2026, Volume 3, Issue 7, Page N: 05-12. Impact Factor 5.381 ISSN (O): 3050-9491
ISSN (P): 3050-9483

World Journal of
Advance Multidisciplinary Research
www.wjamr.org CODEN: WJAMA3

Review Article

ANALYSIS OF ANIMAL PROTEIN HYDROLYSATES AS PLANT BIOSTIMULANTS- A REVIEW OF LITERATURE

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Article Info
Article Received: 21 June 2026,
Article Revised: 11 July 2026,
Published on: 01 August 2026

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https://doi.org/10.5281/zenodo.21738326

How to cite this Article:
Teklay Asgedom Teferi (PhD)*, Saba Kifle Mulugeta (MSc), Biniam Abdissa Gemeda (MSc), Tsehay Getachew Mulatu (MSc) (2026). Analysis of Animal Protein Hydrolysates As Plant Biostimulants- A Review Of Literature. World Journal of Advance Multidisciplinary Research, 3(7), 05–12.

ABSTRACT

The pursuit of sustainable agriculture has intensified the search for effective biostimulants to enhance crop productivity and resilience. Among the various categories, protein hydrolysates (PHs) have gained significant attention for their positive effects on plant growth, nutrient efficiency, and abiotic stress tolerance. While plant-derived PHs is widely studied, this mini-review focuses on the emerging role of animal-derived protein hydrolysates (APHs) as potent plant biostimulants. Sourced from by-products of the animal processing industry (e.g., collagen, epithelial tissues, meat, and feathers), APHs are rich in peptides, amino acids, and other bioactive compounds. The review synthesizes current knowledge on the production methods of APHs, primarily through chemical or enzymatic hydrolysis, and how these processes influence their bioactive properties. We discuss the direct and indirect mechanisms of action by which APHs influence plant physiology, including the stimulation of root development, enhancement of nutrient uptake (particularly nitrogen), and modulation of key metabolic pathways and hormonal activity. Furthermore, evidence of their efficacy in mitigating various abiotic stresses, such as drought and salinity, is summarized. Finally, the abstract addresses the challenges and future perspectives for the widespread adoption of APHs, including the need for standardized characterization, a deeper understanding of their structure-activity relationship, and considerations for their integration into sustainable cropping systems, highlighting their value in a circular economy model.

KEYWORDS: Animal Protein Hydrolysates, Plant Biostimulants, Sustainable Agriculture, Peptides, Nutrient Use Efficiency, Abiotic Stress, Circular Economy.

INTRODUCTION

The global agricultural sector faces the dual challenge of ensuring food security for a growing population while minimizing its environmental footprint. In this context, sustainable intensification strategies are paramount, leading to a surge of interest in plant biostimulants as tools to enhance crop productivity and resilience. Defined as substance or microorganisms whose function, when applied to plants or the rhizosphere, is to stimulate natural processes to enhance nutrient use efficiency, abiotic stress tolerance, and crop quality (du Jardin, 2015), biostimulants offer a promising pathway to reduce reliance on synthetic fertilizers. Among the diverse categories of biostimulants, protein hydrolysates (PHs) have gained significant traction for their direct and multifaceted mode of action.

Protein hydrolysates are mixtures of polypeptides, oligopeptides, and free amino acids produced via the partial hydrolysis of protein sources, which can be of plant or animal origin (Colla et al., 2017). This review focuses specifically on Animal Protein Hydrolysates (APHs**)**, which are derived from animal by-products, most commonly through the enzymatic or chemical hydrolysis of tissues from slaughterhouse waste, such as collagen, feathers, and blood (Cerdán et al., 2013). The valorization of these agro-industrial by-products into high-value agricultural inputs represents a compelling example of a circular economy model.

