* **2025**, *15*, 2160. <https://doi.org/10.3390/agronomy15092160>.
4. Łukowiak, R.; Szczepaniak, W.; Młodecki, D. Impact of Digestate-Derived Nitrogen on Nutrient Content Dynamics in Winter Oilseed Rape Before Flowering. *Agronomy* **2025**, *15*, 1241. <https://doi.org/10.3390/agronomy15051241>.
5. Szczepaniak, W.; Łukowiak, R.; Klikocka, H. Impact of Organic Digestate on Soil and Crop Nitrogen During Critical Periods of Winter Oilseed Rape Growth. *Agronomy* **2026**, *16*, 959. <https://doi.org/10.3390/agronomy16100959>.
6. Kowalski, A.; Trzciński, P.; el Meziane, A.; Sas-Paszt, L.; Malusà, E. Can the Application of Microbial Inocula Allow for Reducing Phosphate Fertilisation Rates in Open Field Tomato Crops? *Agronomy* **2026**, *16*, 170. <https://doi.org/10.3390/agronomy16020170>.
7. Wielbo, J.; Podleśny, J.; Podleśna, A.; Kidaj, D.; Sroka-Bartnicka, A.; Klikocka, H. Combined Effect of Extract Containing Rhizobial Nod Factors and Mineral Fertilization on Growth and Yield of Barley and Triticale. *Agronomy* **2026**, *16*, 723. <https://doi.org/10.3390/agronomy16070723>.
8. Guan, X.; Cao, W.; Liu, D.; Zhao, H.; Lu, M.; Gao, X.; Chen, X.; Liu, Y.; Tian, S. Reducing Cation Leaching and Improving Greenhouse Cucumber’s Nutritional Yield Through Optimized Organic–Inorganic Fertilization. *Agronomy* **2025**, *15*, 1523. <https://doi.org/10.3390/agronomy15071523>.
9. Zhang, R.; Lv, G.; Du, C.; Ma, F.; Liu, S.; Gan, F.; Wu, K. Hierarchically Porous Metal–Organic Frameworks-Based Controlled-Release Fertilizer: Improved Nutrient Loading and Rice Growth. *Agronomy* **2025**, *15*, 2334. <https://doi.org/10.3390/agronomy15102334>.
10. Januszkiewicz, R.; Kulczycki, G.; Sacała, E.; Kabała, C. Effect of Nutrient Forms in Foliar Fertilizers on the Growth and Biofortification of Maize on Different Soil Types. *Agronomy* **2025**, *15*, 1482. <https://doi.org/10.3390/agronomy15061482>.
11. Santa Cruz, J.; Calbucho, D.; Valdebenito, S.; Cortés, J.; Gautier, C.; Amín, A.; Hernández, I.; Allendes, H.; Peñaloza, P. Inter-Day Instability in Plant Sap Composition Undermines Single-Day Diagnostics. *Agronomy* **2025**, *15*, 2509. <https://doi.org/10.3390/agronomy15112509>.

References

1. Grzebisz, W. *Crop Plant Fertilization. Part II. Fertilizers and Fertilization Systems*; PWRiL: Poznań, Poland, 2015; 376p. (In Polish)
2. Pretty, J.; Bharucha, Z.P. Sustainable intensification in agricultural systems. *Ann. Bot.* **2014**, *114*, 1571–1596. [[CrossRef](#)] [[PubMed](#)]
3. Smith, P. Delivering food security without increasing pressure on land. *Glob. Food Secur.* **2013**, *2*, 18–23. [[CrossRef](#)]
4. Licker, R.; Johnston, M.; Foley, J.A.; Barford, C.; Kucharik, C.J.; Monfreda, C.; Ramankutty, N. Mind the gap: How do climate and agricultural management explain the “yield gap” of croplands around the world? *Glob. Ecol. Biogeogr.* **2010**, *19*, 769–782. [[CrossRef](#)]
5. Zhang, X.; Wang, Z.; Song, L.; Duan, X.; Wang, Y.; Zhao, X.; Zhao, X.; Niu, B.; Hao, L.; Yang, Z.; et al. Global meta-analysis reveals soil, climate, and management drivers of crop yield and nitrogen use efficiency under enhanced-efficiency fertilizers. *Front. Agron.* **2026**, *8*, 1819891. [[CrossRef](#)]
6. Hilty, J.; Muller, B.; Pantin, F.; Leuzinger, S. Plant growth: The what, the how, and the why. *New Phytol.* **2021**, *232*, 25–41. [[CrossRef](#)] [[PubMed](#)]

7. Ye, Z.; Liao, L.; Qiu, G.; Xiao, Y.; Huang, D.; Duan, Z.; Pu, S.; Wen, J. Application of crop growth models in crop yield assessment. *Front. Plant Sci.* **2026**, *17*, 1819890. [[CrossRef](#)] [[PubMed](#)]
8. Dobermann, A. Nitrogen use efficiency—State of the art. In Proceedings of the IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt, Germany, 28–30 June 2005; pp. 1–16.
9. Sinclair, T.R.; Rufty, T.W. Nitrogen and water resources commonly limit crop yield increases, not necessarily plant genetics. *Glob. Food Secur.* **2012**, *1*, 94–98. [[CrossRef](#)]
10. Luo, L.; Zhang, Y.; Xu, G. How does nitrogen shape plant architecture. *J. Exp. Bot.* **2020**, *71*, 4415–4427. [[CrossRef](#)] [[PubMed](#)]
11. Wallace, A.; Wallace, G.A. *Closing the Crop—Yield Gap Through Better Soil and Better Management*; Wallace Laboratories: Los Angeles, CA, USA, 2003; 162p.
12. Grzebisz, W.; Łukowiak, R. Nitrogen gap amelioration is a core for sustainable intensification of agriculture—A concept. *Agronomy* **2021**, *11*, 419. [[CrossRef](#)]
13. Sattari, S.Z.; van Ittersum, M.K.; Bouwman, A.F.; Smit, A.L.; Janssen, B.H. Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QEFTS model. *Field Crops Res.* **2014**, *157*, 35–46. [[CrossRef](#)]
14. Córdova, C.; Barrera, J.A.; Magna, C. Spatial variation in nitrogen mineralization as a guide for variable application of nitrogen fertilizer to cereal crops. *Nutr. Cycl. Agroecosyst.* **2018**, *110*, 83–88. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.