Research Journal of Agricultural Science, 57 (3), 2025; ISSN: 2668-926X

http://doi.org/10.59463/RJAS.2025.3.19

EFFICIENCY OF NUTRIENT UPTAKE FROM FERTILIZERS ENHANCED BY BIOSTIMULANTS

Alecsia-Timeea DUȚĂ[1], Karina CSONTI[1], Alina LAȚO[1], Adina BERBECEA[1], Isidora RADULOV[1]

[1] University of Life Science "King Mihai I" from Timişoara, Romania

Corresponding author: isidora_radulov@usvt.ro

Abstract. *Improving nutrient use efficiency (NUE) is a major challenge in modern agriculture due to the environmental and economic drawbacks of excessive fertilizer use. Biostimulants—such as humic substances, seaweed extracts, protein hydrolysates, and microbial inoculants—are gaining attention as sustainable tools to enhance nutrient uptake and crop performance. This review synthesizes recent findings on the synergistic effects of biostimulants when integrated with conventional fertilizers. It addresses prevailing nutrient management challenges, categorizes major biostimulant types, elucidates their mechanisms of action, and evaluates factors influencing their effectiveness. These compounds act through diverse mechanisms, including stimulation of root growth, modulation of hormonal pathways, enhancement of rhizosphere microbial activity, and improved nutrient solubilization. Evidence from field studies indicates that co-application of biostimulants and fertilizers significantly improves absorption and assimilation of macro- and micronutrients, leading to higher yields, better nutritional quality, and increased stress resilience. However, variability in responses across crops and environments, coupled with the absence of standardized application protocols, limits widespread adoption. Key factors influencing biostimulant efficacy include crop genotype, growth stage, soil properties, climate conditions, and formulation type. Future research should focus on optimizing formulations, developing precision application strategies, and establishing regulatory frameworks to ensure safe and effective use. Overall, biostimulants represent a promising approach to complement traditional fertilization, reduce nutrient losses, and advance climate-smart, sustainable agriculture.*

Keywords*: Biostimulants, nutrient uptake, fertilizer efficiency, plant growth, sustainable agriculture, humic acids, microbial inoculants.*

INTRODUCTION

Modern agriculture faces the pressing dual challenge of boosting crop productivity while safeguarding environmental integrity. As global population growth and food demand continue to escalate, nutrient inefficiencies in soils and cropping systems persist as significant obstacles to sustainable production (Asadu et al., 2024; Maaz et al., 2025). Although synthetic fertilizers have historically driven short-term yield gains, their overuse has led to adverse consequences, including soil degradation, water pollution, and increased greenhouse gas emissions. Alarmingly, more than half of applied nitrogen and phosphorus fertilizers are lost through leaching, volatilization, or runoff, posing both ecological risks and economic losses for farmers (USDA, 2022; Yara International, 2022; Jalpa, 2024).

Despite these drawbacks, fertilizers remain essential for global food security due to their direct role in enhancing crop yield and quality (Yara International, 2022). However, their limitations—such as nutrient leaching, soil health deterioration, and reliance on finite raw materials—underscore the need for more sustainable nutrient management strategies (Maaz et al., 2025). In response, recent innovations have emphasized the integration of enhanced-efficiency fertilizers with biological inputs, particularly plant biostimulants (Asadu et al., 2024; Ruzzi et al., 2024).

Biostimulants are defined as natural or synthetic substances and microorganisms that promote plant growth, nutrient uptake, and stress resilience independently of their nutrient content (Gunalarasi & Kumar, 2023; Pereira et al., 2025). These inputs encompass a wide array of categories, including humic substances, seaweed extracts, protein hydrolysates, microbial inoculants, and signaling molecules (Baltazar et al., 2021; García et al., 2020; Hafez et al., 2025). Their role in sustainable agriculture is increasingly recognized due to their capacity to enhance nutrient use efficiency (NUE) and improve crop performance under diverse environmental conditions.

