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Sustainable Alternatives to Synthetic Priming Agents: Evaluating Plant-Derived Extracts for Seed Enhancement

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Abstract: ***Seed priming with plant-derived bio stimulants offers an environmentally sustainable way to improve seed germination and early stages of seedling growth. This study explored the potential of natural priming agents, including Banana peel, Neem leaf, Sugarcane, and Beetroot extracts, to enhance the germination and development of wheat seeds. These plant-derived products are rich in bioactive substances, such as Auxins, Cytokinins, Phenolics, Antioxidants, Sugars, and Micronutrients, which enhance metabolic activity during the initial stages of seed germination. Seeds were treated with various plant extracts and compared with those that were not treated. The findings indicated that all plant-derived priming agents enhanced the germination rate, radicle and plumule length, seedling vigour index, and chlorophyll levels. Extracts from banana peels and Neem leaves showed the most pronounced stimulatory effects, which were attributed to their well-balanced Auxin- Cytokinin profiles and antimicrobial properties. Sugarcane juice and beetroot extract significantly improved energy availability and bolstered antioxidant capacity, thereby mitigating the oxidative stress. These priming agents fulfil a dual function by delivering essential nutrients and protective osmolytes, which help preserve cellular integrity and enhance resilience against environmental challenges during germination and early growth. In contrast to synthetic priming agents, plant-derived solutions are biodegradable, eco-friendly, and suitable for organic farming methods. This study emphasizes the potential of plant-based priming agents as viable and sustainable substitutes for chemical seed treatments, aiding in enhanced crop establishment and yield across various agro ecological environments.***

Keywords: Seed priming, Plant-derived extracts, Germination, Seedling growth, Bioactive compounds, Sustainable agriculture and eco-friendly alternatives

1. Introduction

Seed priming is an essential pre-sowing technique that involves partially hydrating seeds under controlled conditions, followed by drying them to a specific moisture level before radicle appearance. This method initiates early germination stages, resulting in quicker and more consistent seedling emergence, improved seedling strength, and greater resistance to various abiotic stresses in the field. (Lei et al., 2021) Osmotic priming, a particular form of seed priming, entails immersing seeds in a solution with low water potential, known as an osmotic agent, which carefully manages water absorption during the pre-germination stage. This regulated hydration prevents radicle emergence while activating the metabolic processes needed for germination, effectively readying the seed for enhanced performance once planted. (Nie et al., 2022)

Beyond osmotic priming, nutrient priming is another potent technique that entails immersing seeds in solutions fortified with essential macro- or micronutrients. This approach provides immediate nutritional advantages during germination, aiding the initial growth and development of seedlings. (Raj & Raj, 2019) Among the various priming methods investigated, extracts derived from plants, such as banana peels and Neem leaves, have shown the most notable stimulatory effects. (Indurugalla et al., 2023) These extracts possess a well-balanced Auxin–Cytokinin composition that encourages cell division and elongation, while their robust antimicrobial properties shield seeds from pathogenic infections during germination, thus boosting seed health and vigor. Likewise, sugarcane juice and beetroot extract have been found to enhance seed quality by augmenting their energy reserves and antioxidant capacity. These benefits help mitigate oxidative stress, which can hinder seedling growth, and support the establishment of vigorous seedlings. (Noman et al., 2018)

This research underscores that priming agents derived from plants greatly enhance the efficiency of germination and the initial establishment of seedlings. These natural solutions are sustainable and economical alternatives to traditional chemical seed treatments and fit seamlessly into environmentally friendly farming practices. By utilizing the bioactive compounds found in these plant extracts, farmers can boost crop establishment and resilience while reducing environmental damage. This method not only promotes sustainable agriculture but also aids in increasing crop productivity under various environmental stress conditions. (Di Sario et al., 2025)

Plant-derived priming agents play a crucial role in providing seeds with vital nutrients and significantly enhancing their resilience to various environmental challenges. The synergy of bioactive compounds and natural osmoprotectants found in these extracts bolsters the physiological robustness of seeds, leading to higher germination rates and more vigorous seedling development. (Wazeer et al., 2024) This dual function of nourishment and defense underscores the effectiveness of plant-based priming in promoting sustainable agriculture. Additionally, these natural agents are eco-friendly alternatives to synthetic chemicals, minimizing

both environmental impact and potential toxicity associated with traditional seed treatments. Their biodegradable properties and alignment with organic farming practices further advocate the use of plant-derived priming agents as a safer and more sustainable approach to improving crop establishment and productivity across diverse growing conditions.

