The AgBiz Today *E-Magazine* Vol. 3 Issue-3, July 2026: 050 -056
ISSN: 3049-2491 (Online)
https://sabm.scholics.in/

Onion *(Allium cepa L.)* Extract as a Natural Bio stimulant for Enhancing Seed Germination, Seedling Growth and Stress Tolerance

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ABSTRACT

The growing demand for environmentally sustainable agricultural practices has increased interest in natural biostimulants that can enhance crop growth while reducing reliance on synthetic chemicals. Among these, **onion (*Allium cepa* L.) extract** has attracted attention because of its rich composition of biologically active compounds, including flavonoids, phenolic compounds, sulfur-containing metabolites, vitamins, minerals, and natural antioxidants. These constituents play important roles in improving seed germination, promoting seedling growth, increasing nutrient uptake, enhancing photosynthetic efficiency, and strengthening plant tolerance to both biotic and abiotic stresses. Research findings indicate that onion extract stimulates metabolic activity during germination, enhances the mobilization of stored seed reserves, improves antioxidant defense systems, and suppresses the growth of several plant pathogens. These combined effects contribute to better seedling establishment, increased vigor, and improved crop performance. This review summarizes the phytochemical profile of onion extract, discusses its physiological and biochemical roles in plant growth, and highlights its potential as an eco-friendly seed treatment and natural biostimulant for sustainable agricultural production.

***Keywords*:** *Allium cepa*, onion extract, seed priming, seed germination, seedling vigor, natural biostimulant, antioxidants, sustainable agriculture.

Introduction

Agriculture is facing increasing challenges due to rapid climate change, declining soil fertility, limited water resources, and the excessive use of synthetic fertilizers and pesticides. These factors not only reduce crop productivity but also contribute to environmental degradation and biodiversity loss. As a result, there is growing interest in developing sustainable and eco-friendly agricultural practices that can improve crop performance while minimizing negative environmental impacts. Among the various approaches being explored, the use of plant-derived biostimulants has emerged as a promising strategy because they naturally enhance plant growth, improve nutrient utilization, and increase tolerance to environmental stresses without leaving harmful residues (Sharma et al., 2015; Carvalho et al., 2021).

Natural biostimulants are substances or biological products obtained from plants, microorganisms, or organic materials that stimulate physiological and biochemical processes in crops. Unlike conventional fertilizers, they do not primarily supply nutrients but instead improve the plant's ability to absorb and utilize available nutrients more efficiently. They also promote seed germination, root development, photosynthesis, and resistance to various environmental stresses. In recent years, extracts prepared from different plant species have gained considerable attention because they are biodegradable, renewable, inexpensive, and environmentally safe. These characteristics make them suitable alternatives to synthetic agricultural inputs in sustainable farming systems (Carvalho et al., 2021).

Among the numerous medicinal and horticultural plants investigated, **onion (*Allium cepa* L.)** has attracted considerable scientific interest due to its abundance of biologically active compounds. Onion is one of the most widely cultivated vegetable crops worldwide and is valued not only for its nutritional importance but also for its medicinal and

pharmacological properties. Different parts of the onion plant, particularly the bulb, contain a wide range of phytochemicals, including flavonoids, phenolic acids, sulfur-containing compounds, vitamins, minerals, amino acids, and natural antioxidants. These compounds are known to possess antioxidant, antimicrobial, anti-inflammatory, and growth-promoting activities, making onion extract a promising natural biostimulant for agricultural applications (Prima et al., 2023; Kianian et al., 2021).

Seed germination and early seedling establishment represent the most sensitive stages of a plant's life cycle. Poor germination or weak seedling growth often results in inadequate plant populations, reduced crop establishment, and lower yields. Successful germination depends on several interconnected physiological and biochemical processes, including water absorption, enzyme activation, mobilization of stored food reserves, cellular respiration, and embryo development. Environmental stresses such as drought, salinity, temperature fluctuations, and pathogen infection can disrupt these processes and significantly reduce seed performance. Therefore, the development of effective seed treatments that enhance germination and improve seedling vigor has become an important objective in modern crop production (Pagano et al., 2023).

