Scientia Horticulturae 350 (2025) 114281

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Editorial

Unlocking the black box of plant biostimulants

Over the recent years, plant biostimulants have shifted from the margins of agricultural innovation to the forefront of global discussions towards sustainable crop production models. Despite their growing popularity and commercial relevance, key questions persist regarding their actual effects on plants, the validation of their claimed benefits, and the identification of reliable metrics to assess their impact. This editorial aspires to navigate through the definitions, scientific evidence, and regulatory frameworks shaping the current and future landscape of biostimulants. Building on this foundation, the present article reflects on the broader scientific discussion initiated during the ISHS HortForum on plant biostimulants, aiming to distil key conceptual and methodological challenges in the field. An integrated perspective on how biostimulants can be more effectively studied, functionally categorized, and applied in modern agriculture from a range of perspectives is discussed. This analysis provides a critical synthesis of current scientific thinking. It highlights key research priorities, particularly concerning mechanisms of action, quantifiable effects, and the role of biostimulants in promoting resilient, sustainable cropping systems.

1. From concept to definition: the long journey towards clarity

The concept of biostimulants emerged not from formal classification, but from empirical use. For decades, farmers applied seaweed extracts, humic substances, amino acids, and microbial inoculants that seemed to improve plant performance without clearly belonging to known categories like fertilizers or pesticides. These products produced visible effects that could not be explained by simple nutrient supply. The term biostimulant began appearing in the scientific literature in the early 90 s. Russo and Berlyn (1991) were among the first to define them as “non-fertilizer products with beneficial effects on plant growth,” particularly in low-input systems. Zhang and Schmidt (1997) later emphasized that their action often occurs at low concentrations and through non-nutritional pathways, such as hormonal signaling or micronutrient chelation.

These early insights introduced a key conceptual shift: **biostimulants are not defined by what they contain, but by what they do.** Rather than supplying nutrients, they support the plant’s physiological processes, root development, nutrient assimilation, or stress response; they are not fertilizers, but function enhancers. This concept now underpins current regulatory definitions. The *European Union’s Regulation (EU) 2019/1009* (EU, 2019) officially recognizes plant biostimulants as products that “stimulate plant nutrition processes independently of the product’s nutrient content” aiming to improve nutrient use efficiency, tolerance to abiotic stress, crop quality, or nutrient availability in the rhizosphere.

A foundational contribution to this perspective came from du Jardin (2015), who proposed an operational definition that emphasized intended effects over composition, helping to establish a framework that distinguishes biostimulants from fertilizers and pesticides. This “claim-based” model shifts focus from formulation to function. What matters is not the product’s composition, but the validation of its effects.

The internationally adopted ISO/TC 134 definition echoes this concept, describing biostimulants as "substances, microorganisms, or mixtures thereof that support a plant’s natural nutrition processes" (ISO, 2022). However, although aligned in principle, these definitions differ in terminology and regulatory implications. Regulatory definitions of biostimulants vary significantly across regions, with real effects on classification and approval. In the United States, a preference has been observed for the definition “support natural nutrition processes,” unlike the EU’s “stimulate plant nutrition.” This subtle difference leads to broader interpretations in the US and may allow products with less-defined mechanisms to reach the market more easily. The constant evolution of terminology creates confusion, even for researchers. Thus, there is a need for clearer, globally aligned definitions, as inconsistent language hampers scientific communication and regulatory clarity.

Further complications concern microbial biostimulants. In South America, they are classified as inoculants rather than biostimulants, reflecting a different regulatory approach. However, many microbial strains mobilize nutrients, produce hormones, or trigger plant defences, blurring boundaries with biopesticides and highlighting the limits of rigid categories. Such divergences have real implications for regulation, validation, and product communication. Indeed, unclear definitions affect how biostimulants are assessed, positioned in the market, and perceived across regions. In Europe, claim validation is supported by harmonized protocols (CEN/TC 455) and CE-marking, while elsewhere approval may rely on voluntary certifications or unrelated classification schemes.

Definitions shape both research and communication. When terminology is inconsistent, it creates confusion and can lead to misuse. If efficacy is judged only by yield, important effects like priming or stress tolerance may be overlooked, especially when they do not result in immediate biomass gains.