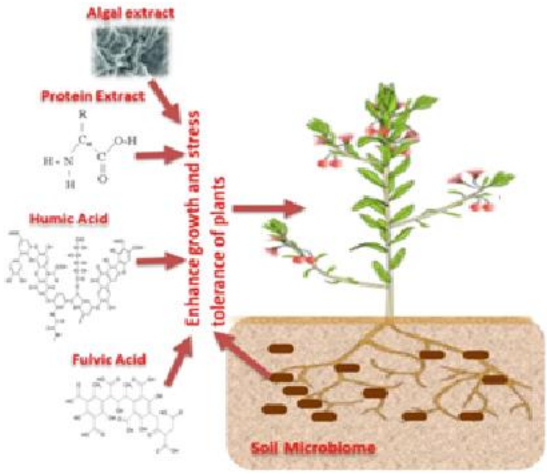

Figure 1. Role of biostimulants in plant development (Panday et al., 2022)

Recent studies have demonstrated the synergistic potential of combining biostimulants with conventional fertilizers, resulting in improved nutrient uptake and overall crop productivity (Basar et al., 2025; Fasani et al., 2025; Boutahiri et al., 2024). These effects are mediated through multiple mechanisms, including stimulation of root development, modulation of plant hormonal pathways, and enhancement of rhizosphere microbial activity (Khardia & Sharma, 2022; Mounaimi et al., 2024). Furthermore, biostimulants contribute to the nutritional and biochemical enrichment of crops, thereby supporting both agricultural sustainability and food quality (Fasani et al., 2025; Boutahiri et al., 2024). Notably, humic-based and microbial biostimulants have shown particular efficacy in increasing micronutrient solubility and facilitating nutrient translocation within plant tissues (Anitha, 2020; Hafez et al., 2025).

This review synthesizes current knowledge on the interactions between biostimulants and fertilizers, focusing on their role in enhancing NUE and promoting sustainable crop production. It addresses prevailing nutrient management challenges, categorizes major biostimulant types, elucidates their mechanisms of action, and evaluates factors influencing their effectiveness. Additionally, it highlights recent field-based evidence, integration strategies, and future directions for biostimulant innovation within the framework of climate-smart agriculture.

MATERIAL AND METHODS

A qualitative analysis was performed on publications released between 2020 and 2025, emphasizing studies that explore biostimulant contributions to nutrient use efficiency and fertilizer performance. Sources were gathered from reputable and accessible databases, including ScienceDirect, Elsevier, Scopus, Web of Science, and Google Scholar. Selection criteria prioritized peer-reviewed articles with open-access availability and direct relevance to biostimulant–fertilizer interactions. The reviewed literature was synthesized to extract key mechanisms, identify emerging trends, and assess practical implications for sustainable nutrient management in agricultural systems.

DISCUSSIONS

1. Fertilizer Use and Nutrient Uptake: Current Challenges

Nutrient uptake in plants involves complex physiological and biochemical pathways, including passive and active transport mechanisms. Nutrients enter root cells via diffusion, mass flow, and ion exchange, facilitated by membrane transporters and root exudates (Anitha, 2020; Khardia & Sharma, 2022). Macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are absorbed as inorganic ions, while micronutrients like iron (Fe), zinc (Zn), and manganese (Mn) rely on chelation and redox reactions to remain bioavailable (Hafez et al., 2025; García et al., 2020). Uptake efficiency is shaped by root architecture, soil conditions, microbial activity, and organic compounds that influence nutrient solubility and metabolism (Basar et al., 2025; Pereira et al., 2025).

Despite advances in fertilizer technology, global nutrient use efficiency (NUE) remains low. Less than half of applied nitrogen is absorbed by crops, with significant losses through volatilization, leaching, and denitrification (USDA, 2022; Jalpa, 2024). Phosphorus and potassium also exhibit poor recovery due to soil fixation and limited mobility (Asadu et al., 2024; Maaz et al., 2025). Contributing factors include poor timing and placement, imbalanced application, soil compaction, and mismatches between nutrient availability and crop demand (Yara International, 2022; Babcock-Jackson et al., 2023). Climate variability further exacerbates nutrient losses, especially under intensive farming systems (Ruzzi et al., 2024; Mounaimi et al., 2024).

The environmental consequences are substantial: excess nutrients drive eutrophication, contaminate groundwater, and increase emissions of nitrous oxide (N_2O), a potent greenhouse gas (Asadu et al., 2024; Maaz et al., 2025). Overuse also degrades soil health, disrupts microbial communities, and reduces long-term fertility (García et al., 2020; Boutahiri et al., 2024). Economically, inefficiencies burden farmers with rising input costs and diminishing returns (Yara International, 2022; Babcock-Jackson et al., 2023). Moreover, reliance on non-renewable resources like phosphate rock and natural gas raises concerns about sustainability and supply security (Maaz et al., 2025; Yara International, 2022).