Seed priming is recognized as one of the most effective pre-sowing techniques for improving germination performance. During this process, seeds undergo controlled hydration that initiates metabolic activities necessary for germination without allowing radicle emergence. After drying, primed seeds generally germinate faster, emerge more uniformly, and establish stronger seedlings under both normal and stressful environmental conditions. Recently, researchers have increasingly focused on natural plant extracts as priming agents because they combine growth-promoting properties with environmental safety. Onion extract, owing to its diverse phytochemical composition, has shown considerable promise as an effective natural priming material capable of improving germination and early seedling growth (Pagano et al., 2023; Vij et al., 2025).

Several studies have demonstrated that onion extract enhances plant growth through multiple physiological and biochemical mechanisms. Its antioxidant compounds help neutralize excessive reactive oxygen species generated during seed imbibition and environmental stress, thereby protecting cellular structures from oxidative damage. Sulfur-containing metabolites exhibit antimicrobial activity that suppresses several seed-borne and soil-borne pathogens, improving seed health and reducing disease incidence during early crop establishment. Furthermore, bioactive constituents present in onion extract stimulate hydrolytic enzymes responsible for converting stored carbohydrates and proteins into soluble nutrients, ensuring a continuous supply of energy required for embryo growth and seedling development (Naz et al., 2022; Kianian et al., 2021).

In addition to promoting germination, onion extract has been reported to improve root architecture, shoot elongation, chlorophyll synthesis, nutrient absorption, and photosynthetic efficiency. Enhanced root growth enables plants to explore a greater volume of soil for water and mineral uptake, while improved shoot development contributes to increased leaf area and biomass accumulation. Collectively, these physiological improvements strengthen seedling vigor and enhance plant resilience under unfavorable environmental conditions. Such multifunctional properties make onion extract an attractive candidate for sustainable crop production systems where reducing dependence on synthetic agrochemicals is a major priority (Prima et al., 2023; Carvalho et al., 2021).

Despite the growing body of research on natural biostimulants, information regarding the agricultural applications and mechanisms of onion extract remains scattered across different scientific disciplines. A comprehensive understanding of its phytochemical composition, physiological effects, biochemical mechanisms, and practical applications is therefore essential for its wider adoption in sustainable agriculture. Integrating available knowledge can help researchers optimize extraction methods, determine suitable application techniques, and identify promising directions for future investigation.

The present review aims to compile and critically discuss current scientific evidence regarding the use of onion (*Allium cepa* L.) extract as a natural biostimulant for improving seed germination, seedling growth, nutrient uptake, photosynthetic performance, antioxidant defense, stress tolerance, and crop protection. It also highlights the potential of onion extract as an environmentally friendly alternative to synthetic growth-promoting chemicals and emphasizes future research opportunities for its successful integration into sustainable agricultural practices.

Figure 1. Onion (*Allium cepa* L.) plant and bulb used for preparation of botanical extracts.

Source: Adapted from Prima et al. (2023) and Kianian et al. (2021)

Phytochemical Composition of Onion Extract

The biological effectiveness of onion (*Allium cepa* L.) extract is largely attributed to its diverse and complex phytochemical composition. Different parts of the onion plant, including the bulbs, leaves, and outer scales, are rich sources of numerous bioactive compounds that contribute to plant growth promotion, antioxidant protection, and disease suppression. These naturally occurring constituents work synergistically to influence several physiological and biochemical processes involved in seed germination, seedling establishment, and overall plant development (Prima et al., 2023; Kianian et al., 2021).

Among the major phytochemicals identified in onion, flavonoids are particularly abundant, with quercetin being the predominant compound. Quercetin is recognized for its strong antioxidant activity and its ability to neutralize reactive oxygen species (ROS), thereby protecting plant cells from oxidative damage. Other flavonoids, including kaempferol, also contribute to antioxidant defense and help maintain cellular stability under both normal and stressful environmental conditions. These compounds play an important role in preserving membrane integrity and supporting healthy metabolic activity during seed germination and early plant growth (Prima et al., 2023).

