Fruit waste-derived extracts as natural biostimulants for seed priming in maize and common beans

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Research Article

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Abstract

Seed germination and early seedling vigor are critical for successful crop establishment, especially in stress-prone, resource-limited agroecosystems. This study evaluated aqueous extracts from overripe/spoiled papaya (*Carica papaya*), banana (*Musa spp.*), lemon (*Citrus limon*), and pineapple (*Ananas comosus*) fruits as natural seed priming agents for maize (Zea mays L.) and common bean (*Phaseolus vulgaris L.*). Certified seeds were primed for 4–6 h with 1:4 (v/v) diluted extracts and compared with distilled water (control) under laboratory conditions (25 ± 2°C). Papaya and banana extract significantly outperformed other treatments, increasing final germination percentage to 90–94% in maize and bean (vs. 74–76% in controls) and markedly reducing mean germination time. Banana-primed maize seedlings exhibited the longest shoots (14.1 cm) and roots (7.9 cm), whereas papaya-primed bean seedlings reached 13.4 cm and 8.2 cm, respectively. All vigor indices followed the same trend (papaya ≈ banana > pineapple > lemon > control). These low-cost, waste-derived biostimulants therefore represent a sustainable alternative to synthetic priming agents and are particularly suitable for smallholder farming systems in semi-arid regions.

1. Introduction

Seed germination and early seedling vigor are pivotal for uniform crop establishment and final yield, particularly in rainfed, semi-arid agroecosystems where erratic rainfall and high evapotranspiration frequently compromise stand density[1–3]. In staple crops such as maize (*Zea mays*) and common beans (*Phaseolus vulgaris*), delayed or uneven germination often results in patchy crop stands, reduced resource-use efficiency, and increased susceptibility to biotic and abiotic stresses. On average, maize seeds take 5–7 days[4] to achieve 50% germination under optimal conditions, while beans require approximately 4–6 days [5, 6]. However, in challenging agroecological zones where temperatures fluctuate and soil moisture is often limited, these durations can extend significantly. This delays critically affects seedling emergence and compromises overall field performance.

Seed priming is a proven, low-cost technique that triggers early metabolic events, resulting in faster, more synchronous germination and enhanced seedling vigor[7–9]. Conventional priming techniques often involve the use of synthetic chemicals [10–14], plant extracts[12, 15, 16], or osmotic agents[7, 17, 18]. These techniques are effective but are frequently inaccessible or unaffordable for farmers in low-input systems[19–21]. Moreover, concerns about the environmental persistence and toxicity of some synthetic compounds[22–24] have led to increasing interest in sustainable alternatives.

Overripe or spoiled fruits are rich in phytohormones (gibberellins, auxins, cytokinins), organic acids, vitamins, and proteolytic enzymes (papain, bromelain, amylase) that can stimulate seed metabolism and radicle emergence[25, 26]. Despite this potential, very few studies have systematically explored fruit waste-derived fruit extracts as seed priming agents, and none have compared papaya, banana, lemon, and pineapple extracts on both maize and common bean two cornerstone crops of East African farming systems.

This study is the first to evaluate aqueous extracts from market-discarded overripe papaya (Carica papaya), banana (*Musa spp.*), lemon (*Citrus limon*), and pineapple (*Ananas comosus*) as natural, zero-cost seed priming agents under controlled conditions representative of the semi-arid Dodoma region, Tanzania. The specific objectives were to (i) quantify the effects of these fruit waste extracts on germination percentage, mean germination time, and early seedling vigor of maize and common bean, (ii) identify the most effective fruit sources, and (iii) assess their potential as sustainable alternatives to synthetic priming agents for smallholder farmers.

2. Materials and Methods

2.1 Plant Material

Certified seeds of maize (Zea mays L.) and common bean (Phaseolus vulgaris L.) were obtained from Seed Co Tanzania Limited, a registered agricultural trading company that supplies high-quality field crop and vegetable seeds to farmers in the Manyara, Singida, and Dodoma regions. The seeds were commercially produced cultivars selected for their adaptability to semi-arid conditions in Dodoma, Tanzania, ensuring genetic purity, high viability, and freedom from pests and diseases. No plant material was collected from wild populations or natural habitats

2.2 Fruit Extract Preparation and Seed Priming

Overripe or spoiled fruits of papaya (*Carica papaya*), banana (*Musa spp.*), lemon (*Citrus limon*), and pineapple (*Ananas comosus*) no longer suitable for human consumption were collected from local markets in Dodoma, Tanzania. Fruits were thoroughly washed with clean water, peeled, and blended into a fine pulp. The pulp was filtered through muslin cloth to obtain the aqueous extract, which was then diluted with distilled water at a 1:4 (v/v) ratio. Fresh extracts were prepared on the day of use to preserve bioactive compound integrity. Extract quality was characterized prior to priming: pH ranged from 4.2 (lemon) to 5.7 (banana), and total soluble solids (TSS), measured with a digital refractometer, ranged from 4.6 °Brix (papaya) to 7.0 °Brix (banana). Papaya and pineapple extracts exhibited notable proteolytic enzyme activity (papain and bromelain, respectively), assessed qualitatively.