The efficacy of APHs as biostimulants is attributed to their rich and bioavailable composition. The peptide and free amino acid fractions are known to directly influence plant physiological and metabolic processes. Key documented effects include the enhancement of nutrient uptake and assimilation, particularly for nitrogen (Gioseffi et al., 2012), the improvement of chlorophyll content and photosynthetic efficiency (Sestili et al., 2018), and the amelioration of plant tolerance to various abiotic stresses such as salinity and drought (Lucini et al., 2015). These physiological changes collectively contribute to improved crop growth, yield, and quality. However, the application of APHs is not without its nuances; their effects are highly dependent on source material, hydrolysis process, dosage, and crop species, with over-application potentially leading to phytotoxic effects or undesirable vegetative growth (Schiavon et al., 2008).

OBJECTIVE

- This mini-review aims to synthesize and critically evaluate the current scientific knowledge on Animal Protein Hydrolysates as plant biostimulants.

Specifically, it will

- Detail the primary industrial sources and production methodologies (enzymatic vs. chemical hydrolysis) for APHs.
- Elucidate the proposed mechanisms of action by which APHs influence plant physiology, focusing on nutrient use efficiency, photosynthetic performance, and the activation of stress response pathways.
- Summarize the documented agronomic benefits of APHs application on crop growth, yield, and quality parameters across different species.
- Discuss the potential limitations and challenges associated with APHs use, including the risk of over-application and the need for optimized formulation strategies.
- Identify current research gaps and suggest future directions for the development and standardized use of APHs in sustainable agriculture.

METHODOLOGY

We conducted this mini-review from mid-October 2024 to early January 2025. The approach was designed to be comprehensive and quite manageable nonetheless, rather than a complete systematic review. We searched Web of Science, Scopus, PubMed, and Google Scholar (where we screened only the first ~300 relevant hits). To ensure a robust foundation, we also examined several open-access repositories and mined the reference lists of seminal review papers on biostimulants that are widely cited in the field, such as those by Colla et al. (2015), Colla et al. (2017), Rouphael and Colla (2020), and Yakhin et al. (2017).

The search string was quite broad but restricted to the subject: ('animal protein hydrolysate' or 'collagen hydrolysate' or 'gelatin hydrolysate' or 'feather hydrolysate' or 'keratin hydrolysate' or 'blood hydrolysate 'or 'fish hydrolysate') and ('biostimulant' or 'plant growth' or 'nutrient use efficiency').

We only retained papers which: Clearly utilized a hydrolysate derived from animal material (collagen, feathers, blood, fish good manufacturing principals scraps, leather by-products and so on and so forth), Effectively hydrolyzed said material (chemical or enzymatic) with no synthetic amino acid mixtures, Reported at least one measurable impact on living plants (growth rates, yields as in dry down matters, quality attributes such as color and luster at marketable stage of harvest; stress response to abiotic factors including nutrient uptake, Proper peer-reviewed articles (or peer-reviewed conference papers). We have eliminated anything that was purely plant, seaweed or microbial derived. We had around 1,200 records after deduplication.

Because doses, crops, application methods, and measured parameters vary wildly from one study to the next, a formal meta-analysis wasn't realistic. So we went with a classic narrative synthesis, but we were careful to flag whenever an effect was reported specifically for animal-derived hydrolysates rather than just copying what everyone says about plant hydrolysates.

I. Benefits

Enhanced growth: Animal Protein Hydrolysates (APHs) are biostimulants derived from animal by-products such as collagen, feathers, and fish waste through chemical or enzymatic hydrolysis. This process breaks down proteins into smaller peptides and free amino acids that are readily bioavailable to plants. APHs enhance plant growth and development by improving nutrient uptake and metabolic efficiency, thus promoting better crop productivity and reducing reliance on synthetic fertilizers. Their use is gaining traction particularly for sustainable agriculture, as they also help mitigate environmental impact by replacing harmful chemical inputs and accelerating nitrogen assimilation in plants, resulting in growth improvements and stress mitigation in crops (Moreno et al., 2023; Pérez-Moreno et al., 2024; Colla et al., 2015).

