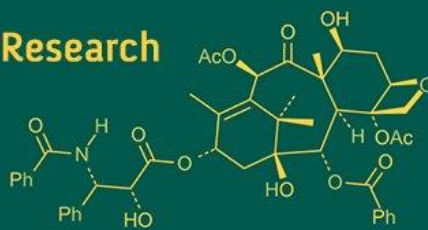


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Role of Seed Priming in increasing the production of Oat (*Avena sativa* L.): A Review

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Abstract

Oat (*Avena sativa* L.) is a cool season cereal that is appreciated due to its ability to generate a high level of biomass, quality fodder nutritive value and the ability to adapt to a wide range of agro-climatic environments. Improving the early crop establishment is important in achieving its yield potential especially in subtropical valleys like the Doon Valley of India. Seed priming is a low-cost, environmentally friendly pre-sowing treatment, which speeds up germination and enhances seedling vigor. This is a critical review of peer-reviewed articles on organic priming (e.g., bijamrit, vermiwash and cow urine) and bio-priming (e.g., *Azotobacter* and *Trichoderma* spp.), emphasizing their physiological mechanism, agronomic performance and economic viability in oat. It has always been shown that priming enhances enzymatic activation, repair of membranes, and mobilization of reserves contributing to more rapid emergence, better stand establishment, higher tillering, and more biomass accumulation. Bio-priming also plays a role by adding biological fixation of nitrogen, production of phytohormones, pathogen control and enhancement of nutrient solubilization. Integrated (organic + bio) priming tends to have synergistic impacts on growth and yield characteristics, which translate to increased benefit:cost ratios and higher green fodder yield. The major gaps in knowledge are the lack of location-specific validations, protocol standardization, and impacts of long-term soil-plant systems. The review also gives future research directions to streamline the use of priming strategies towards sustainable oat production systems.

Keywords: Seed priming, seedling vigour, organic priming, bio-priming, *Azotobacter*, *Trichoderma*, fodder yield, sustainable agriculture, biomass production, agro-climatic adaptation, integrated priming

Introduction

Oat (*Avena sativa* L.) is a significant rabi cereal crop widely grown and used due to its dual-purpose use as both grain and green fodder, especially in temperate and subtropical regions. In North India, oats are important in maintaining livestock production during winter seasons because it grows rapidly, accumulates high biomass, and is high in palatability, as well as, relatively high in crude protein content in comparison to other winter fodders (Sood *et al.*, 2022) [25]. Its adaptability to a wide range of agro-climatic factors and the ability to produce nutritious fodder are also valued qualities of the crop (Kumar & Yadav, 2023) [16]. Although oat under the field conditions of farmers is potentially very productive, it frequently does not achieve the level of productivity it has the potential to reach. This gap is mainly explained by the limitations, such as low-quality seed, irregular and delayed germination, inefficient nutrient management, and exposure to abiotic stressors, such as low temperature, frost, and periodic stresses of moisture during the initial stages of growth (Chand *et al.*, 2025) [5]. These conditions negatively influence the establishment of crops, resulting in a decrease in the stand of plants, in the tillering of plants, and finally in the biomass and grain yield of plants. Seed priming has been found to be an effective, low-cost and environmentally friendly method of overcoming these limitations and improving crop performance. Seed priming refers to the controlled hydration of seeds to a certain level that triggers pre-germinative metabolic activities without allowing the emergence of radicles, followed by drying to the initial level of moisture content before sowing (Paparella *et al.*, 2015; most recent applications discussed in (Sharma *et al.*, 2022) [10]. This process boosts enzymatic activity, membrane integrity, and speeds up metabolic repair processes, leading to faster and more coordinated germination (Iqbal *et al.*, 2023). Primed seeds have several physiological and agronomic benefits, such as a reduced durability of the germination lag

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period, an increased germination rate, enhanced seedling vigor, and better tolerance to abiotic stresses like drought and extreme temperatures (Farooq *et al.*, 2019) ^[8]. updated findings in (Verma *et al.*, 2024) ^[27]. All these advantages are summed up to provide better crop establishment and increased productivity.