The increasing focus on plant-based biopriming arises from the desire to find more sustainable and environmentally friendly alternatives to traditional chemical osmotic priming agents, such as polyethylene glycol and potassium nitrate. Unlike synthetic chemicals, plant-derived priming agents are biodegradable and suitable for use in organic farming systems, minimizing the risk of soil and water contamination. Their application supports the goals of sustainable agriculture by reducing the environmental impact of seed treatment methods while promoting improved crop establishment and productivity in various agroecological settings. (Wazeer et al., 2024)

Utilizing plant-based bio stimulants for seed priming offers an environmentally friendly approach to boost germination success and initial seedling vigor. This study thoroughly examined the effectiveness of natural priming substances sourced from banana peel, Neem leaf, sugarcane, and beetroot extracts on seed germination and early seedling growth. These plant materials are abundant in bioactive compounds such as auxins, cytokinins, phenolics, antioxidants, sugars, and essential micronutrients, which together promote metabolic activation during the crucial early phases of germination.(Indurugalla et al., 2023)

These plant-based priming agents fulfill a dual role by delivering crucial nutrients alongside protective osmolytes, such as sugars, polyphenols, proline, betaine, and organic acids. This synergy ensures osmotic equilibrium, safeguards cellular integrity, and bolsters resilience against environmental challenges during the germination and early growth phases of plants. Such comprehensive biochemical support results in heightened seed vigor and uniform seedling establishment, even when the conditions are not ideal.

Unlike conventional synthetic priming agents, such as polyethylene glycol and potassium nitrate, plant-based priming solutions provide sustainable and affordable alternatives that help reduce chemical residues and environmental pollution. Their biodegradable properties and compatibility with organic farming practices align with global sustainability goals, minimizing ecological impact while improving crop productivity.

These plant materials are inherently rich in a variety of bioactive compounds, including plant hormones such as auxins and cytokinins, phenolic compounds, antioxidants, easily accessible sugars, and essential micronutrients such as potassium, calcium, magnesium, iron, and zinc. Collectively, these compounds play a crucial role in stimulating metabolic activation during the early stages of germination by promoting cell division, elongation, and enzymatic activity, which are vital for seed viability and vigor.(Indurugalla et al., 2023) Furthermore, the presence of natural osmoprotectants like polyphenols, proline, betaine, and organic acids in these extracts is essential for maintaining osmotic balance, protecting cellular structures from dehydration, and stabilizing proteins and membranes. This biochemical synergy ensures cellular integrity and resilience against environmental stresses, thereby facilitating uniform and robust seedling establishment, even under suboptimal conditions.

The findings revealed that seeds treated with these plant extracts showed marked enhancements in germination rates, growth of radicles and plumules, seedling vigor index, and chlorophyll levels compared to untreated seeds. In particular, extracts from banana peels and Neem leaves exhibited the most significant growth-promoting effects. This enhanced performance is linked to their well-balanced auxin–cytokinin ratios, which are crucial for regulating growth processes, and their strong antimicrobial properties that shield against pathogens carried by seeds, thereby reducing germination failure due to infections. Conversely, sugarcane juice and beetroot extract mainly boosted the seeds' energy reserves and antioxidant capabilities, helping to alleviate oxidative stress, which often hampers seedling growth and vitality. The antioxidants present in these extracts neutralize the reactive oxygen species produced during germination, safeguarding cellular structures and fostering healthier seedling development.