Evaluating biostimulants means more than measuring outcomes. It requires connecting agronomic goals to specific physiological traits and building claims around that relationship. Without a clear target, even

https://doi.org/10.1016/j.scienta.2025.114281

Available online 30 July 2025

promising innovations may be misapplied. Therefore, biostimulants are not just rebranded inputs. They reflect a broader shift in plant care, from adding inputs to enhancing biological potential, from reacting to stress to building resilience. Defining what they are, what they are not, or how they work is essential to gaining trust.

2. Rethinking biostimulants: why yield alone does not tell the full story

Yield remains the standard for evaluating agricultural inputs, but it often misrepresents the value of biostimulants. These products do not directly stimulate growth like fertilizers or pesticides. Instead, they support internal functions such as root development, antioxidant defence, and nutrient redistribution. Their effects are subtle, shaped by environmental conditions, and may not lead to immediate biomass increases.

Many biostimulants act by inducing or by priming stress responses. ‘Induction’ means that protective genes are upregulated before stress occurs, while ‘priming’ means that the stress responsive genes are not activated until stress occurs but that the rapidity and/or amplitude of the stress response will be enhanced by the priming stimulus (e.g. the biostimulant). Enhanced stress tolerance may require some energy, which may slightly reduce growth under ideal conditions. This trade-off means that greater resilience does not always translate into higher yield. To capture their true value, evaluation must go beyond productivity and consider physiological responses.

The importance of timing and stress exposure is particularly relevant in perennial crops. When applied before events like heatwaves, biostimulants can be partially effective. But in the absence of stress, their impact may be minimal. In long-cycle crops, visible results may take months or even years, while both regulations and markets often demand quick, measurable returns. Microbial biostimulants are also particularly effective in horticulture, where farmers can adjust timing and application based on crop needs. This flexibility makes it easier to optimize responses and reduce reliance on chemical inputs. In contrast, large-scale systems like maize or soybean offer fewer adjustment opportunities, making it harder to detect subtle physiological benefits. This reinforces the idea that yield alone is not sufficient to evaluate biostimulants. Emphasis has been placed on the importance of measuring functional traits such as root development, nutrient utilization, and production of anti-stress compounds. Integrating biostimulants into broader fertilization strategies is considered essential to support long-term system performance, rather than providing short-term fixes.

It is thus evident that plant biostimulants need broader evaluation methods since yield efficiency alone is not adequate as a single indicator. Physiological traits and metabolic profiles must be considered as complementary indicators. Tools such as chlorophyll fluorescence, osmotic potential, and gene expression are used in research, but applying them in the field requires a shift in thinking that values plant fitness as part of productivity.

3. Evidence first: redefining how biostimulants are validated

If biostimulants are defined by function, proving their effects is essential. Unlike fertilizers or pesticides, their impact is indirect and highly context-dependent, making validation more complex. Trials with humic and fulvic acid-based seed treatments in winter wheat, as reported by commercial sources, have produced outcomes ranging from positive to neutral or even negative. These variations reflect environmental and crop-specific factors rather than product failure, underscoring the importance of context in assessing efficacy.

Variability is a normal feature of field trials. Questions often arise about why a product performs well in one setting but not in another, and clear answers are not always available. In the absence of mechanistic markers, even well-designed studies can yield ambiguous results.

In Europe, biostimulants are required to meet efficacy standards established by the European Committee for Standardization (CEN/TC 455, 2021). However, many products still make bold claims based on weak or non-replicable data, leading to inconsistencies that undermine growers’ confidence. The issue is not necessarily product ineffectiveness, but rather the difficulty of verifying results under real-world conditions.

Questions have been raised about whether current regulations require not only proof of efficacy but also an explanation of how biostimulants work. In most cases, approval is based solely on the demonstration of a measurable agronomic benefit, without the need to clarify the biological mechanisms involved. This allows products to enter the market based on observed outcomes, even when the underlying processes remain unclear. While such an approach encourages innovation and broadens market access, it may reduce scientific transparency and make it more difficult for growers to distinguish between empirically effective products and those supported by a clear mode of action. As confirmed under EU rules, a mechanistic explanation is not required, but only reproducible results. This creates a regulatory gap in which compliance is possible without a full understanding of product function, leaving a blind spot in validation.