The last few years have been characterized by an increased interest in the incorporation of organic and biological methods into seed priming methods. Organic priming agents, including farmyard manure extracts, vermiwash, botanical extracts, and microbial priming agents, such as *Azotobacter*, *Trichoderma*, and phosphate-solubilizing bacteria (PSB) have shown promise in improving seed performance and crop yield (Kumar *et al.*, 2021; Meena *et al.*, 2023) ^[17, 19]. These bio-priming methods not only enhance the availability and uptake of nutrients but also elicit plant growth-promoting substances and induce a systemic response to stress. Moreover, the application of bio-priming can be aligned with the principles of sustainable agriculture by minimizing the reliance on chemical inputs, enhancing the health of the soil, and facilitating the implementation of crop production systems that are more eco-friendly (Chand *et al.*, 2025) ^[5]. (Gupta *et al.*, 2022) ^[10]. Such combined priming strategies have been reported to greatly improve the growth parameters such as plant height, the number of tillers, leaf area index and ultimately the fodder yield and quality in oats.

Therefore, exploring the role of different organic and bio-priming agents in oat cultivation is essential for improving productivity, ensuring sustainability, and meeting the increasing demand for quality fodder in livestock-based farming systems.

Concept and Physiological Basis of Seed Priming

During priming, several physiological processes are triggered: (i) repair of cellular membranes, (ii) activation of hydrolytic enzymes (e.g., α -amylase, proteases), (iii) mobilization of seed reserves, and (iv) synthesis of nucleic acids and proteins. Collectively, these changes enable rapid water uptake upon sowing and synchronized emergence (Ashraf & Foolad, 2005; Farooq *et al.*, 2008) ^[1, 7].

Seed Priming

Seed priming is a high-tech pre-sowing method that has been significantly relevant in contemporary agriculture to enhance the performance of seeds and the establishment of crops. It is a method of controlled hydration of seeds to enter the initial stages of germination-related metabolic events without allowing the emergence of radicles, and then drying to the initial moisture level prior to sowing (Paparella *et al.*, 2015) ^[214]. This method is used to make seeds physiologically ready to quickly and uniformly germinate once they are sown in the field.

The poor and uneven germination in many crops including cereals, pulses, and fodder crops such as oat (*Avena sativa* L.) is a significant limitation that reduces productivity. The problem is further exacerbated by environmental stresses like low temperature, drought and salinity at the initial stages of the crop growth (Sharma *et al.*, 2022) ^[10]. Seed priming under these conditions has proven to be an effective, low-cost, and farmer-friendly approach to improving the germination performance of seeds and to guarantee a better establishment of crop stands. Physiological background of seed priming is the activation

of metabolic processes including the synthesis of enzymes, repair of cellular components, mobilization of stored food reserves and enhancing membrane integrity. All these processes have been shown to decrease the lag phase of germination and stimulate faster and synchronized seed germination (Iqbal *et al.*, 2023) ^[14]. Consequently, the primed seeds tend to show improved seedling growth, enhanced root development and increased tolerance to abiotic stresses in comparison with the non-primed seeds.

Seed priming in recent years has not only developed in terms of the hydration techniques but also in terms of the organic and biological agents. Other strategies that have provided promising results in enhancing plant growth and yield include biopriming with beneficial microorganisms (e.g., *Azotobacter*, *Trichoderma*, and phosphate-solubilizing bacteria) and organic priming using natural extracts (Meena *et al.*, 2023; Kumar *et al.*, 2021) ^[19, 17]. Such practices have the added advantage of increasing nutrient availability and uptake, as well as contributing to sustainable agricultural practices due to the reduction in reliance on synthetic inputs. In addition, seed priming has been reported to enhance the performance of crops under stress-prone conditions by enhancing stress-tolerance mechanisms such as antioxidant activity and osmotic adjustment (Verma *et al.*, 2024) ^[27]. This renders it especially useful in the backdrop of climate variability and farming systems that have resource limitations.

Thus, seed priming is an easy to use yet effective tool of enhancing seed quality, crop establishment and overall productivity. Its combination with organic and bio-based inputs have tremendous potential in realizing sustainable and resilient agricultural production systems.