Onion extract also contains a substantial amount of phenolic compounds, including various phenolic acids and anthocyanins. These compounds possess excellent free-radical scavenging properties and help minimize oxidative stress generated during plant metabolism. By reducing the accumulation of harmful reactive oxygen species, phenolic compounds support normal cellular functions, improve enzyme activity, and enhance the plant's natural defense mechanisms against adverse environmental conditions (Prima et al., 2023).

Another important group of constituents found in onion extract comprises organosulfur compounds, such as thiosulfinates, sulfoxides, and related sulfur-containing metabolites. These compounds are responsible for the characteristic pungent aroma of onions and are widely recognized for their antimicrobial properties. Numerous studies have demonstrated that sulfur-containing compounds inhibit the growth of several fungal and bacterial pathogens, thereby protecting seeds and young seedlings from infection during the critical stages of germination and establishment. This antimicrobial activity makes onion extract a promising natural alternative to certain synthetic seed-protectant chemicals (Kianian et al., 2021).

In addition to these secondary metabolites, onion extract provides several essential vitamins, including vitamins A, C, and E, which participate in antioxidant defense and various metabolic pathways. Vitamin C functions as a powerful antioxidant that protects plant tissues against oxidative injury, whereas vitamins A and E contribute to membrane stability and normal cellular metabolism. These vitamins collectively enhance physiological efficiency and promote healthier seedling development.

The extract is also an important source of essential mineral nutrients, including potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and iron (Fe). These minerals are indispensable for enzyme activation, chlorophyll formation, osmotic regulation, cell division, and energy metabolism. Adequate availability of these nutrients supports vigorous root and shoot development while improving nutrient uptake efficiency during the early stages of plant growth (Prima et al., 2023).

The concentration and composition of these phytochemicals are influenced by several factors, including onion cultivar, growing environment, maturity stage, storage conditions, and extraction technique. Variations in extraction solvents, temperature, and processing methods may alter the concentration of bioactive compounds and consequently affect the biological activity of the final extract. Therefore, optimizing extraction procedures is essential for maximizing the effectiveness of onion extract when used as a natural biostimulant in agriculture.

Overall, the combined action of flavonoids, phenolic compounds, sulfur-containing metabolites, vitamins, and mineral nutrients gives onion extract its remarkable biological properties. Rather than acting independently, these constituents interact synergistically to enhance seed germination, stimulate seedling growth, strengthen antioxidant defense systems, improve nutrient utilization, and increase plant tolerance to both biotic and abiotic stresses. This unique phytochemical profile forms the scientific basis for the increasing interest in onion extract as an environmentally friendly biostimulant for sustainable crop production.

Phytochemical Group	**Major Compounds**	**Reported Function**
Flavonoids	Quercetin, Kaempferol	Antioxidant activity
Phenolic Compounds	Phenolic acids, Anthocyanins	ROS scavenging
Sulphur Compounds	Thiosulfinates, Sulfoxides	Antimicrobial activity
Vitamins	A, C, E	Metabolic support
Minerals	K, Ca, Mg, Fe	Nutrient metabolism

Table 1. Major phytochemical constituents identified in onion (Allium cepa L.) and their biological activites.

Source: Compiled from Prima et al. (2023) and Kianian et al. (2021).