Certified maize and common bean seeds were primed by soaking in the respective diluted extracts or in distilled water (control). Priming duration was 6 h for maize and 4 h for common bean, based on species-specific seed coat permeability and water absorption kinetics. Soaking was conducted at room temperature (~ 25°C). After priming, seeds were gently blotted and air-dried under shade until they regained their original moisture content (~ 12%), preventing premature germination while allowing safe handling and short-term storage.

2.3 Germination Test

To evaluate the effects of spoiled fruit-based seed priming on germination performance, seeds (*n = 50 per treatment*) were uniformly placed in sterilized 9-cm Petri dishes lined with double layers of moistened *Whatman No. 1* filter paper. Each dish represented an independent replicate and was kept under controlled laboratory conditions at a constant temperature of 25 ± 2° C to ensure uniform germination stimuli across all treatments. Filter papers were regularly moistened with distilled water to maintain optimal hydration levels without waterlogging. Germination was monitored daily for a period of 7 days, with a seed considered germinated upon visible radicle protrusion of at least 2 mm. This duration captured both early and delayed germinative responses, allowing assessment of germination kinetics such as mean germination time, germination percentage, and synchronization index. This standardized setup ensured reproducibility, minimized environmental variability, and provided robust data for comparative evaluation of biostimulant efficacy across treatments.

2.4 Data Collected

To comprehensively assess the physiological impact of fruit-based seed priming, key germination and early growth parameters were quantified. Germination Percentage (GP) provided a direct measure of seed viability, while Mean Germination Time (MGT) captured the speed and uniformity of germination critical indicators for rapid stand establishment. Root and shoot lengths served as proxies for ESV and developmental potential under controlled conditions. The Seedling Vigor Index (SVI), integrating germination capacity with growth performance, offered a robust indicator of seedling fitness. These indices are widely recognized for their predictive value in determining field emergence, resilience to early-season stressors, and overall agronomic performance, particularly in challenging environments such as the semi-arid zones. Their inclusion was essential for drawing evidence-based conclusions on the practical efficacy of fruit-derived biostimulants as a sustainable, low-cost seed enhancement strategy. Figure 1 schematically represent the experimental methodology, depicting the preparation of aqueous extracts from overripe fruit waste and the subsequent seed priming procedure for maize and common bean.

2.6 Statistical Analysis

Data collected from germination and seedling growth assays were subjected to statistical analysis to determine the significance of differences among treatments. One-way Analysis of Variance (ANOVA) was employed to evaluate the effects of different fruit-based priming treatments on GP, MGT, root and shoot lengths, and SVI. Where significant differences were detected, means were separated using Tukey’s Honest Significant Difference (HSD) test at a 5% probability level. This statistical approach was selected for its robustness in comparing multiple treatment means while controlling for type I error. The use of ANOVA enabled the identification of treatments that significantly enhanced seed performance parameters, while Tukey’s test clarified the relative effectiveness of each fruit extract.

3. Results and Discussion

This section presents the effects of fruit-derived seed priming on germination and early seedling development in maize (*Zea mays L.*) and common bean (*Phaseolus vulgaris L.*). Key physiological parameters: final GP, MGT, shoot length, root length, and seedling vigor index (SVI) were evaluated to assess treatment performance. All data were subjected to one-way ANOVA followed by Tukey's HSD test

($p < 0.05$) to identify significant differences between treatments and the distilled water control. Figure 2 and Table 1 summarize the primary germination and seedling vigor parameters across treatments.

Table 1
Seedling Vigor Parameters: Mean Root and Shoot Lengths and SVI

Treatment	**Maize shoot(cm)**	**Maize root (cm)**	**Maize SVI**	**Beans shoot(cm)**	**Beans root (cm)**	**Beans SVI**
Control^{H2O}	10.3 ± 0.5	5.3 ± 0.1	1201	9.7 ± 0.3	5.0 ± 0.1	1191
Control $_{PEG}$	13.1 ± 0.4	7.0 ± 0.1	1648	12.7 ± 0.2	7.2 ± 0.1	1652
Papaya	13.6 ± 0.2	7.2 ± 0.2	1872	13.4 ± 0.2	8.2 ± 0.2	2030
Banana	14.1 ± 0.6	7.9 ± 0.1	2024	12.9 ± 0.1	7.6 ± 0.3	1907
Pineapple	11.3 ± 0.7	6.0 ± 0.1	1505	11.1 ± 0.1	6.2 ± 0.1	1557
Lemon	10.6 ± 0.1	5.6 ± 0.1	1312	10.5 ± 0.2	5.6 ± 0.1	1352