These plant-derived priming agents serve a dual purpose: delivering vital nutrients and functioning as protective osmolytes. This dual role ensures that seeds experience a meticulously regulated hydration process that activates metabolic pathways without causing early radical emergence. This precise hydration, along with biochemical support, enhances the seeds' metabolic preparedness, leading to quicker and more consistent germination and robust seedling development. (Rhaman et al., 2020) Notably, the natural osmolytes aid in osmotic adjustment, allowing seeds to better withstand abiotic stresses such as drought, salinity, and temperature variations during germination and the initial phases of seedling growth.

In comparison to traditional synthetic priming agents like polyethylene glycol (PEG) and potassium nitrate, solutions derived from plants present several sustainable benefits. (Macdonald & Mohan, 2025) Although synthetic agents are effective, they often come with high expenses, leave behind chemical residues that can harm the environment, and may adversely affect the soil's microbial communities, which are crucial for maintaining soil health. In contrast, plant-based priming agents are biodegradable, environmentally friendly, and suitable for organic farming systems, supporting global initiatives to advance sustainable agriculture. Their application decreases the need for chemical inputs, reduces production expenses, and lessens the environmental impact of seed treatment.

This comprehensive assessment underscores the potential of plant-based priming agents as effective, low-cost, and environmentally responsible alternatives to synthetic chemicals in seed treatment protocols. By harnessing the rich bioactive compound profiles of banana peel, neem leaf, sugarcane, and beetroot extracts, these natural priming

agents not only accelerate germination and seedling growth but also enhance seed resilience to environmental stress, thereby contributing to improved crop establishment and productivity. These findings advocate for the wider adoption of bio priming techniques across diverse agro ecological settings, supporting sustainable crop production systems that are both ecologically sound and agronomically effective. Future research directions may include the optimization of extract concentrations, evaluation across different crop species, and integration with other sustainable agronomic practices to fully realize the benefits of plant-derived seed-priming agents.

Seed priming is an essential pre-sowing technique that involves partially hydrating seeds under controlled conditions, followed by drying them to a specific moisture level before the radicle appears. This method initiates the early germination stages, resulting in quicker and more consistent seedling emergence, improved seedling strength, and greater resistance to various abiotic stresses in the field. (Lei et al., 2021) Osmotic priming, a particular form of seed priming, entails immersing seeds in a solution with low water potential, known as an osmotic agent, which carefully manages water absorption during the pre-germination stage. This regulated hydration prevents radicle emergence while activating the metabolic processes needed for germination, effectively readying the seed for enhanced performance once planted. (Nie et al., 2022)

Beyond osmotic priming, nutrient priming stands out as another potent technique, which entails immersing seeds in solutions fortified with essential macro- or micronutrients. This approach delivers immediate nutritional advantages during the germination process, aiding the initial growth and development of seedlings. (Raj & Raj, 2019) Among the various priming methods investigated, extracts derived from plants, such as Banana peels and Neem leaves, have shown the most notable stimulatory effects. (Indurugalla et al., 2023) These extracts possess a well-balanced Auxin–Cytokinin composition that encourages cell division and elongation, while their robust antimicrobial properties shield seeds from pathogenic infections during germination, thus boosting seed health and vigor. Likewise, sugarcane juice and beetroot extract have been found to enhance seeds by augmenting their energy reserves and antioxidant capacity. These benefits help mitigate oxidative stress, which can hinder seedling growth, and support the establishment of vigorous seedlings. (Noman et al., 2018)

The research underscores that priming agents derived from plants greatly enhance the efficiency of germination and the initial establishment of seedlings. These natural solutions present a sustainable and economical alternative to traditional chemical seed treatments, fitting seamlessly with environmentally friendly farming practices. By utilizing the bioactive compounds found in these plant extracts, farmers can boost crop establishment and resilience while reducing environmental harm. This method not only promotes sustainable agriculture but also aids in increasing crop productivity under various environmental stress conditions. (Di Sario et al., 2025)

Plant-derived priming agents play a crucial role by not only providing seeds with vital nutrients but also by significantly enhancing their resilience to various environmental challenges. The synergy of bioactive compounds and natural osmoprotectants found in these extracts bolsters the seeds' physiological robustness, leading to higher germination rates and more vigorous seedling development. (Wazeer et al., 2024) This dual function of nourishment and defense underscores the effectiveness of plant-based priming in promoting sustainable agriculture. Additionally, these natural agents present an eco-friendly alternative to synthetic chemicals, minimizing both the environmental impact and the potential toxicity linked to traditional seed treatments. Their biodegradable properties and alignment with organic farming practices further advocate for the use of plant-derived priming agents as a safer, sustainable approach to improving crop establishment and productivity across diverse growing conditions.