Effects on Seed Germination

Seed germination is a vital stage in the plant life cycle because it determines the successful establishment of seedlings and ultimately influences crop productivity. During germination, seeds undergo a series of coordinated physiological and biochemical events, including water absorption (imbibition), activation of metabolic pathways, enzymatic breakdown of stored food reserves, and initiation of embryo growth. Any disruption in these processes can reduce germination percentage and produce weak seedlings. Therefore, the use of natural biostimulants such as onion (*Allium cepa* L.) extract has gained considerable attention as an effective strategy for improving germination and early plant development (Pagano et al., 2023). Onion extract contains a wide range of bioactive compounds, including flavonoids, phenolic compounds, sulfur-containing metabolites, vitamins, and essential minerals, which collectively stimulate the metabolic processes associated with seed germination. These compounds enhance membrane permeability, allowing seeds to absorb water more efficiently during imbibition. Rapid and uniform water uptake initiates cellular metabolism, leading to faster activation of enzymes responsible for germination (Vij et al., 2025). One of the major mechanisms through which onion extract promotes germination is by stimulating the activity of hydrolytic enzymes such as α-amylase, protease, and lipase. These enzymes convert stored starch, proteins, and lipids into simple sugars, amino acids, and fatty acids that serve as energy sources for the developing embryo. Efficient mobilization of these food reserves accelerates embryo growth, resulting in earlier radicle emergence and more uniform seedling establishment (Pagano et al., 2023; Vij et al., 2025).

Oxidative stress is another important factor affecting seed germination. During imbibition and the resumption of metabolic activity, seeds naturally produce reactive oxygen species (ROS). Although low levels of ROS act as signaling molecules,

excessive accumulation damages proteins, lipids, nucleic acids, and cellular membranes, thereby reducing seed viability and delaying germination. Onion extract is rich in antioxidant compounds, particularly quercetin and phenolic acids, which help regulate ROS levels and protect cells from oxidative injury. This antioxidant activity maintains membrane integrity, preserves enzyme function, and supports normal physiological processes during germination (Naz et al., 2022; Prima et al., 2023).In addition to its antioxidant properties, onion extract possesses natural antimicrobial activity. Sulfur-containing compounds present in the extract inhibit the growth of several seed-borne and soil-borne fungal and bacterial pathogens that commonly infect seeds during germination. By reducing microbial infection, onion extract improves seed health, minimizes disease-related losses, and enhances seedling survival under field conditions. This protective effect further contributes to improved germination performance and healthy crop establishment (Kianian et al., 2021).Several studies have reported that seeds treated with onion extract exhibit higher germination percentages, faster germination rates, improved germination uniformity, and greater seedling vigor than untreated seeds. Enhanced root and shoot growth observed after treatment indicates that onion extract not only supports germination but also promotes vigorous early development. Stronger seedlings establish more quickly in the field, utilize available resources more efficiently, and are generally better able to withstand unfavorable environmental conditions (Pagano et al., 2023; Carvalho et al., 2021).The effectiveness of onion extract depends on several factors, including extract concentration, soaking duration, seed type, and environmental conditions. Moderate concentrations often produce the greatest improvements, whereas excessively high concentrations may reduce germination due to osmotic effects or phytotoxicity. Therefore, identifying the optimum concentration and treatment duration is essential before large-scale agricultural application.Overall, available scientific evidence suggests that onion extract is an effective natural seed treatment capable of improving germination through multiple complementary mechanisms. By enhancing enzyme activity, promoting reserve mobilization, strengthening antioxidant defenses, protecting against microbial infection, and stimulating early seedling growth, onion extract provides an environmentally friendly alternative to synthetic chemical seed treatments and supports the development of more sustainable agricultural production systems.