Advanced formulations such as smart polymers and nanoparticle carriers present new challenges. These innovations enhance delivery efficiency but may fall outside the scope of current regulatory definitions. This raises concerns about whether the existing framework can adapt quickly enough. Progress depends on linking a clear biological rationale with agronomic objectives and field evidence. Without this connection, product identity and function remain ambiguous.

The EU has introduced structured categories of biostimulant claims, supported by validated data and standardized protocols (Table 1). This offers a solid regulatory foundation, but compliance alone is not sufficient. Products must prove their effectiveness under real farming conditions. Meeting regulatory standards is not enough if they fail to deliver tangible benefits, especially under stress. Validation should reflect on-farm realities to ensure both credibility and practical adoption. A clear gap persists between scientific rigor and how products are marketed. When practical results do not align with simplified claims, confidence in individual products declines and trust in the entire category is undermined.

The global situation introduces additional complexity. In the United States of America, voluntary certification schemes exist but vary in quality. In many regions, the absence of harmonized standards creates confusion and regulatory uncertainty. This makes it essential to base agronomic practices on solid evidence, not only to ensure credibility but also as an ethical responsibility toward farmers and sustainable agriculture. Validation should include both efficacy data and an explanation of how products achieve agronomic benefits. Without international alignment, this process becomes more challenging. The goal is not to prove universal outcomes but to show where and how biostimulants

Table 1
Biostimulant claim categories allowed under EU Regulation 2019/1009.

Claim Category	Expected Effect	Example Parameters
Nutrient Use Efficiency (NUE)	Enhancing the plant’s ability to acquire, transport, or assimilate nutrients more efficiently	Root morphology, nutrient uptake rates, tissue nutrient levels
Abiotic Stress Tolerance	Improving plant performance under environmental stress (e.g., drought, salinity, temperature extremes)	Accumulation of osmolytes (e.g., proline), antioxidant enzyme activity, stomatal regulation
Crop Quality Traits	Enhancing quality characteristics of the harvested product	Fruit sugar content, phenolic profiles, protein concentration
Nutrient Availability in Soil/ Rhizosphere	Increasing the bioavailability of nutrients through soil or rhizosphere interactions	Soil microbial activity, pH modulation, enzymatic solubilization

work. Collecting context-specific evidence is crucial to understanding their function and building credibility in the sector.

4. Push and pull: biostimulants in the era of ecological transition

Biostimulants are more than functional inputs; they are strategic tools shaped by scientific progress and environmental demands. Advances in plant physiology, epigenetics, and microbiome research have shown how external inputs influence gene expression, metabolism, and stress responses. Biostimulants modulate plant-environment interactions through subtle but significant mechanisms. In plant-microbe systems, they shape the rhizosphere, enhance nutrient availability, and support beneficial microbial communities. Acting as mediators within the plant holobiont, they help optimize plant function. At the same time, farmers must reduce inputs, adapt to climate change, and maintain productivity. These challenges underscore the role of biostimulants in building resilience and supporting the ecological transition.

The European policy goals, including those of the Green Deal, call for a significant reduction in nutrient losses and fertilizer use by 2030. In this context, biostimulants play a supportive role: they do not replace nutrients but enhance their use efficiency. By promoting root development and stimulating rhizosphere activity, they help plants access nutrients already present in the soil. Although the law of the minimum still applies, the use of biostimulants reduces waste and improves the overall efficiency of inputs.

From a global perspective, the increasing unpredictability of climate presents major challenges. Farmers are more impacted by abrupt events such as late frosts, heatwaves, and irregular rainfall than by gradual temperature increases. These short-term stresses can compromise flowering, fruit set, and growth, particularly in high-value crops. Biostimulants may help mitigate such effects when applied preventively. Their value lies in preparing plants for stress, shifting the approach from reaction to prevention. This strategy requires more than new products; it calls for a shift in mindset, with biostimulants used to support physiological balance rather than merely stimulate growth.