Types of Priming

- **Hydro-priming:** Soaking seeds in water for a defined duration.
- **Osmo-priming:** Use of osmotic solutions (e.g., PEG, salts) to control water uptake.
- **Organic priming:** Use of natural, nutrient-rich solutions.
- **Bio-priming:** Inoculation with beneficial microorganisms.

Across cereals, priming is associated with improved germination percentage, reduced mean germination time, enhanced seedling vigor index, and better early crop establishment.

Organic Seed Priming

Organic seed priming is an environmentally-friendly, sustainable pre-sowing method that utilizes biologically-derived solutions that are rich in macro- and micronutrients, enzymes, vitamins, and natural growth-promoting substances to enhance seed performance and early crop establishment. Farmyard manure (FYM) extract, vermiwash, cow urine, bijamrit and plant-based extracts are the common organic priming agents that contribute to the improvement of the physiological and biochemical status of seeds before sowing. In priming, these organic solvents help in the partial hydration of the seeds, following which the seeds undergo key metabolic processes, which encompass the synthesis of enzymes (e.g., α -amylase), repair of cellular membranes, and mobilization of stored food reserves. This leads to quicker and more even germination, better seedling vigor

and increased root development. Organic priming also provides a favourable microenvironment in the vicinity of the seed by enriching it with benevolent microorganisms and organic compounds, which facilitate improved interactions between the soil and plant and nutrient availability. The early plant growth and development is further accelerated by the presence of naturally occurring plant growth regulators like auxins, gibberellins and cytokinin's. In addition, the priming with organic substances has also been reported to enhance tolerance to abiotic stresses like drought, salinity, and changes in temperature by increasing antioxidant activity and osmotic regulation in seedlings. Agronomically, this results in increased plant height, tillering, biomass accumulation and eventually higher yield especially in fodder crops such as oat (*Avena sativa* L.). Significantly, the idea of organic priming is consistent with the principles of sustainable agriculture in terms of decreasing the reliance on synthetic chemicals, enhancing soil health, and supporting the system of environment-safe production of crops. Thus, it is becoming an increasingly popular low-cost and farmer-friendly technology to enhance crop productivity and resilience to diverse agro-climatic environments (Ramesh *et al.*, 2021; Gupta *et al.*, 2022; Paparella *et al.*, 2015) ^[10, 21].

Bijamrit

Bijamrit is a traditional formulation prepared from cow dung, cow urine, jaggery, and soil. It supplies a consortium of beneficial microbes and readily available nutrients, enhancing seed surface microbiota and early metabolic activity.

Vermiwash

Vermiwash is a leachate collected from vermicompost systems and contains soluble nutrients, vitamins, enzymes, and plant growth regulators (auxins, cytokinin's). Its application during priming has been associated with improved germination and root proliferation.

Cow Urine

Cow urine contains nitrogenous compounds, potassium, trace elements, and bioactive molecules that can stimulate enzymatic activity and early seedling growth.

Bio-Priming

Bio-priming of seed with *Azotobacter* and *Trichoderma* is an efficient and sustainable seed enhancement strategy, which combines controlled seed hydration and inoculation with beneficial microorganisms. This strategy promotes early colonization of seed surface and new roots resulting in the establishment of a protective and growth-promoting rhizosphere interface. A free-living nitrogen-fixing bacterium, *Azotobacter* helps to enhance nitrogen availability and produces plant regulations factors, including indole-3-acetic acid, gibberellins and vitamins, whereas *Trichoderma* spp. are potent bio-controlling agents and bio-stimulant because of their ability to enhance nutrient solubilization, root growth and plant defence responses. Recent research has shown that microbial consortia, in particular, *Azotobacter*, *Trichoderma*, and their combinations, have synergistic effects that have a significant beneficial effect on seed germination, seedling vigor, nutrient uptake, and crop productivity when compared with that of single inoculation. In addition, bio-priming has been

demonstrated to increase tolerance to abiotic stresses like drought and changes in temperature by the activation of antioxidant defence systems and stress memory in plants. Indicatively, recent reports have shown that priming by *Trichoderma* can enhance drought resilience as well as even impart stress tolerance characteristics on subsequent plant generations. Also, co-inoculation methods have been documented to enhance the nutrient availability of the soil, microbial activities, and overall performance of the plant using lower fertilizer inputs. These breakthroughs underscore the potential of bio-priming using *Azotobacter* and *Trichoderma* as bio-priming agents both to enhance crop establishment, productivity, and sustainability in contemporary agriculture (Woo *et al.*, 2023) ^[31].