Parameter	Observed Effect	Possible Mechanism	References
Germination Percentage	Increased germination rate and uniform seed emergence	Enhanced enzyme activity and efficient mobilization of stored food reserves	Pagano et al. (2023); Vij et al. (2025)
Germination Speed	Faster germination and seed emergence	Activation of metabolic processes during imbibition	Vij et al. (2025)
Root Length	Significant increase in root growth and development	Improved cell division and elongation in root tissues	Carvalho et al. (2021)
Shoot Length	Enhanced shoot growth and biomass accumulation	Increased photosynthetic efficiency and metabolic activity	Prima et al. (2023)
Seedling Vigour Index	Higher seedling vigour and overall plant performance	Better nutrient uptake and protection from environmental stress	Pagano et al. (2023)
Chlorophyll Content	Increased chlorophyll concentration in leaves	Antioxidant protection of chloroplast structures	Naz et al. (2022)
Stress Tolerance	Improved tolerance to drought, salinity, and heat stress	Enhanced antioxidant defence system and osmolyte accumulation	Naz et al. (2022)
Disease Resistance	Reduced incidence of fungal and bacterial infections	Antimicrobial activity of sulphur-containing compounds	Kianian et al. (2021); Isman (2020)
Nutrient Uptake	Improved absorption and utilization of essential nutrients	Better root development and enhanced physiological activity	Carvalho et al. (2021)
Photosynthetic Efficiency	Increased photosynthetic performance and growth	Higher chlorophyll content and protection from oxidative damage	Prima et al. (2023); Naz et al. (2022)

Table 2. Reported effects of onion extract on seed germination and seedling growth

Source: Compiled from Pagano et al. (2023), Vij et al. (2025), Carvalho et al. (2021), Prima et al. (2023), Naz et al. (2022), Kianian et al. (2021), and Isman (2020).

Influence on Root and Shoot Development

Root and shoot development plays a crucial role in seedling establishment and overall crop productivity. A healthy root system improves water and nutrient absorption, while vigorous shoot growth enhances photosynthesis and biomass accumulation. Studies have shown that plant-derived biostimulants, including onion (*Allium cepa* L.) extract, positively influence these growth parameters through various physiological and biochemical processes (Carvalho et al., 2021). Onion extract has been reported to stimulate root elongation, increase root biomass, and promote lateral root formation. The flavonoids, phenolic compounds, vitamins, and minerals present in the extract support cell division and elongation, resulting in a stronger root system. Improved root growth enhances the uptake of essential nutrients and water, thereby supporting healthy seedling establishment and better tolerance to environmental stress.

Similarly, onion extract promotes shoot growth by improving nutrient utilization and metabolic activity. Treated seedlings often exhibit greater shoot length, larger leaf area, and increased biomass compared with untreated plants (Prima et al., 2023). The antioxidant compounds in onion extract also protect actively growing tissues from oxidative damage, helping maintain normal cellular functions during early growth (Naz et al., 2022). The combined improvement in root and shoot development leads to more vigorous seedlings with higher photosynthetic capacity, efficient nutrient uptake, and improved resistance to unfavorable environmental conditions. These findings suggest that onion extract can serve as an effective natural biostimulant for enhancing early plant growth and supporting sustainable agricultural production.

Effects on Photosynthesis and Nutrient Uptake

Photosynthesis is the primary process responsible for plant growth and biomass production. Onion (Allium cepa) extract has been reported to improve photosynthetic performance by increasing chlorophyll content and protecting chloroplast structures from oxidative damage. The flavonoids and phenolic compounds present in the extract act as antioxidants, reducing the harmful effects of reactive oxygen species and helping maintain efficient photosynthetic activity (Naz et al., 2022). Enhanced root development caused by onion extract also contributes to better nutrient absorption. A stronger root system improves the uptake of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, which are required for chlorophyll synthesis, enzyme activation, and energy metabolism (Carvalho et al., 2021). As a result, treated plants often show improved growth, higher biomass accumulation, and better physiological performance. Increased nutrient availability and efficient photosynthesis together support rapid seedling development and greater plant vigor. These effects indicate that onion extract can function as a natural biostimulant by improving both photosynthetic efficiency and nutrient utilization, ultimately contributing to enhanced crop growth and productivity (Prima et al., 2023).