Addressing these challenges calls for integrated nutrient management strategies that combine mineral fertilizers with biological and organic amendments (Basar et al., 2025; Ruzzi et al., 2024). Incorporating biostimulants enhances nutrient uptake, reduces environmental losses, and promotes soil resilience—advancing the goals of sustainable and climate-smart agriculture (Mounaimi et al., 2024; Gunalarasi & Kumar, 2023).

2. Biostimulants: Classification and Mechanisms

http://doi.org/10.59463/RJAS.2025.3.19

Biostimulants are gaining prominence in sustainable agriculture for their ability to enhance nutrient uptake, plant growth, and stress resilience. Unlike fertilizers, they act through distinct physiological pathways, improving nutrient use efficiency and soil health (Ruzzi et al., 2024; Gunalarasi & Kumar, 2023). Classified by origin and mode of action, biostimulants include humic substances, seaweed extracts, protein hydrolysates, microbial inoculants, and other bioactive compounds (Basar et al., 2025; Pereira et al., 2025; Baltazar et al., 2021).

Table 1

Classification and Mechanisms of Biostimulants

Biostimulant Type	Key Components	Primary Functions	Mechanisms of Action
Humic Substances	Humic and fulvic acids	Improve soil structure, root growth, and micronutrient mobility	Chelation, cation exchange, stimulation of root elongation [García et al., 2020; Hafez et al., 2025]
Seaweed Extracts	Polysaccharides, phytohormones, antioxidants	Enhance chlorophyll synthesis, stress tolerance, and root proliferation	Hormonal modulation, antioxidant activation [Mounaimi et al., 2024; Fasani et al., 202]
Protein Hydrolysates	Amino acids, peptides	Boost nitrogen assimilation, photosynthesis, and crop quality	Signaling molecule activity, nutrient transport enhancement [Gunalarasi & Kumar, 2023; Pereira et al., 2025]
Microbial Inoculants	PGPR, mycorrhizal fungi	Improve nutrient solubilization, water uptake, and symbiotic interactions	Nitrogen fixation, phosphorus solubilization, rhizosphere enhancement [Ruzzi et al., 2024; Mounaimi et al., 2024]
Other Compounds	Chitosan, silicon, phenolic extracts	Strengthening plant defenses and stress resilience	Elicitation of defense responses, cell wall reinforcement [Baltazar et al., 2021; Boutahiri et al., 2024]

Humic substances improve soil structure, stimulate root elongation, and chelate micronutrients for better mobility and uptake (García et al., 2020; Hafez et al., 2025). Seaweed extracts, rich in phytohormones and antioxidants, promote chlorophyll synthesis and stress tolerance (Mounaimi et al., 2024; Fasani et al., 2025). Protein hydrolysates enhance nitrogen assimilation and photosynthesis through amino acid signaling (Gunalarasi & Kumar, 2023; Pereira et al., 2025). Microbial inoculants, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, improve nutrient solubilization and water uptake via symbiotic interactions (Ruzzi et al., 2024; Mounaimi et al., 2024). Additional compounds like chitosan, silicon, and phenolic extracts contribute to defense activation and stress protection (Baltazar et al., 2021; Boutahiri et al., 2024).

Biostimulants function through multiple mechanisms (Table 1): stimulating root growth, enhancing nutrient solubilization via acidification and chelation, and activating microbial enzymes (García et al., 2020; Basar et al., 2025). They also modulate hormonal pathways, improving growth regulation and reproductive success (Baltazar et al., 2021; Pereira et al., 2025), while boosting stress tolerance through antioxidant activity and osmotic balance (Boutahiri et al., 2024; Ruzzi et al., 2024).

3. Factors Influencing Biostimulant Efficiency

Biostimulant performance is highly context-dependent, shaped by agronomic, environmental, and biological variables (Table 2). Their effectiveness varies with formulation type, crop species, growth stage, soil characteristics, and climatic conditions (Basar et al., 2025;

Ruzzi et al., 2024). Understanding these interactions is key to optimizing nutrient use efficiency (NUE) and achieving sustainable crop outcomes.