3.1 Germination Percentage and Mean Germination Time

Fruit-derived seed priming markedly influenced germination dynamics in both maize and common bean. Papaya and banana extracts yielded the highest final germination percentages: 90% for maize and 92–94% for common bean compared with 74% and 76% in the respective controls (Table 1; Fig. 2). These differences were statistically significant ($p < 0.05$; one-way ANOVA followed by Tukey's HSD test), confirming the robustness of the observed effects.

The substantial improvements can be attributed to the rich biochemical composition of the extracts. Papaya is abundant in gibberellins and the proteolytic enzyme papain [27–29], while banana extracts contain elevated levels of auxins and cytokinins phytohormones[30, 31] renowned for stimulating early metabolic reactivation in seeds[32, 33]. These compounds likely accelerated water imbibition, activated hydrolytic enzymes, and mobilized reserve nutrients, leading to faster radicle protrusion. This is reflected in the pronounced reductions in MGT: papaya-primed common bean seeds emerged in 2.2 days (versus 5.7 days in controls), whereas papaya- and banana-primed maize seeds required only 2.7–2.9 days (versus 5.3 days), representing 48–61% shorter MGT. (Fig. 3).

These findings align with previous studies on natural biostimulants yet underscore the unique advantages of overripe fruit waste. For example, [34]reported comparable MGT reductions and elevated germination indices in hybrid maize primed with moringa (*Moringa oleifera*) leaf extract, owing to its high zeatin, mineral, and antioxidant content. The present fruit extracts achieved similar kinetic accelerations using discarded market produce rather than cultivated leaves, thereby enhancing sustainability and providing zero-cost accessibility for resource-constrained farmers.

In common bean[35], reported that crude aqueous papaya extracts (at low concentrations) enhanced germination percentages (> 90%) and reduced mean emergence time in the presence of fungal pathogens (*Colletotrichum lindemuthianum*), outperforming controls under biotic stress. The present findings extend this to non-stressed laboratory conditions, with papaya and banana extracts yielding 92–94% germination marginally superior to the pathogen-challenged scenarios while utilizing overripe pulp waste, which is richer in accumulated phytohormones and enzymes due to advanced ripening[36]. This contrast underscores the robustness of fruit-derived biostimulants across abiotic and biotic constraints. Broader literature reinforces these trends: phytohormone-rich natural extracts consistently mimic endogenous signals to promote rapid, synchronous germination[37]. However, the magnitude of MGT reduction and germination percentage gains observed here rivals or exceeds those from moringa- or garlic-based priming, without requiring dedicated crop cultivation for extract production.

From an agronomic standpoint, such rapid and uniform emergence is particularly salient in semi-arid agroecosystems, where fleeting rainfall events demand swift crop establishment to mitigate risks of desiccation, soil crusting, and early-season stressors. By valorizing fruit waste into effective priming agents, this approach not only enhances physiological performance but also aligns with circular economy principles, providing smallholder farmers in regions like Dodoma with a scalable, eco-friendly alternative to synthetic treatments.

3.2 Seedling Growth Parameters

Significant improvements in seedling vigor parameters were observed following fruit-based priming, with pronounced enhancements in both shoot and root elongation. Maize seeds primed with banana extract exhibited the highest shoot length, averaging 14.1 cm, and root length of 7.9 cm. Similarly, common bean seeds treated with papaya extract achieved superior seedling growth, with mean shoot and root lengths of 13.4 cm and 8.2 cm, respectively. These results indicate stronger early seedling development, which supports better field performance, particularly in resource-constrained and stress-prone environments. The observed trends can be attributed to the bioactive constituents present in banana and papaya extracts, including auxins, cytokinins, gibberellins, and proteolytic enzymes such as papain. These phytohormones and enzymes are known to regulate cell elongation, division, and nutrient mobilization during early seedling development. Auxins, in particular, have been implicated in promoting root initiation and elongation by enhancing the expression of cell wall-loosening enzymes such as expansions[38, 39]. Gibberellins, on the other hand, stimulate shoot elongation by facilitating the degradation of DELLA proteins, thereby promoting growth-related gene expression.

These findings are consistent with those of Iqbal[40] and Tounkti[41] who demonstrated that biostimulant seed priming significantly improved root and shoot growth under both optimal and stress conditions. The enhanced seedling growth reported in this study further supports the assertion that plant-derived priming agents not only accelerate germination but also improve post-germinative development through improved physiological and biochemical activation. From a practical standpoint, increased shoot and root lengths confer a competitive advantage to seedlings by enhancing early nutrient and water uptake, canopy establishment, and resistance to early-season abiotic stress.