Azotobacter

Azotobacter spp. are free-living nitrogen-fixing bacteria that are involved in the fixation of N in the atmosphere and release of phytohormones (e.g., indole-3-acetic acid), vitamins, and siderophores. Their connection to roots increases nutrient uptake and plant health.

***Trichoderma* spp. (e.g., *Trichoderma viride*)**

The *Trichoderma* species are used as biocontrol agents against soil-borne pathogens and have been shown to enhance plant growth through a wide range of mechanisms such as mycoparasitism, antibiosis, induced systemic resistance, and enhanced nutrient solubility (particularly phosphorus).

***Azotobacter* and *Trichoderma* together.**

Synergistic Interaction

A combination of the *Azotobacter* and *Trichoderma* has a powerful synergistic effect on crop growth and productivity. As a biological nitrogen fixer, *Azotobacter* improves the availability of nitrogen to plants, thus enhancing their nutrition. At the same time, *Trichoderma* inhabits the rhizosphere and root surface, safeguarding plants against soil-borne pathogen and increasing nutrient solubilization and uptake.

This symbiotic relationship results in better root structure, increased nutrient uptake, and general increase in plant vigor. Research has indicated that co-inoculation of beneficial microorganisms will lead to greatly increased growth performance than single inoculation (Vessey, 2003; Harman *et al.*, 2004) ^[30, 11].

Agronomic Effects of Bio-Priming and Organic Priming in Oat (*Avena sativa* L.)

Priming of seeds has been adopted as a cost-effective, efficient and environmentally friendly agronomic method to enhance crop establishment and productivity. Bio-priming and organic priming are some of the different approaches that have been receiving growing interest owing to their application in improving seed performance using biological and natural inputs. These methods are especially pertinent to the fodder crops such as oat (*Avena sativa* L.) where quick establishment, high growth rate and greater biomass production are of critical relevance in attaining optimal yield.

Bio-Priming and Its Agronomic Effects

Bio-priming consists of treating seeds with advantageous micro-organisms like *Trichoderma*, *Azotobacter* and

controlled hydration. Not only does this method initiate pre-germinative metabolic processes but also forms a favourable microbial population around the seed and emerging roots. Among the major agronomic advantages of bio-priming is an increased germination rate and germination uniformity. The research has demonstrated that bio-primed oat seeds have their germination period shortened by 1-2 days, and the percentage of germination increased by 10-15% compared to non-primed seeds (Verma *et al.*, 2023) ^[29]. *Azotobacter*. This results in improved field emergence and crop stand uniformity, which is key in maximizing the fodder yield. Root system architecture, such as longer root length, more root volume and root surface area, is also significantly enhanced by bio-priming. Root length has also been reported to be increased by inoculating oats with *Azotobacter* and *Trichoderma* (Kumar *et al.*, 2021) ^[17]. Improved root development further enhances improved nutrient uptake, especially the nitrogen and phosphate, through the action of the microbes, like the nitrogen fixation and phosphate solubilization. Disease suppression and stress tolerance is another significant impact of biopriming. The sperm sphere and rhizosphere are colonized by beneficial microbes that compete with the pathogens and produce antifungal compounds. As an example, *Trichoderma* spp. are reported to decrease the seedling diseases and enhance the plant vigor. Moreover, bio-primed oat plants have enhanced resistance to abiotic stresses like low temperature and moisture stress which is common during the rabi season in North India (Sharma *et al.*, 2022) ^[10]. These accumulative effects will lead to enhanced growth parameters and yield attributes. In the field condition of oats, the bio-priming was reported to increase the plant height by 8-12% and number of tillers by 12-20% and the green fodder yield by 15-25% (Meena *et al.*, 2023) ^[19]. The increased physiological activity and increased uptake of nutrients eventually lead to an increase in the biomass accumulation and quality of fodder.