Table 2

Key Factors Affecting Biostimulant Efficiency

Factor	Influence on Biostimulant Performance	References
Crop Species & Genotype	Different species and cultivars vary in responsiveness due to genetic and physiological traits.	Pereira et al., 2025; Fasani et al., 2025
Growth Stage	Early application enhances root and leaf growth; later stages support nutrient translocation and stress tolerance.	Gunalarasi & Kumar, 2023; Ruzzi et al., 2024
Soil Properties	Texture, pH, organic matter, and fertility affect nutrient availability and microbial activity.	García et al., 2020; Hafez et al., 2025
Soil Fertility Level	Greater benefits in nutrient-poor soils; limited response in already fertile conditions.	Basar et al., 2025; Maaz et al., 2025
Climate Conditions	Temperature, rainfall, and radiation influence biostimulant stability and plant stress response.	Baltazar et al., 2021; Boutahiri et al., 2024
Application Method	Foliar sprays offer rapid uptake; soil or seed treatments provide sustained effects.	Gunalarasi & Kumar, 2023; Fasani et al., 2025
Formulation & Stability	Liquid vs. granular forms, concentration, and compatibility with other inputs affect efficacy.	Ruzzi et al., 2024; Hafez et al., 2025
Synergistic Combinations	Combining biostimulants (e.g., humic acids + microbes) can enhance nutrient uptake and stress resilience.	Pereira et al., 2025; Mounaimi et al., 2024

Plant species and cultivars respond differently due to genetic and physiological traits. Cereals with fibrous roots often benefit more from microbial inoculants and humic substances, while fruit and vegetable crops show improved yield and quality with seaweed or amino acid-based treatments (Anitha, 2020; Mounaimi et al., 2024; Fasani et al., 2025; Boutahiri et al., 2024). Timing also matters—applications during vegetative stages support root and leaf development, whereas reproductive-phase treatments enhance nutrient translocation and stress resilience (Gunalarasi & Kumar, 2023; Ruzzi et al., 2024).

Soil properties such as texture, pH, organic matter, and cation exchange capacity significantly influence biostimulant efficacy. In degraded soils, humic and microbial inputs boost nutrient solubility and microbial activity (Basar et al., 2025; Mounaimi et al., 2024), while fertile soils may show limited response due to existing nutrient availability (Yara International, 2022; Maaz et al., 2025). Extreme pH levels can also hinder microbial colonization and nutrient exchange (Pereira et al., 2025).

Environmental conditions—temperature, rainfall, and solar radiation—affect biostimulant stability and bioactivity. Under stress conditions like drought or salinity, compounds such as seaweed extracts, protein hydrolysates, and chitosan enhance plant defense and osmoprotection (Basar et al., 2025; Boutahiri et al., 2024). However, high temperatures and UV exposure may degrade bioactive molecules, reducing field performance (Baltazar et al., 2021; Ruzzi et al., 2024).

Application method and formulation also play critical roles. Foliar sprays offer rapid uptake, while granular forms provide sustained release (Gunalarasi & Kumar, 2023; Fasani et al., 2025; Basar et al., 2025). Stability, concentration, and compatibility with other inputs influence efficacy, and synergistic combinations—such as humic acids with microbes or amino acids with seaweed—can amplify nutrient assimilation and stress tolerance (Ruzzi et al., 2024; Hafez et al., 2025; Pereira et al., 2025; Mounaimi et al., 2024).

Research Journal of Agricultural Science, 57 (3), 2025; ISSN: 2668-926X
http://doi.org/10.59463/RJAS.2025.3.19

4. Integration with Fertilizer Strategies

Integrating biostimulants with conventional fertilizer regimes offers a promising pathway to enhance nutrient use efficiency (NUE), boost crop productivity, and support environmentally sustainable agriculture. Rather than replacing mineral fertilizers, biostimulants act as complementary inputs that improve nutrient uptake, assimilation, and utilization (Basar et al., 2025; Ruzzi et al., 2024). Their synergy with organic and inorganic fertilizers promotes balanced nutrition, stimulates soil biological activity, and reduces nutrient losses.