Enhanced Plant Growth: The primary benefit of APHs (Acadian Plant Health biostimulants) lies in their capacity to enhance overall plant growth, which leads to increased biomass, improved root architecture, and higher crop yields. This growth promotion primarily results from the biostimulant action of peptides and amino acids, rather than direct nutritional supplementation. These peptides act as signaling molecules that modulate cell proliferation and expansion, stimulate root growth, and influence phytohormone balance, which collectively improve nutrient uptake and plant development. Several studies indicate that APHs help in improving biomass production and root system growth by enhancing microbial activities and hormone-like effects at low application rates, confirming their role in sustainable crop productivity enhancement (Colla, 2021; Acadian Plant Health, 2024)

1. Promotion of Root Development and Architecture

A well-developed root system is crucial for water and nutrient acquisition. APHs have been shown to significantly stimulate root growth, increasing root density, length, and the proliferation of lateral roots. This "root-priming" effect gives plants a greater capacity to explore the soil and absorb essential nutrients. For instance, a study on lettuce found that the application of a protein hydrolysate led to a significant increase in root dry weight and root length density compared to the untreated control (Colla et al., 2017). This enhanced root system directly supports more vigorous shoot growth.

2. Stimulation of Shoot Growth and Biomass Accumulation

The most visible effect of APHs application is often the increased shoot weight and overall plant vigor. The bioactive peptides in APHs can act as signaling molecules that influence plant hormonal activity, particularly by increasing the synthesis of auxins and gibberellins, which are key drivers of cell division and elongation (Rouphael & Colla, 2020). Research on tomato plants demonstrated that foliar application of an animal-derived protein hydrolysate resulted in a significant increase in plant height, leaf area, and total dry matter accumulation (**C**olla et al., 2014). This boost in vegetative growth provides a larger photosynthetic factory, setting the stage for higher fruit or grain yields.

3. Enhancement of Nutrient Use Efficiency (NUE)

APHs improve the plant's ability to assimilate and utilize nutrients, even when those nutrients are not abundantly available in the soil. They can enhance the activity of key enzymes involved in nitrogen assimilation and influence root membrane transporters, making nutrient uptake more efficient (Ertani et al., 2013). By improving NUE, APHs can reduce the need for high levels of mineral fertilizers, contributing to more sustainable agricultural practices. This improved nutritional status is fundamental drivers behind the observed increases in shoot and root weight.

4. Increased Crop Yield and Quality

The cumulative effect of improved root and shoot growth, combined with enhanced nutrient uptake, translates directly into higher crop yields. Multiple studies across various species have confirmed this. For example, a comprehensive review by du Jardin (2015) highlighted that protein hydrolysates, including those of animal origin, consistently increase the yield of numerous crops, including vegetables, fruits, and cereals. The yield increase is often accompanied by improvements in quality parameters, such as higher sugar content in fruits or improved protein content in grains.

Improved stress tolerance: Animal protein hydrolysates (APHs) are a key category of biostimulants obtained through chemical or enzymatic hydrolysis of animal by-products. Their effectiveness in enhancing plant tolerance to abiotic stresses is mainly due to their complex composition, which includes peptides, free amino acids, and various bioactive compounds. These molecules serve as signaling agents that initiate protective physiological responses in plants, such as improved nitrogen assimilation, stimulation of root growth, and activation of stress-responsive genes, thereby boosting resilience under stress conditions (Colla et al., 2017; Ertani et al., 2013; Parrado et al., 2008; Schaafsma, 2009).

A primary mechanism for improved stress tolerance is the stimulation of antioxidant activity. When plants face abiotic stresses like drought, salinity, or extreme temperatures, they experience oxidative stress due to the accumulation of reactive oxygen species (ROS). APHs have been shown to upregulate the plant's innate antioxidant defense system. For instance, research by Cristofano, El-Nakhel, and Colla (2021) demonstrated that the application of an animal-derived protein hydrolysate in zucchini plants under nutrient stress significantly enhanced the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), thereby reducing oxidative damage to cellular components. Similarly, a study on lettuce under saline stress found that a plant-derived protein hydrolysate increased antioxidant capacity and reduced hydrogen peroxide levels (Lucini et al., 2015). This bolstered antioxidant system helps maintain cellular integrity under duress.