Organic Priming and its Agronomic impacts.

Organic priming is the use of natural materials like vermiwash, farmyard manure (FYM) extract, cow urine and botanical extracts to treat seeds. This method is increasingly becoming popular because it can be applied in sustainable and organic agriculture. Organic priming is the procedure that improves seed germination and seedling vigor by supplying essential nutrients, enzymes and growth promoting substances. Priming of oat and wheat seeds with vermiwash or FYM extract has demonstrated a significant increase in the percentage of germination by 812% and increase in the index of seedling vigor by 31.6% (Gupta *et al.*, 2022) ^[10]. One of the key agronomic benefits of organic priming is improved soil-plant interaction and nutrient dynamics. Organic materials induce microbial growth within the rhizosphere resulting in increased mineralization and availability of nutrients. This leads to increased absorption of vital nutrients like nitrogen, phosphorus and micronutrients. Organic priming, in addition, enhances soil structure and water retention that is especially useful in soils with moisture constraints. Other factors leading to improved root growth and plant growth include organic priming. The presence of more root biomass and better root-soil contact provide better absorption of water and nutrients. Organic priming treatments that have been reported to increase plant height by 6-10% and tiller number by 10-15% in oat leading

to improved crop growth (Singh *et al.*, 2021). Moreover, organic priming positively influences the yield and biomass production. According to field studies, organic priming has the potential to increase green fodder yield in oat by 10-18 per cent, and improve dry matter accumulation and content of crude protein (Kumar and Yadav, 2023) ^[16]. These gains are due to increased physiological efficiency and improved utilization of nutrients.

Integrated Effect: Organic and Bio-Priming (Combined Approach).

Organic and bio-priming has become an effective fodder crop management strategy to enhance growth, productivity and sustainability of fodder crops such as oat (*Avena sativa* L.). Biopriming, unlike organic priming, which provides the seed with essential nutrients, enzymes, vitamins and natural growth promoting substances, introduces beneficial microorganisms, which actively interact with the seed and rhizosphere. Combination of these methods produces a complementary and synergistic effect leading to higher benefits than either of the methods alone (Farooq *et al.*, 2008) ^[7]. Organic priming agents like bijamrit, vermiwash, and cow urine enhance the microenvironment of the seed with readily available nutrients and natural growth regulators that accelerate early metabolic activities, enhances enzyme activation, and improves seedling vigor (Jatana *et al.*, 2024) ^[15]. Simultaneously, beneficial associations with plant roots are formed by bio-inoculants, such as *Azotobacter* and *Trichoderma* spp. (Meena *et al.*, 2023) ^[19]. The organic substrates also help support the growth of the microbes by providing a favorable medium on which the microbes can colonize and be active in the spermosphere and rhizosphere (Ashraf and Foolad, 2005) ^[1]. This combined interaction increases nutrient availability and enhances the efficiency of nutrient uptake, resulting in a higher rate of root proliferation and improved water and mineral uptake efficiency (Farooq *et al.*, 2008) ^[7]. The enhanced microbial activity further enhances nutrient solubilization and mineralization, which increases the soil fertility and plant growth (Meena *et al.*, 2023) ^[19]. This leads to a faster and more even germination of crops, increased root and shoot growth, increased tillering, enhanced leaf area growth, and greater accumulation of dry matter (Jatana *et al.*, 2024) ^[15]. Such integrated priming strategies have been reported to enhance the yield of green fodder, grain yield and crude protein content when compared to the individual treatments.