These insights point to the need for a more integrated approach. Biostimulants should be embedded within a broader framework of sustainable practices, including precision irrigation, site-specific fertilization, and microbiome management. Rather than acting as standalone solutions, they function as tools to optimize resource use when applied strategically. Fig. 1 illustrates how innovation in this field emerges from the convergence of two forces: scientific and technological '*push* drivers', and societal and agricultural '*pull* drivers'.

As agricultural production systems are shifting from abundance to constraint, biostimulants may help balance productivity with sustainably-sourced approaches. Their value lies not in acting alone but in supporting living, dynamic systems. Beyond enhancing plant growth, they enable systemic improvements by supporting nutrient cycling, reducing runoff, and improving soil function. They strengthen resilience by enhancing plant function rather than controlling pests, aligning with a broader view of plant health based on adaptability and performance. Their adoption is especially relevant in high-pressure sectors like horticulture, where resilience is necessary. However, this transition requires more than new products. It depends on farmer training, technical support, and policies that promote long-term ecological stability over short-term yield gains.

5. Redefining innovation beyond the label

Although biostimulants are formally defined by their function rather than their composition, current regulations impose strict limits on what they can be. In the European Union, they must enhance plant nutrition or stress tolerance without acting as pesticides or mimicking hormones such as auxins or gibberellins.

This boundary is increasingly challenged by recent research. New formulations using biopolymers such as sodium alginate or green-synthesized nanoparticles derived from agricultural waste aim to improve delivery efficiency and align with circular economy principles. These developments raise concerns about whether existing definitions can evolve rapidly enough. While microbial biostimulants benefit from clearer regulatory pathways, innovation in non-microbial products, particularly those involving nanocarriers, is advancing at a faster pace than regulation. One emerging approach involves nanocarriers that deliver double-stranded RNA to modulate gene expression. Although not yet commercialized, such technologies have the potential to alter current definitions of biostimulants.

Materials like cellulose and chitosan also acquire new bioactive properties at the nanoscale, influencing plant physiology, soil interactions, and microbiome composition. Current validation methods often fail to capture these complex, multifactorial effects.

Inconsistencies persist in the regulation of microbial strains that produce phytohormones. When these hormones act within microbial systems, their use is permitted, but the same molecules face stricter controls when isolated. This highlights the difficulty of regulating

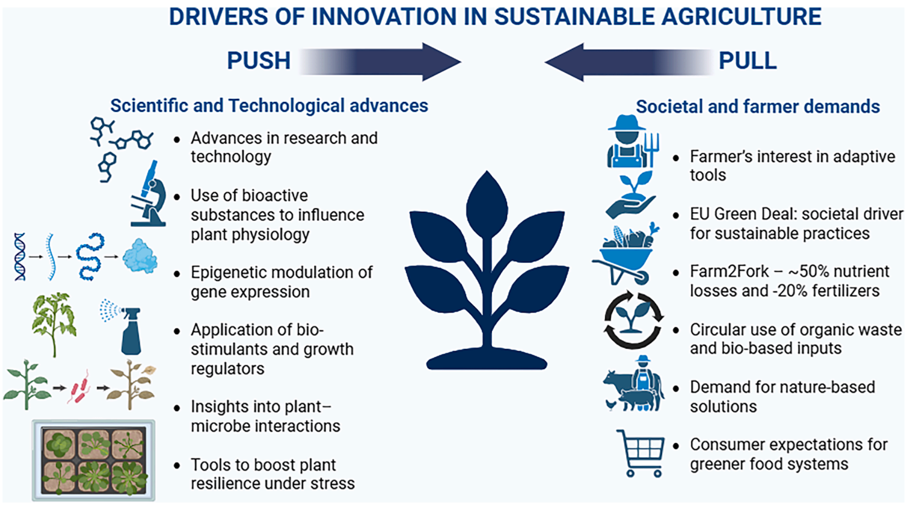

Fig. 1. Drivers of innovation in sustainable agriculture. The dynamic interaction between scientific and technological *push* drivers, and societal and agricultural *pull* drivers shapes resilient, efficient, and environmentally aligned farming solutions.

biological complexity through composition-based criteria. Modern biostimulants act through synergistic mechanisms involving microbes, molecules, and carriers. Their efficacy depends on context, and traditional testing frameworks may be too limited to capture their full effects.