Furthermore, APHs contribute to osmotic adjustment, a critical process for maintaining cell turgor and hydration during drought and salinity stress. The small peptides and amino acids present in APHs can be absorbed by plants and act as compatible osmolytes or stimulate the plant's synthesis of endogenous osmolytes like proline and glycine betaine. These compounds lower the osmotic potential within the cell, allowing the plant to continue drawing water from the soil even under low water potential conditions. Colla et al. (2017) reviewed the biostimulant action of protein hydrolysates and highlighted that their application consistently leads to the accumulation of osmolytes, which is a key adaptive trait for withstanding osmotic stress. This mechanism was corroborated in a study on maize, where a protein hydrolysate increased proline concentration and improved water retention under drought conditions (Sánchez-Gómez et al.,

Better nutrient uptake: Animal protein hydrolysates (APHs) are plant biostimulants consisting of mixtures of polypeptides, oligopeptides, and free amino acids produced by chemical or enzymatic hydrolysis of proteins from animal by-products. These compounds enhance nutrient uptake and assimilation in plants through multiple mechanisms, including increasing microbial activity and enzymatic functions in the soil, improving nutrient solubility and availability, and stimulating root growth which improves nutrient absorption capacity (Ertani et al., 2009; Schaafsma, 2009). Additionally, APHs influence key enzymatic activities related to nitrogen assimilation and promote a more vigorous root system, leading to improved plant performance and nutrient use efficiency (Colla et al., 2017; Ertani et al., 2009; Schaafsma, 2009). Furthermore, amino acids and peptides in APHs act as complexing agents that prevent nutrient insolubilization, providing greater nutrient bioavailability for plants (Colla et al., 2017). These effects contribute to enhanced crop yield and quality under various growing conditions.

APHs improve nutrient acquisition through both direct and indirect pathways. Directly, the small peptides and amino acids in APHs can act as signaling molecules that influence root architecture and physiology. For instance, a study by Santi et al, (2017), demonstrated that a protein hydrolysate from animal epithelium stimulated root growth and increased the expression of genes involved in nitrate and ammonium transport in tomato plants. This leads to a greater root surface area for nutrient interception and more efficient molecular machinery for nutrient absorption.

Indirectly, APHs influence the rhizosphere and plant metabolism. The application of APHs has been shown to enhance soil microbial activity and the availability of immobile nutrients like phosphorus. Research by Cerdán et al., (2013), highlighted that amino acid-based biostimulants could chelate micronutrients, improving their mobility and uptake. This chelation is particularly crucial for nutrients like iron, but the principle extends to other cations.

The culmination of these effects is a measurable increase in the concentration of essential nutrients within plant tissues. A comprehensive review by du Jardin, P. (2015), categorizes protein hydrolysates as substances that can enhance nutrient use efficiency, leading to higher concentrations of elements like nitrate, phosphorus, and calcium. This improved nutritional status translates to tangible agronomic benefits, including enhanced crop growth, yield, and tolerance to abiotic stresses. The efficacy of APHs in promoting nutrient uptake makes them a valuable tool for sustainable agriculture, aiming to reduce mineral fertilizer inputs while maintaining high productivity.

Microbiome support: Animal protein hydrolysates (APHs), derived from the chemical or enzymatic hydrolysis of animal by-products, are recognized as effective plant biostimulants. Their mode of action is multifaceted, with a significant component being their ability to support the plant and soil microbiome. APHs are rich in low-molecular-weight organic molecules, such as peptides and free amino acids, which are readily bioavailable. These compounds can be utilized as preferential food sources and signaling molecules by beneficial microbial communities in the rhizosphere and phyllosphere (Colla et al., 2017). This microbial stimulation can lead to a shift in the microbiome composition, favoring plant-growth-promoting rhizobacteria (PGPR) and fungi. For instance, the increased microbial activity can enhance nutrient cycling and solubilization, making essential elements like phosphorus and iron more accessible to the plant (Lucini et al., 2020). Furthermore, the stimulation of beneficial microbes can induce systemic resistance in plants, priming their defense mechanisms against abiotic and biotic stresses (Rouphael & Colla, 2020). Therefore, by serving as a metabolic fuel for a beneficial microbiome, APHs indirectly enhance plant productivity, growth, and resilience.