Soil Health Enhancement

The joint inoculation of *Azotobacter* and *Trichoderma* is important in enhancing the health of the soil and in the long-term sustainability of the crop production systems. These useful microorganisms increase the diversity of the microorganisms in the rhizosphere, which leads to the development of a stable and biologically active soil ecosystem (Woo *et al.*, 2014) ^[31]. Greater microbial diversity promotes positive interactions among soil organisms, which facilitates soil structure and the overall fertility of soil. Moreover, joint inoculation will improve nutrient cycling, especially of key nutrients like nitrogen and phosphorus. *Azotobacter* is involved in biological fixation of nitrogen, whereas *Trichoderma* spp. mediate the solubilization and release of nutrients, which increases nutrient uptake by plants (Meena *et al.*, 2023) ^[19]. This leads

to a greater economic utilization of soil nutrients and also less reliance on chemical fertilizer. Moreover, these microorganisms have significant effects on increasing soil enzymatic activities, such as dehydrogenase and phosphatase, which are important indicators of soil biological activity and fertility status. Increased enzyme activity indicates increased microbial metabolism and faster rate of decomposition of organic matter, thus enhancing nutrient mineralization.

All these enhancements help to promote the long-term soil fertility, improvement of soil biological processes, and the long-term productivity of oat-based systems. Therefore, introduction of microbial inoculants like *Azotobacter* and *Trichoderma* is a sustainable practice to maintain the soil health and to promote viable and productive oat production (Woo *et al.*, 2014; Meena *et al.*, 2023)^[31, 19].

Growth and Yield Response

Combined application of *Azotobacter* and *Trichoderma* are significant in enhancing growth and yield characteristics in oat (*Avena sativa* L.). This interaction is synergistic, improving plant height because of increased fixation of nitrogen by *Azotobacter* and the release of plant growth-promoting hormones including auxins, gibberellins and cytokinin's. Meanwhile, *Trichoderma* spp. enhance root growth and solubilization of nutrients, resulting in increased nutrient absorption and general plant vigor. Consequently, the number of tillers per plant is significantly increased, and it leads to the increased biomass accumulation. The increase in chlorophyll level and rate of photosynthesis further enhances green fodder yield. Also, the enhanced nutrient absorption and metabolic activity lead to better production of dry matter. In addition to enhanced growth, *Trichoderma* is also a biocontrol agent, and reduces soil-borne pathogens and promotes a healthier rhizosphere environment. Combined utilization of these biofertilizers has been demonstrated to increase physiological and biochemical mechanisms including enzyme activity, protein synthesis and efficiency of utilization of nutrients and ultimately increased productivity and sustainability in oat growing. The experimental results confirm the idea that the use of integrated biofertilizers provides significant improvements to the crop yield by increasing the fertility of the soil and metabolic processes in plants (Verma *et al.*, 2019)^[28]. A similar finding was that (Yadav *et al.* 2021) who reported that oat when treated with biofertilizers developed higher growth and fodder yield, and that (Singh *et al.* (2022). who observed that cereal crops treated with microbial inoculations exhibited improved nutrient uptake and fodder yield.

Oat Growth Parameters.

Seed priming has been extensively reported to enhance important growth parameters in cereals and forage crops, such as oat (*Avena sativa* L.). It results in a steady increase in key growth characteristics including, but not limited to, plant height that indicates enhanced vigor and increased assimilate production. Both the number of tillers per plant which is also a significant determinant of fodder yield as well is greatly increased under primed conditions. Also, the level of leaf area index (LAI) that indicates the development of the canopy and light interception ability improves significantly, which adds to the increase in photosynthetic efficiency. The build-up of dry matter, which is a significant

measure of overall biomass productivity is also improved as a result of an increase in physiological activity and nutrient uptake. The primed seeds tend to have a shorter emergence period, increased germination consistency, and accelerated initial growth rates. These benefits allow improved use of resources including light, water, and nutrients during the vegetative stage which eventually results in the high performance of crops. The beneficial impact of seed priming on early crop establishment and resource-use efficiency in cereal crops have been well established (Farooq *et al.* 2008)^[7] who pointed out its potential in enhancing seedling vigor and resource-use efficiency in cereal crops.