Regulation should reflect biological function rather than formulation. Frameworks need to consider how multiple components interact to produce effects. Without such adaptation, the flexibility originally envisioned for the biostimulant category may be lost. Evolving definitions are needed to align with scientific progress and support resilient agriculture.

6. Functional nutrition and the evolution of plant health concepts

The concept of plant health is evolving beyond the mere absence of disease or nutrient deficiency. In the context of unstable climates and complex production systems, it is increasingly understood as the dynamic ability to maintain balance, respond to stress, and recover function. Biostimulants are viewed as tools that support adaptability rather than stimulate growth.

Similar to functional foods in human nutrition, biostimulants do not supply essential nutrients but deliver bioactive signals that modulate physiological pathways and enhance resilience. Their value lies in reinforcing internal regulatory mechanisms rather than increasing external inputs. This reflects a broader shift in agronomy, from resource supplementation to the management of physiological stability under variable conditions.

This shift in perspective is particularly relevant for perennial crops, where yield represents only one aspect of performance. In fruit trees, long-term success depends on maintaining physiological balance across seasons, which influences bud formation, resource accumulation, and flowering. When applied strategically, biostimulants can support these processes even if their benefits are not immediately visible.

Field trials in drought-stressed tree crops have shown that biostimulants improve water use efficiency, reduce oxidative damage, and preserve oil quality, even in the absence of yield increases. These findings indicate that biostimulants contribute to stabilizing plant function under stress conditions, reducing performance variability and protecting crop quality. Such effects, although not always captured by yield metrics, are increasingly important under growing environmental pressure. This concept parallels what human medicine defines as *preventive physiology*: building resilience proactively rather than reacting to damage after it has occurred. In agronomy, as in human health, *timing is critical*. Biostimulants are most effective when applied in advance of stress, during critical stages such as bud break or early fruit development, to prepare plants physiologically. This approach requires predictive tools, decision-support systems, and a shift toward anticipatory management.

Early applications can also induce a form of *stress memory*, leading to lasting physiological changes that improve responses to future stress events. This priming effect, potentially involving epigenetic mechanisms, opens new strategies to enhance resilience through early and targeted interventions.

Shifting to a functional view of plant health changes how biostimulants should be evaluated and applied. Yield alone cannot capture their complexity. Assessment must include physiological indicators like photosynthetic efficiency, antioxidant activity, osmotic regulation, and stress-related molecular markers. Broadening evaluation criteria is essential to recognize and validate their true contributions. Moreover, management strategies must shift from reactive to preventive. Biostimulants are most effective during key stress periods, such as flowering or drought, helping plants prepare before symptoms appear. This approach requires better forecasting, deeper phenological insight, and closer integration with fertilization and irrigation. Plant health, in this view, is dynamic and adaptable. When used wisely and alongside other practices, biostimulants can support more resilient and efficient systems. Recognizing their *functional role*, beyond short-term yield, is crucial to unlock their full value under growing environmental and production pressures.

Framing biostimulants as tools of agronomic intelligence, defined by function, validated through mechanisms, and integrated into complex systems, requires a broad conceptual shift. Table 2 summarizes the key principles that should guide research, application, and communication strategies. They contribute not by adding more, but by enabling smarter, system-based solutions grounded in biology. Their role in sustainable agriculture depends on our ability to embed them within a broader mindset that values care, complexity, and long-term functionality over short-term control.

7. Building credibility through scientific coherence

The credibility of biostimulants relies on coherence between claims, biological mechanisms, and supporting evidence. The main risk lies not in regulation, but in the loss of trust among farmers and researchers, a loss that is difficult and slow to recover. This is especially critical for products defined by function rather than input content.