Physiological and Biochemical Mechanisms

The growth-promoting effects of onion (*Allium cepa* L.) extract are attributed to several physiological and biochemical processes that enhance seed germination and early seedling development. During seed imbibition, the bioactive compounds present in onion extract stimulate the activity of hydrolytic enzymes such as **α-amylase** and **protease**, which convert stored carbohydrates and proteins into soluble nutrients required for embryo growth (Vij et al., 2025). Another important mechanism is the enhancement of the plant's antioxidant defense system. Flavonoids and phenolic compounds present in onion extract help scavenge reactive oxygen species (ROS), thereby reducing oxidative damage to cellular components. In addition, these compounds may stimulate antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), improving the plant's ability to withstand environmental stresses (Naz et al., 2022). Onion extract may also influence hormonal balance and cellular signaling pathways involved in plant growth. These combined physiological and biochemical responses improve nutrient mobilization, metabolic activity, and stress tolerance, resulting in enhanced seedling vigor and healthier plant development (Prima et al., 2023).

Antioxidant Activity and Stress Tolerance

Environmental stresses such as drought, salinity, temperature extremes, and nutrient deficiencies often limit agricultural productivity. These stresses induce excessive production of reactive oxygen species, resulting in cellular damage (Naz et al., 2022). Onion extract possesses strong antioxidant activity due to its high concentration of flavonoids and phenolic compounds (Prima et al., 2023). These antioxidants protect cellular membranes, proteins, and nucleic acids from oxidative damage (Kianian et al., 2021). Studies have shown that antioxidant-rich plant extracts improve chlorophyll retention, membrane stability, water relations, and stress tolerance. Therefore, onion extract may contribute to improved plant resilience under unfavourable environmental conditions.

Antimicrobial Properties and Crop Protection

Environmental stresses such as drought, salinity, heat, and nutrient deficiency often increase the production of reactive oxygen species (ROS), which can damage cellular components and inhibit plant growth. Onion (*Allium cepa* L.) extract is rich in flavonoids, phenolic compounds, and sulfur-containing metabolites that possess strong antioxidant properties. These compounds help neutralize excess ROS, protect cell membranes, and maintain normal physiological functions under stress conditions (Prima et al., 2023; Naz et al., 2022). In addition to directly scavenging free radicals, onion extract may enhance the activity of antioxidant enzymes, thereby strengthening the plant's natural defense system. Improved antioxidant capacity helps maintain chlorophyll content, membrane stability, and water balance, enabling plants to better tolerate unfavorable environmental conditions. Consequently, onion extract can improve seedling survival, growth, and overall plant resilience under abiotic stress (Naz et al., 2022).

Agricultural Applications and Future Prospects

The diverse biological properties of onion (*Allium cepa* L.) extract make it a promising natural biostimulant for sustainable agriculture. It can be applied as a seed priming agent, seed coating material, foliar spray, or soil amendment to improve plant growth and productivity. Among these methods, seed priming is considered one of the most effective approaches, as it enhances germination, seedling vigor, and stress tolerance while ensuring better crop establishment (Pagano et al., 2023; Vij et al., 2025). The use of onion extract offers an environmentally friendly alternative to synthetic growth promoters by improving nutrient uptake, antioxidant activity, and natural disease resistance. Its biodegradable nature and easy availability also make it an economical option for sustainable crop production (Carvalho et al., 2021). Although current studies have demonstrated encouraging results, further research is needed to standardize extraction methods, determine optimum application concentrations, and evaluate its performance under different field conditions and crop species. Understanding the molecular mechanisms underlying its growth-promoting effects will also support the development of efficient onion-based biostimulant formulations for commercial agriculture.

Conclusion

Onion (*Allium cepa* L.) extract is a valuable source of bioactive compounds that can significantly enhance seed germination, seedling growth, nutrient uptake, photosynthetic efficiency, antioxidant defense, and stress tolerance. Its antimicrobial properties further contribute to improved seed health and early crop establishment. These combined effects highlight its potential as a sustainable and eco-friendly alternative to synthetic agricultural inputs. Based on the available scientific evidence, onion extract can be effectively utilized as a natural biostimulant to improve crop performance while supporting environmentally sustainable farming practices. Future research focusing on formulation, application methods, and large-scale field evaluation will further strengthen its role in modern agriculture.

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