Co-application of biostimulants with fertilizers has shown superior results compared to either input alone. Biostimulants enhance nutrient availability by stimulating root exudation, microbial activity, and enzymatic processes (Mounaimi et al., 2024; García et al., 2020). For instance, humic substances combined with nitrogen fertilizers improve nitrogen uptake and reduce volatilization (Hafez et al., 2025; Asadu et al., 2024), while microbial inoculants like PGPR and mycorrhizal fungi mobilize phosphorus and micronutrients, especially when paired with organic amendments (Pereira et al., 2025; Maaz et al., 2025). Protein hydrolysates and seaweed extracts further enhance chlorophyll synthesis, nutrient translocation, and crop quality when used with balanced fertilization (Fasani et al., 2025; Boutahiri et al., 2024).

Precision agriculture technologies offer new opportunities for optimizing biostimulant–fertilizer integration. Tools such as remote sensing, soil mapping, and variable-rate application enable site-specific delivery based on crop stage and soil variability (Ruzzi et al., 2024; Babcock-Jackson et al., 2023). Digital platforms and sensor-based monitoring help align nutrient availability with plant demand, improving efficiency and reducing waste (Yara International, 2022; Basar et al., 2025).

Field studies confirm these benefits. Fasani et al. (2025) reported improved yield and grain quality in wheat with seaweed extract and nitrogen co-application. Basar et al. (2025) observed enhanced nitrogen uptake and stress tolerance in vegetables treated with humic substances and mineral fertilizers. Mounaimi et al. (2024) demonstrated improved microbial diversity and phosphorus efficiency in maize systems using microbial biostimulants. Collectively, these findings support the role of integrated biostimulant–fertilizer strategies in improving agronomic outcomes while reducing nutrient losses and greenhouse gas emissions (Asadu et al., 2024; Maaz et al., 2025).

5. Future Perspectives

Biostimulants are poised to become central components of next-generation nutrient management systems, driven by advances in formulation science, molecular biology, and precision agriculture (Ruzzi et al., 2024; Maaz et al., 2025). As agriculture grapples with soil degradation, nutrient inefficiency, and climate stress, biostimulants offer a resource-efficient and environmentally sound solution.

Emerging research is enabling the development of multi-functional biostimulants that combine humic substances, microbial inoculants, and signaling compounds for synergistic plant responses (Basar et al., 2025; Pereira et al., 2025). Omics technologies—genomics, transcriptomics, and metabolomics—are deepening our understanding of biostimulant action, paving the way for crop- and soil-specific formulations (Baltazar et al., 2021). Innovations in nanoencapsulation and controlled-release systems are further improving product stability and targeted delivery (Mounaimi et al., 2024; Hafez et al., 2025).

In regenerative agriculture, biostimulants support soil health, nutrient cycling, and reduced reliance on synthetic inputs (Maaz et al., 2025; Gunalarasi & Kumar, 2023). Their integration into practices like cover cropping and composting enhances carbon sequestration and water-use efficiency, aligning with circular economy principles (García et al., 2020; Mounaimi et al., 2024; Ruzzi et al., 2024; Asadu et al., 2024).

Biostimulants also strengthen plant resilience to abiotic stresses—drought, salinity, and heat—by modulating antioxidant systems, osmolyte levels, and hormonal balance (Basar et al., 2025; Boutahiri et al., 2024). By improving NUE and reducing fertilizer dependence, they help lower greenhouse gas emissions and nutrient runoff (Asadu et al., 2024; USDA, 2022). As global policies shift toward carbon-neutral and low-input agriculture, biostimulants will play a pivotal role in achieving climate-smart and sustainable farming goals.

CONCLUSIONS

Enhancing nutrient use efficiency (NUE) is a critical priority for modern agriculture, given the mounting challenges of soil degradation, climate variability, and the environmental costs of fertilizer overuse. This review highlights the growing potential of biostimulants as complementary tools that improve nutrient uptake, optimize fertilizer performance, and support sustainable crop production. By acting through diverse physiological and biochemical mechanisms, biostimulants—ranging from humic substances and microbial inoculants to seaweed extracts and protein hydrolysates—can significantly enhance root development, nutrient solubilization, and stress resilience.

The integration of biostimulants into conventional and precision-based fertilization strategies offers a promising pathway toward more efficient and climate-smart nutrient management. Field evidence confirms their synergistic benefits in improving yield, nutrient recovery, and soil health while reducing environmental losses and input dependency. As scientific innovation continues to refine biostimulant formulations and delivery systems, their role in regenerative and low-input farming systems is expected to expand.