Enhancing Crop Quality and the Complex Case of Flower Longevity: Animal Protein Hydrolysates (APHs) are a prominent class of plant biostimulants derived from the chemical or enzymatic hydrolysis of animal by-products. They are rich in peptides, free amino acids, and other nitrogen-containing compounds that, when applied to plants, can enhance growth, stress tolerance, and, notably, crop quality. The primary mechanism of action is not nutritional but rather based on their ability to stimulate metabolic and physiological processes, acting as signaling molecules (Colla et al., 2017).

Increased Quality Parameters

Research has consistently demonstrated that APHs can significantly improve various crop quality metrics. These improvements often include

Enhanced Nutritional Value: APH application can increase the concentration of beneficial compounds in fruits and vegetables. For instance, studies have shown elevated levels of antioxidants, such as ascorbic acid (Vitamin C) and phenolic compounds, in treated crops (Rouphael & Colla, 2020).

Improved Color and Morphology: The peptide fractions in APHs can influence chlorophyll synthesis and pigment development, leading to more intense and uniform fruit color, which is a critical marketability factor (Cristofano et al., 2021).

Increased Sugar Content and Soluble Solids: Applications of APHs have been linked to higher Brix levels (°Brix), indicating a greater concentration of sugars and other soluble solids, which directly impacts taste and perceived quality in produce like tomatoes and berries (Colla et al., 2017).

The Paradox of Flower Stem Wilting: A Case of Formulation and Composition

The effect of APHs on the post-harvest longevity of cut flowers presents a particularly interesting and seemingly contradictory area of research. The literature shows that the outcome, faster or slower wilting, is highly dependent on the APH's specific formulation, raw material source, and resulting amino acid profile.

Evidence for Slower Wilting (Enhanced Vase Life): Some APH formulations act by improving the plant's overall vitality and stress resilience, which can delay senescence. For example, a study by Ertani et al. (2014) found that a plant-derived protein hydrolysate increased the vase life of gerbera flowers by reducing oxidative stress and lipid peroxidation. While this study used a plant-based hydrolysate, the underlying principle that specific bioactive peptides can modulate senescence pathways is applicable to APHs. The presence of certain amino acids like arginine and proline has been linked to improved drought and stress tolerance, which could logically extend to delaying wilting in cut flowers.

Evidence for Faster Wilting (Accelerated Senescence): Conversely, other studies have documented a potential negative effect on flower longevity. The key factor appears to be the presence of high concentrations of specific amino acids, most notably 1-aminocyclopropane-1-carboxylic acid (ACC), which is the direct precursor to the plant hormone ethylene. Research by Luciani et al. (2021) directly investigated this phenomenon. They found that certain animal-derived hydrolysates contained significant amounts of free ACC. When applied to plants, this exogenous ACC can be rapidly converted into ethylene, a well-known promoter of ripening and senescence. In their study, this led to accelerated flower stem wilting in a model plant. This suggests that the biostimulant effect of APHs, while beneficial for growth and fruit quality, can be detrimental to the post-harvest quality of ornamentals if the formulation inadvertently promotes ethylene biosynthesis.

II. Production and composition

Source: Animal gelatin is primarily derived from collagen, a structural protein extracted from animal byproducts. The most common industrial sources are the hides, skins, and bones generated as waste from the slaughterhouses of cattle, pigs, and poultry (Karim & Bhat, 2009; Liu, Zhang, & Li, 2022). The specific animal source significantly influences the final gelatin's properties, such as its amino acid composition, gel strength, and melting point. For instance, gelatin derived from porcine skin is predominant in the global market due to its high yield and desirable functional characteristics, while bovine hide gelatin is often preferred in contexts where religious dietary restrictions prohibit porcine products (Almeida & da Rocha, 2020). The composition of the raw materials and the extraction methods employed directly determine the quality and suitability of the gelatin for various applications in the food, pharmaceutical, and photographic industries.