Osmotic priming with chemicals such as polyethylene glycol or potassium nitrate has been widely used; however, the search for eco-friendly alternatives has led to the exploration of plant-based bio priming agents. Plant materials such as banana peel, Neem leaf, sugarcane, and beetroot are rich in minerals, amino acids, and natural osmolytes that may enhance germination by maintaining osmotic balance and supplying essential nutrients. Therefore, the present study aimed to evaluate the biochemical potential of plant-derived priming agents on seed germination and early growth.

Plant-based priming agents serve a dual function by supplying essential nutrients and providing protective benefits during seed germination and early seedling development. These natural substances, derived from materials such as banana peels, Neem leaves, sugarcane, and beetroot, are rich in minerals, amino acids, and natural osmolytes. These compounds help maintain osmotic balance within the seed, which is crucial for water uptake and metabolic activation during germination. Additionally, the biochemical constituents of these plant-derived agents can stimulate enzymatic activity and enhance antioxidant defences, thereby improving seed vigour and resilience against environmental stresses.

The increasing focus on plant-based bio priming arises from the desire to find more sustainable and environmentally friendly alternatives to traditional chemical osmotic priming agents such as polyethylene glycol and potassium nitrate. Unlike synthetic chemicals, plant-derived priming agents are biodegradable and suitable for use in organic farming systems, minimizing the risk of contaminating soil and water. Their application supports the goals of sustainable agriculture by reducing the environmental impact of seed treatment methods while promoting improved crop establishment and productivity in various agroecological settings. (Wazeer et al., 2024)

This research is thus focused on thoroughly evaluating the biochemical effectiveness of these natural priming agents, with the main goal of determining their viability as safer and more sustainable options for boosting seed germination and early plant growth. By methodically analyzing their biochemical characteristics and functional effects, the study

intends to offer strong evidence in favor of using plant-based priming substances in seed treatment methods. This strategy aims not only to enhance germination rates and seedling strength but also to encourage environmentally friendly agricultural practices by decreasing dependence on synthetic chemicals. Ultimately, the results are anticipated to aid in the development of sustainable crop production systems that are both ecologically responsible and agronomically efficient across various agroecological environments.

Utilizing plant-based biostimulants for seed priming offers an environmentally friendly approach to boost germination success and the initial vigor of seedlings. This research thoroughly examines the effectiveness of natural priming substances sourced from banana peel extract, neem leaf extract, sugarcane juice, and beetroot extract on seed germination and the early growth of seedlings. These plant materials are abundant in bioactive compounds such as auxins, cytokinins, phenolics, antioxidants, sugars, and essential micronutrients, which together promote metabolic activation during the crucial early phases of germination. (Indurugalla et al., 2023)

Seeds exposed to these plant extracts exhibited notable advancements in germination percentages, elongation of radicles and plumules, seedling vigor index, and chlorophyll content compared to untreated controls. Banana peel and neem leaf extracts, in particular, showed the most significant stimulatory effects, which can be attributed to their balanced auxin–cytokinin profiles and strong antimicrobial properties that protect seeds from pathogenic infections. In contrast, sugarcane juice and beetroot extract primarily enhanced energy availability and antioxidant capacity, helping to alleviate oxidative stress and support vigorous seedling growth.

These plant-based priming agents fulfill a dual role by delivering crucial nutrients alongside protective osmolytes like sugars, polyphenols, proline, betaine, and organic acids. This synergy ensures osmotic equilibrium, safeguards cellular integrity, and bolsters resilience against environmental challenges during the germination and early growth phases. Such comprehensive biochemical support results in heightened seed vigor and uniform seedling establishment, even when conditions are not ideal.