Ultimately, biostimulants represent a transformative approach to nutrient management—one that aligns agronomic performance with ecological stewardship and long-term sustainability. Their strategic deployment will be essential in building resilient agroecosystems capable of meeting future food security and environmental goals.

BIBLIOGRAPHY

ANITHA, K.V., 2020 – Role of biostimulants in uptake of nutrients by plants. Journal of Pharmacognosy and Phytochemistry, 9(4S): S-9-3-20-701, Delhi, India.

ASADU, C.O., NWOKE, O.C., & EZE, V.U., 2024 – Enhanced efficiency fertilizers: Production, properties, and performance. ScienceDirect Review, Elsevier, Netherlands.

BABCOCK-JACKSON, L., NGUYEN, P., & TOMA, R., 2023 – Sustainable fertilizers: Publication landscape and research trends. Sustainability (MDPI), 15(2): 1025, Basel, Switzerland.

BALTAZAR, M.T., PEREIRA, R., & LOPES, C., 2021 – Recent advances in the molecular effects of biostimulants. Plants (MDPI), 10(8): 1749, Basel, Switzerland.

BASAR, H., YILDIZ, A., & KAYA, C., 2025 – Synergies between biostimulants and plant nutrients: A review of eco-friendly nutrient management in crop production. Environmental Science and Pollution Research, 32(5): 345-356, Berlin, Germany.

BOUTAHIRI, S., EL-MOURID, M., & BENSAID, R., 2024 – Effects of biostimulants on the chemical composition of food crops. ScienceDirect, Elsevier, Netherlands.

FASANI, E., ROMANO, D., & BIANCHI, M., 2025 – Effect of biostimulants combined with fertilization on yield and nutritional value of wheat crops. BMC Plant Biology, 25(1): Article 6804, London, United Kingdom.

GARCÍA, A.C., OLAETXEA, M., SANTOS, L.A., & MORA, V., 2020 – Agro-environmental applications of humic substances. Frontiers in Plant Science, 11: 426, Lausanne, Switzerland.

GUNALARASI, R., & KUMAR, S., 2023 – Biostimulants for sustainable crop production: A review. International Journal for Multidisciplinary Research, 6(6): 11053, Tamil Nadu, India.

HAFEZ, M., ABDEL-RAHMAN, A., & EL-SAYED, S., 2025 – Enhancing micronutrient availability through humic-based biostimulants. Plants (MDPI), 14(8): 1224, Basel, Switzerland.

JALPA, L., 2024 – Nitrogen use efficiency and yield using soluble vs. controlled-release urea. HortScience, 59(4): 442-450, Alexandria, USA.

KHARDIA, N., & SHARMA, R., 2022 – Role of biostimulants in nutrient uptake and plant growth. ResearchGate Preprint, Jaipur, India.

MAAZ, T.M.C., LIAO, H., & ZHANG, X., 2025 – Review of research and innovation on novel fertilizers for sustainable agriculture. Nature Reviews Earth & Environment, 6(2): 115-130, London, United Kingdom.

MOUNAIMI, S., BOUTOUIL, A., & EL-FASSI, M., 2024 – Integrating biostimulants and nutrient management for sustainable agriculture. Frontiers in Sustainable Food Systems, 8: 1452823, Lausanne, Switzerland.

PANDEY, B., BHARDWAJ, V., RAMAWAT, N. (2022). The Role of Biostimulants in Plant Growth, Development, and Abiotic Stress Management: Recent Insights. In: Ramawat, N., Bhardwaj, V. (eds) Biostimulants: Exploring Sources and Applications. Plant Life and Environment Dynamics. Springer, Singapore. https://doi.org/10.1007/978-981-16-7080-0_9

PEREIRA, C., SILVA, T., & OLIVEIRA, R., 2025 – Use of biostimulants in beneficial plant–microbe interactions. Frontiers in Plant Science, 16: 1592681, Lausanne, Switzerland.

RUZZI, M., TENCA, M., & PUGLISI, I., 2024 – Biostimulants in agriculture II: Towards a sustainable future. Frontiers in Plant Science, 15: 11176606, Lausanne, Switzerland.

***USDA, 2022 – Highly Soluble Nitrogen Fertilizers: Recommendations and Management. USDA Agricultural Bulletin, Washington, D.C., USA.

***Yara International, 2022 – Fertilizer Industry Handbook. Yara Reports, Oslo, Norway.