Yield and Yield Attributes

The seed priming method has great effect on the yield traits and general productivity of oat (*Avena sativa* L.). It improves important components of yield like quantity of panicles in a plant, quantity of grains per panicle, and weight of test in instances where grain production is taken into account. Priming in fodder crops results in significant increases in both green and dry biomass yield as a result of enhanced germination and early seedling vigor, and evenly distributed crop establishment. Combination of organic priming agent with bio-priming technology usually has additive or synergistic effects, where organic inputs enhance the nutrient availability of soils and bio-inoculating agents catalyze microbial growth and development of plants. This is an integrated strategy that has been shown to increase nutrient uptake, root development and physiological efficiency, leading to better crop performance. Moreover, research has shown that a combination of organic and bio-priming practices has a significant positive effect on the total biomass production and the crude protein content of fodder crops, thus improving the yield and the quality. Recent reports (Kushwaha *et al.* 2025) and (Chand *et al.* 2025)^[5] also indicated significant improvements in growth parameters, biomass accumulation, and nutritional quality of oat under combined priming treatments, which indicates the effectiveness of such sustainable nutrient management strategies.

Applicability to Doon Valley Conditions.

A subtropical to temperate climate with cool winters conducive to rabi oats is characteristic of the Doon Valley (Uttarakhand, India). Nevertheless, the germination and the initial growth may be hampered by factors like fluctuating soil fertility, winter rainfall and temperature variations. Context-specific priming, especially of locally sourced organic inputs and robust microbial inoculants, is a pertinent approach to stabilizing establishment, developing tillering, and maximizing fodder yield in such situations (Farooq *et al.*, 2008; Verma *et al.*, 2023; Gupta *et al.*, 2025; Ramesh *et al.*, 2021)^[7, 29, 9].

Research Gaps

Although there are positive outcomes that have been documented in relation to seed priming in oat (*Avena sativa* L.), there are still some significant gaps in research. The lack of overall comparative studies to assess the relative effectiveness of organic priming, bio-priming and the combined application of these two modes of priming under specific agro-ecological conditions is a limitation to the capacity to recommend location specific practices. Besides, the majority of the available studies are short-term in nature

and there is also lack of information on the long-term impacts of priming on the health of soil, microbial diversity and lingering effects of priming on subsequent crops. The relationship between soil microbiomes and its interaction with bio-inoculants like *Azotobacter* and *Trichoderma* need to be further explored especially in different environmental conditions. Moreover, it is necessary to conduct multi-location experiments to establish the consistency and scalability of priming technologies to various climatic conditions and soils. Economic studies are also restricted particularly in terms of the size of the farms, the availability of resources, and the variability of cost and benefit among the small, medium, and large farms. Systematic, long-term, and location-specific research, aimed at addressing these gaps, will be essential in streamlining the priming techniques, as well as, in encouraging the increased use of priming techniques in the production of oats in a sustainable system.

Conclusion

Organic and bio-priming are viable and eco-friendly interventions to improve the productivity of oats. Priming enhances crop establishment and yield formation by increasing the germination dynamics, early vigor and resource-use efficiency. The most promising option seems to be the integrated methods of incorporating organic inputs with microbial inoculants that can provide agronomic and economic benefits and contribute to soil health. To scale these technologies in different production settings, specific research and standardization will be needed. The organic priming agents play a role in their provision of the necessary nutrients, natural growth regulators, and other valuable compounds that trigger early plant growth. Simultaneously, bio-priming presents the introduction of functional microorganisms, which increase nutrient availability, stimulates plant growth by producing phytohormones, and effective protection against soil-borne pathogens. All of these mechanisms enhance plant vigor, resource-use efficiency, and tolerance to stress. It has been discovered that the combination of organic and bio-priming can especially be encouraging as it brings the merits of the two methods to form a synergistic effect. This integrated approach does not only improve the parameters of growth, including plant height, number of tillers and leaf area index, but also greatly improves green fodder quantity and quality. In addition, it enhances the returns to the economy by cutting down input expenses and boosting productivity and is, therefore, most appropriate when dealing with small and marginal farmers. Although the presented advantages are proven, extensive scales of priming technologies need additional studies to unify protocols, improve the combination of treatments, and confirm its performance in various agro-ecological settings. It is important to also conduct long-term research on soil health, microbial processes and sustainability measures to capture the overall effects of such practices.

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