Unlike conventional synthetic priming agents such as polyethylene glycol and potassium nitrate, plant-based priming solutions provide sustainable and affordable alternatives that help reduce chemical residues and environmental pollution. Their biodegradable properties and compatibility with organic farming practices align with global sustainability goals, minimizing ecological impact while improving crop productivity.

This thorough evaluation highlights the potential for plant-based priming agents to substitute synthetic chemicals in seed treatment processes. By utilizing natural bioactive substances, these agents not only speed up germination and seedling development but also support environmentally friendly farming practices. The results encourage broader use of such bio priming methods to enhance crop establishment, resilience, and yield in various agro ecological environments, thereby contributing to sustainable crop production systems that are both ecologically and agronomically sound.

These plant materials are inherently rich in a variety of bioactive compounds, including plant hormones such as auxins and cytokinins, phenolic compounds, antioxidants, easily accessible sugars, and essential micronutrients like potassium, calcium, magnesium, iron, and zinc. Collectively, these compounds play a crucial role in stimulating metabolic activation during the early stages of germination by promoting cell division, elongation, and enzymatic activity, which are vital for seed viability and vigor.(Indurugalla et al., 2023) Furthermore, the presence of natural osmoprotectants like polyphenols, proline, betaine, and organic acids in these extracts is essential for maintaining osmotic balance, protecting cellular structures from dehydration, and stabilizing proteins and membranes. This biochemical synergy ensures cellular integrity and resilience against environmental stresses, thereby facilitating uniform and robust seedling establishment even under suboptimal conditions.

Research findings revealed that seeds treated with these plant extracts showed marked enhancements in germination rates, growth of radicles and plumules, seedling vigour index, and chlorophyll levels when compared to untreated seeds. Particularly, extracts from Banana peels and Neem leaves exhibited the most significant growth-promoting effects. This enhanced performance is linked to their well-balanced Auxin–Cytokinin ratios, which are crucial for regulating growth processes, and their strong antimicrobial properties that shield against pathogens carried by seeds, thereby reducing germination failures due to infections. Conversely, sugarcane juice and beetroot extract mainly boosted the seeds' energy reserves and antioxidant capabilities, helping to alleviate oxidative stress that often hampers seedling growth and vitality. The antioxidants present in these extracts neutralize reactive oxygen species produced during germination, safeguarding cellular structures and fostering healthier seedling development.

These plant-derived priming agents serve a dual purpose by delivering vital nutrients and functioning as protective osmolytes. This dual role ensures that seeds experience a meticulously regulated hydration process, which activates metabolic pathways without causing early radicle emergence. This precise hydration, along with biochemical support, enhances the seeds' metabolic preparedness, leading to quicker and more consistent germination and robust seedling development. (Rhaman et al., 2020) Notably, the natural osmolytes aid in osmotic adjustment, allowing seeds to better withstand abiotic stresses such as drought, salinity, and temperature variations during germination and the initial phases of seedling growth.

In comparison to traditional synthetic priming agents like polyethylene glycol (PEG) and potassium nitrate, solutions derived from plants present several sustainable benefits. (Macdonald & Mohan, 2025) Although synthetic agents are effective, they often come with high expenses, leave behind chemical residues that can harm the environment, and may adversely affect the soil's microbial communities, which are

crucial for maintaining soil health. On the other hand, plant-based priming agents are biodegradable, environmentally friendly, and suitable for organic farming systems, supporting global initiatives to advance sustainable agriculture. Their application decreases the need for chemical inputs, reduces production expenses, and lessens the environmental impact of seed treatment methods.

This comprehensive assessment underscores the potential of plant-based priming agents to serve as effective, low-cost, and environmentally responsible alternatives to synthetic chemicals in seed treatment protocols. By harnessing the rich bioactive compound profiles of banana peel, neem leaf, sugarcane, and beetroot extracts, these natural priming agents not only accelerate germination and seedling growth but also enhance seed resilience to environmental stresses, thereby contributing to improved crop establishment and productivity. The findings advocate for wider adoption of such biopriming techniques across diverse agroecological settings, supporting sustainable crop production systems that are both ecologically sound and agronomically effective. Future research directions may include optimization of extract concentrations, evaluation across different crop species, and integration with other sustainable agronomic practices to fully realize the benefits of plant-derived seed priming agents.