Early signs of mistrust are already becoming evident. Many farmers feel overwhelmed by the growing number of biostimulant products, often promoted with exaggerated promises and minimal explanation. Even when a product works, the lack of a clear biological rationale can make it seem unreliable. From a regulatory standpoint, EU legislation requires evidence of field efficacy but does not demand disclosure of how the product actually works. This opens the door to vague or superficial claims, such as general references to antioxidant activity, that may not be directly linked to plant performance. In some cases, identifying the active compounds in natural extracts may lead to their reclassification under stricter plant protection laws. As a result, transparency can become a risk rather than a value, discouraging scientific efforts to better understand these products.

These problems are amplified by weak communication in the field. The gap between marketing language and biological reality, especially under challenging agronomic conditions, contributes to unrealistic expectations and loss of confidence. In order to address this, biostimulant

Table 2
Key conceptual principles for framing, evaluating, and communicating plant biostimulants.

Key topic	Key message
Functional framing	Biostimulants must be defined as functional supplements based on their physiological effects, not their composition.
Beyond yield	Success metrics must include resilience, stress tolerance, and stability of quality traits, not just biomass or yield increases.
Mechanism-based validation	Validation must link biological mechanisms, target physiological traits, and real field outcomes through clear, reproducible evidence.
Integration into systems	Biostimulants must be incorporated within broader, evidence-based agronomic systems rather than treated as standalone solutions.
Embracing complexity	Regulation and evaluation should accommodate the complexity of microbial consortia, multifunctional matrices, and emerging technologies.
Preventive strategy	Some biostimulants are most effective when applied proactively to prepare plants for future stress, not reactively after symptoms appear.
Credible communication	Transparent communication of mechanisms, benefits, and limitations is essential to align grower expectations with real product performance.
Responsibility in innovation	Innovation must prioritize biological plausibility and agronomic relevance over marketing appeal or regulatory shortcuts.
Agronomy of care	Biostimulants represent a shift from an agriculture of control to an agriculture of care, resilience, and intelligent adaptation.

products should (i) clearly state the biological process it targets, (ii) specify the physiological trait or agronomic condition it is intended to affect, and (iii) provide evidence of effectiveness under field-relevant conditions. This triad would help shifting the focus from promotional claims to demonstrable agronomic performance.

Scientific coherence does not require exhaustive molecular detail or long-term trials for every product. What matters is that biological plausibility is part of the narrative from the start. In a context defined by environmental variability and complex interactions, both the potential and the limits of a product must be communicated clearly. Credibility will not come from bold promises, but from transparent, evidence-backed claims that reflect actual agronomic results.

Farmers should be treated as informed actors capable of understanding both potential and limitations of biostimulants. Scientific plausibility, not vague optimism, must define the narrative. Without this shift, even promising innovations risk being ignored or misused. Moving from *faith-based marketing* to a *science-based dialogue* is essential for ensuring that biostimulants are integrated into sustainable agricultural systems as credible, functional, and responsible tools.

8. Conclusions

The 2025 ISHS HortForum on biostimulants (ISHS, 2025) marked a turning point in their understanding. No longer viewed as experimental, they are now seen as essential components of crop management. Their integration calls for alignment across scientific knowledge, regulatory frameworks, and field application, moving beyond isolated effects and short-term yield gains. The biostimulants belong within functional plant nutrition, focusing on physiological balance and resilience rather than nutrient input. This approach supports a shift toward preventive, adaptive crop care that enhances intrinsic plant functions under variable conditions. Scientific validation must be accompanied by clear communication. Relying solely on yield efficiency may obscure their real contribution, which lies in stabilizing plant function and reducing stress sensitivity. A deeper understanding of how and when they work helps aligning expectations and application.

Biostimulants are not magic bullets, but functional tools and potentially drivers of a broader shift in agricultural thinking. Their adoption requires more than just data: it calls for scientific consistency, clear regulatory standards, and open communication. When defined by their effects on plant function and integrated into coherent agronomic strategies, they can contribute to a more resilient, adaptive, and biologically informed agriculture. As the Hort Forum made clear, their value does not lie in isolated claims, but in their capacity to support dynamic, living systems. Used with insight and responsibility, they can become powerful allies in the transition toward sustainability.

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