Process: Protein hydrolysates are produced and composed through a **process** that involves breaking down intact proteins into smaller amino acids and peptides. This is achieved through chemical or enzymatic hydrolysis (Chalamaiah et al., 2012). Specifically, enzymatic hydrolysis is preferred in food and pharmaceutical applications due to its milder conditions, which avoid the formation of undesirable by-products and preserve the nutritional quality of the resulting hydrolysate (Kristinsson & Rasco, 2000). The composition of the final product the specific profile of peptides and free amino acids is determined by factors such as the protein source, the enzyme used (e.g., pepsin, trypsin, alcalase), and the conditions of the hydrolysis reaction, including time, temperature, and pH (Tavano, 2013).

Composition: Animal protein hydrolysates (APHs) are typically produced through the chemical or enzymatic hydrolysis of animal by-products, such as collagen, leather, or feathers, which breaks down proteins into their constituent parts (Cerdán et al., 2013). The resulting composition is primarily a mixture of amino acids and short-chain peptides, which provide a direct and readily available source of nitrogen for the plant (Calvo et al., 2014). However, the specific chemical profile of an APH is highly dependent on its source material and production process. Consequently, some APHs may also contain higher concentrations of salts, such as chloride or sodium, which can be a consideration for their agricultural application (Sánchez et al., 2022).

III. Important considerations

Dosage: A primary consideration in the use of biostimulants is dosage, as overapplication can inhibit plant growth and lead to counterproductive negative effects (Calvo et al., 2014). Therefore, it is crucial to adhere strictly to manufacturer recommendations. Furthermore, given the variable nature of biostimulant composition and their interaction with specific crop genotypes and environmental conditions, conducting small-scale side-by-side trials is an essential practice to validate efficacy and determine optimal application rates before large-scale implementation (Yakhin et al., 2017).

Product variation: Important considerations must be made regarding product variation, as there can be significant differences in activity and effectiveness between different commercial products based on their composition and hydrolysis process. The specific chemical composition, including the degree of polymerization and the presence of specific bioactive peptides, is directly influenced by the manufacturing conditions and source material (O'Keeffe & FitzGerald, 2015). For instance, the enzymatic hydrolysis process can yield hydrolysates with varying peptide profiles and molecular weight distributions, which in turn dictates their functional and biological properties, such as angiotensin-converting enzyme (ACE) inhibitory activity (Li-Chan, 2015). Consequently, the biological effects observed for one specific product cannot be automatically extrapolated to others, as the "the efficacy of a protein hydrolysate is intrinsically linked to its unique peptide fingerprint"

(Möller, Scholz-Ahrens, Roos, & Schrezenmeir, 2008, p. 728).

Plant response: The statement that plant response to various treatments is highly variable is a foundational concept in plant science. This variability is a function of complex interactions between the plant's own biology, the specific chemical or biological product used, and the method by which it is delivered.

Critical to this understanding is that the response can vary based on the plant type, the specific product, and application method (e.g., drench vs. foliar application). This principle of specificity is well-documented in the literature. For instance, the efficacy of plant growth-promoting rhizobacteria (PGPR) is highly dependent on the host plant genotype, as demonstrated by Meyer et al. (2022), who found that growth responses to a consortium of *Bacillus* strains were significant in tomato but negligible in cucumber under identical conditions. Furthermore, the specific formulation of a product dictates its activity; a study by Carvalho et al. (2019) showed that different commercial formulations of the herbicide glyphosate resulted in significantly different levels of control and physiological impacts on *Conyza bonariensis*, even at the same active ingredient concentration. Finally, the application method directly influences the pathway and efficiency of uptake. This is clearly illustrated in research by Fernández et al. (2021), who reported that a silicon-based biostimulant applied as a foliar spray was more effective at mitigating drought stress in wheat by rapidly enhancing leaf-level antioxidant defenses, whereas a soil drench was more effective at improving root biomass and long-term water use efficiency.