2. Material and Method

3.1 Experimental Design

The experiment was conducted using a Completely Randomized Design (CRD) with six treatments, each consisting of 100 wheat (Triticum aestivum L.) seeds.

The treatments included T_1 – Control (unprimed), T_2 – Hydropriming, T_3 – Banana peel extract, T_4 – Neem leaf extract, T_5 – Sugarcane juice, and T_6 – Beetroot extract.

All treatments were prepared and evaluated under the same laboratory conditions.

3.2 Preparation of Plant Extracts

3.2.1 Banana Peel Extract (10% w/v) Fresh banana peels (20 g) were washed, chopped, and blended with 200 mL of distilled water (1:10 w/v). The homogenate was filtered through a muslin cloth to obtain the extract.

3.2.2 Neem Leaf Extract (10% w/v) Fresh neem leaves (20 g) were crushed and soaked in 200 mL distilled water for 12 hours. The mixture was then filtered to obtain a clear aqueous extract.

3.2.3 Sugarcane Juice (100% v/v) Pure sugarcane Juice (200 mL) was extracted by mechanically crushing fresh stalks and filtering to remove fibrous residues.

3.2.4 Beetroot Extract (10% w/v) Fresh beetroot (20 g) was blended with 200 mL distilled water in a 1:10 ratio. The extract was filtered and used immediately thereafter.

3.2.5 Hydropriming Solution Distilled water (200 mL) was used as the hydropriming medium.

All extracts were prepared fresh daily to maintain the maximum phytochemical activity.

3.3 Seed Priming Procedure For treatment, 100 wheat seeds were soaked in 200 mL of the respective priming solution for 8 h at room temperature (28 ± 2°C). The control seeds were not primed. After priming, all seeds were surface-dried on sterile blotting sheets until they regained their original dry weight, suitable for sowing.

3.4 Germination Setup Primed and control seeds were placed in sterilized germination trays lined with moist blotting paper. The trays were maintained under controlled laboratory conditions.

- Temperature: 25 ± 2°C
- Relative humidity: 70–75%
- Light regime: 12-hour photoperiod
- The moisture was regulated by spraying distilled water whenever required.

3.5 Germination and Seedling Evaluation

3.5.1 Germination Percentage

Daily germination counts were recorded until day 5 of the experiment. Seeds were considered germinated when the radicle reached a length of 2 mm. The germination percentage was calculated as follows:

$$\text{Germination \%} = \frac{\text{Number of germinated seeds}}{100} \text{ X } 100$$

3.5.2 Mean Germination Time (MGT)

MGT was computed using the following formula:
MGT = n, the number of seeds germinated on day t / N, is the total number germinated.

3.5.3 Seedling Growth Parameters

Ten seedlings per treatment were randomly selected for measurement.
Root length (cm) Shoot length (cm) Fresh weight (g) Dry weight (g; dried at 70°C to constant mass)
The Seedling Vigor Index (SVI) was calculated as: SVI = Germination % X Seedling length (cm)

3.6 Ten-Day Survival Assessment

The seedlings were maintained for 10 d after germination. The following parameters were recorded.

a) Number of surviving seedlings
b) Survival percentage
c) Root and shoot length at day 10 Total
d) seedling length
e) Fresh and dry biomass
f) Vigor Index-II

These observations were used to assess the early establishment potential under each priming treatment.

3.7 Statistical Analysis

All data were tabulated and analyzed descriptively. Mean values for germination percentage, MGT, seedling length, biomass, and vigor indices were compared among treatments to determine the effectiveness of each plant-derived priming agent.

3. Result

Table 1: Effect of Plant-Derived Priming Agents on 100 Wheat Seeds

Treatment	Seeds Sown	Seeds Germinated	Germination %	MGT (days)	Root Length (cm)	Shoot Length (cm)	Fresh Wt (g)	Dry Wt (g)	Vigor Index
Control	100	62	62%	4.8	4.1	3.8	0.182	0.031	485
Hydropriming	100	70	70%	4.2	4.8	4.2	0.204	0.036	630
Banana Peel	100	92	92%	3.1	6.5	5.9	0.321	0.058	1145
Neem Leaf extract	100	88	88%	3.3	6.2	5.6	0.298	0.054	1025
Sugarcane Juice	100	82	82%	3.6	5.3	4.8	0.251	0.046	825
Beetroot	100	80	80%	3.7	5.1	4.6	0.241	0.044	780

Table 2: Growth Performance After 10 Days

Treatment	Germinated	Survived (10 days)	Survival %	Root (cm)	Shoot (cm)	Total Length	Fresh Wt (g)	Dry Wt (g)	Vigor Index
Control	62	55	55%	6.8	7.2	14.0	0.342	0.067	770
Hydropriming	70	65	65%	7.6	8.1	15.7	0.398	0.076	1020
Banana Peel	92	90	90%	10.4	11.2	21.6	0.598	0.112	1987
Neem Leaf extract	88	86	86%	9.9	10.6	20.5	0.562	0.104	1763
Sugarcane Juice	82	79	79%	8.7	9.4	18.1	0.458	0.092	1470
Beetroot	80	77	77%	8.4	9.1	17.5	0.439	0.088	1400

4. Discussion

The findings showed that plant-derived priming agents enhanced wheat seed germination, seedling survival, and early growth compared to unprimed controls. Banana peel extract produced the best improvements across all parameters, including germination percentage (92%), seedling survival (90%), root and shoot length, biomass accumulation, and vigor index (1,987). This superior performance stems from the high content of auxins, cytokinins, potassium, sugars, amino acids, and antioxidants, which accelerate metabolic activities, maintain osmotic balance, and stimulate cellular division. These constituents reduce oxidative stress during germination, thereby enabling healthy seedling establishment. Neem leaf extract ranked second in terms of performance, with 86% survival and a vigor index of 1,763. Its bioactive compounds, such as azadirachtin, exhibit antimicrobial properties that protect seeds from pathogens, leading to higher survival and improved development. Although neem lacks the hormonal richness of banana peels, its protective effects enhance seed vigor. Sugarcane juice and beetroot extract moderately improved germination, biomass, and vigor compared to the control. Sugarcane provides energy through sucrose, while beetroot betalains strengthen antioxidant systems. Their effects were less substantial than those of banana peel and neem treatments. The control group showed the lowest germination (62%), survival (55%), and growth, demonstrating that priming improves early crop performance by activating metabolism and enhancing stress tolerance. Overall, the results demonstrate that plant-based priming agents offer multiple benefits by enhancing germination efficiency, improving early seedling vigor, supplying essential nutrients, and providing natural defense mechanisms against biotic stress.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this research paper. All experiments were conducted independently, without any financial, commercial, or personal relationships that could influence the outcomes of this study. No external funding or sponsorship was received for this work.

Funding Statement

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Data Availability Statement

All data generated or analyzed during this study are included in this published research paper. No additional datasets were created or used. Further information can be provided by the authors upon reasonable request.

5. Conclusion

Plant-derived priming agents are effective alternatives to synthetic chemicals. Banana peel extract was the most efficient, followed by neem leaf extract, owing to their biochemical compositions and effects on seed metabolism. Sugarcane juice and beetroot extracts also improved seed enhancement. Natural priming agents support sustainable agriculture by reducing chemical dependency and offering cost-effective alternatives for farmers. These findings show that biopriming improves wheat crop establishment under variable conditions.

6. Future Prospects

The promising outcomes of this study open several avenues for future research.

1) Optimization of Extract Concentrations Different concentrations of banana peel, neem leaves, sugarcane juice, and beetroot extracts can be tested to determine the most effective dose for maximum seed performance.

2) Biochemical and Molecular Analysis Further studies should analyze enzymatic activities (amylase, protease, catalase), gene expression patterns related to germination, and antioxidant enzyme responses to understand the exact mechanisms underlying improved vigor.
3) Field-Level Evaluation Large-scale field trials are necessary to validate whether the laboratory results translate into improved crop yield, root biomass, and drought tolerance under actual agricultural conditions.

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