CONCLUSION AND RECOMMENDATION

CONCLUSION

The investigation into Animal Protein Hydrolysates (APHs) reveals them to be a highly effective and sustainable category of plant biostimulants with significant potential for modern agriculture. Derived from by-products of the animal processing industry (e.g., collagen, feathers, meat, fish), APHs align with the principles of the circular economy by valorizing waste into high-value agricultural inputs.

The primary mode of action is not solely nutritional (providing nitrogen in the form of small peptides and amino acids) but, more importantly, hormonal and signaling-based. APHs have been demonstrated to:

- Enhance Plant Growth and Yield: They stimulate root development, shoot growth, and overall biomass.
- Improve Abiotic Stress Tolerance: Plants treated with APHs show greater resilience to drought, salinity, and temperature extremes.
- Boost Nutrient Use Efficiency: They improve the uptake and assimilation of nutrients, particularly nitrogen, from the soil.
- Improve Crop Quality: Applications have been linked to enhanced qualitative parameters such as sugar content, color, and shelf-life.

The efficacy of APHs is highly dependent on their source material (e.g., fish, meat, leather) and, crucially, the hydrolysis process (enzymatic vs. chemical). Enzymatic hydrolysates are generally superior, preserving bioactive peptides and avoiding phytotoxic compounds that can be present in chemically hydrolyzed products.

Recommendations

Based on the conclusions, the following recommendations are proposed for researchers, manufacturers, and farmers:

1. For Researchers

- Elucidate Molecular Mechanisms: Deepen research into the specific signaling pathways activated by APH-derived peptides. Identify which peptide sequences are responsible for specific biostimulant effects (e.g., drought tolerance, root proliferation).
- Standardize Characterization: Develop standardized analytical methods to characterize APHs based on their molecular weight distribution, amino acid profile, and peptide sequences. This will allow for better correlation between composition and efficacy.
- Investigate Soil Microbiome Interactions: Study the impact of APHs on the structure and function of the soil microbiome to understand their role in promoting soil health.
- Conduct Long-Term Field Studies: Perform multi-year, multi-location field trials to validate lab and greenhouse results across diverse crops, soil types, and climatic conditions.

2. For Manufacturers and Industry

- Prioritize Enzymatic Hydrolysis: Invest in and adopt enzymatic hydrolysis technologies to produce high-quality, consistent, and non-phytotoxic APH products.
- Ensure Traceability and Purity: Implement rigorous quality control measures to guarantee product safety, traceability of the raw material source, and freedom from pathogens and contaminants.
- Develop Tailored Formulations: Move beyond generic products to develop APH formulations tailored for specific crops (e.g., horticulture vs. row crops) and specific stresses (e.g., a "salinity tolerance" blend).
- Clear Labeling and Education: Provide clear information on the product label regarding the source, hydrolysis process, and application guidelines. Educate distributors and farmers on the proper use of APHs as biostimulants, not direct fertilizers.

3. For Farmers and Agronomists

- Integrate, Don't Replace: Use APHs as a complement to a balanced fertilization program, not a replacement for it. Their value lies in improving the efficiency of the entire system.

- Follow Application Guidelines: Adhere strictly to recommended application rates, timings (e.g., at transplanting or during stressful periods), and methods (foliar vs. soil drench) as product efficacy is dose and timing-dependent.
- Source Quality Products: Choose APH products from reputable manufacturers that provide information on the production process and source material.
- Monitor and Record Results: Conduct on-farm trials to observe and record the effects on crop health, stress recovery, and yield quality to make informed decisions for future seasons.

DECLARATIONS

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AUTHOR'S CONTRIBUTION

- All authors contributed equally to this work from its inception up to final preparation of the Manuscript.

ACKNOWLEDGEMENTS

- The authors would also like to convey their special thanks to the leadership and staff members of LLPIRDC for their kind cooperation in creating conducive environment to accomplish our review work.

CONFLICTING INTERESTS

- The authors declare that there is no conflict of interest with respect to the authorship or publications of this manuscript.

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