3.3 Comparative Efficacy of Fruit Extracts

Among the tested biostimulants, papaya and banana extract consistently outperformed the others across all germination and seedling vigor parameters in both maize and common bean (Tables 1; Figs. 2, 3 and 4). This superiority is likely due to the synergistic effects of their abundant phytohormones: gibberellins, auxins, and cytokinins combined with enzymatic constituents such as papain in papaya and amylase-rich compounds in banana. These bioactive molecules are well-established for promoting cell elongation, enhancing nutrient mobilization from reserves, and accelerating key physiological processes during seedling establishment.

Consequently, seedlings primed with papaya or banana extracts displayed markedly greater shoot and root elongation, higher seedling vigor indices, and shorter mean germination times attributes that collectively favor rapid and uniform stand establishment under field conditions[42]. Pineapple extract exhibited moderate efficacy, presumably owing to bromelain, a proteolytic enzyme that supports protein metabolism in early growth stages. Although it did not match papaya or banana, its consistent superiority over the control indicates potential for further improvement through concentration optimization or blending with other extracts. In contrast, lemon extract effectively reduced mean germination time but provided only marginal gains in seedling vigor. This limited response may stem from its high acidity (pH 4.2)[43] and elevated citric acid content, which at the tested dilution could have exerted mild osmotic stress or interfered with membrane permeability and enzymatic function. These results highlight the critical need for precise calibration of priming parameters, particularly extract concentration and soaking duration, to maximize benefits while avoiding phytotoxic effects.

3.4 Limitations and Future Outlook

Although the present study provides robust evidence for the efficacy of overripe fruit-derived extracts as seed priming agents, several limitations warrant acknowledgment. The experiments were conducted under controlled laboratory conditions (25 ± 2°C, optimal moisture), which may not fully capture the variability of field environments in semi-arid regions, such as fluctuating temperatures, soil heterogeneity, or biotic stresses (pests, pathogens). Additionally, only one dilution ratio (1:4 v/v) was tested, potentially overlooking optimal concentrations for each fruit extract. The biochemical characterization of extracts was limited to pH, total soluble solids, and qualitative enzyme activity, without quantitative profiling of phytohormones (e.g., gibberellins, auxins) or other metabolites that could elucidate precise mechanisms. Finally, long-term effects on yield, nutrient uptake, or stress tolerance were not assessed, restricting inferences to early establishment phases.

Despite these constraints, the findings open promising avenues for sustainable agriculture. Future research should prioritize multi-location field trials across diverse agroecological zones to validate performance under real-world conditions, including drought, salinity, or nutrient-deficient soils. Dose-response studies and combinatorial priming (e.g., papaya + banana extracts) could refine formulations for maximal efficacy. Advanced metabolomics and transcriptomics would uncover molecular mechanisms, such as gene expression changes during imbibition. Scale-up investigations focusing on extract stability, storage, and farmer-led production would facilitate adoption in circular economy models, repurposing fruit waste at community levels. Integration with other biostimulants (e.g., seaweed or microbial inoculants) and evaluation of economic impacts (cost-benefit analysis for smallholders) are also essential. Figure 5 presents a proposed research roadmap for advancing fruit waste-derived biostimulants, outlining short-, medium-, and long-term priorities toward commercialization and widespread adoption in climate-resilient cropping systems.

4. Conclusion

This study provides compelling evidence that fruit-derived biostimulants particularly papaya and banana extracts can serve as effective, eco-friendly seed priming agents capable of significantly enhancing germination performance and ESV in two important staple crops: maize and common bean. Compared to untreated controls, seeds primed with these natural extracts exhibited markedly higher GP, reduced MGT, and enhanced seedling growth parameters, including root and shoot lengths and SVI. These improvements directly enhance crop establishment which directly influences yield potential and resilience to early-season abiotic stress particularly in semi-arid environments, where delayed emergence can severely impact productivity due to erratic rainfall and high evapotranspiration rates. The efficacy of papaya and banana extracts is likely attributed to their rich composition of phytohormones and micronutrients that act synergistically to stimulate metabolic processes during germination and early growth. These results align with emerging literature supporting the use of botanical biostimulants as viable alternatives to synthetic agrochemicals, particularly within the context of climate-resilient and resource-efficient agriculture. The practical significance of these findings is substantial. Fruit waste, especially from overripe or spoiled produce not suitable for human consumption, can be repurposed into value-added agricultural inputs, thus contributing to circular bioeconomy models. Moreover, the accessibility and affordability of these materials offer immediate benefits to smallholder farmers who may lack access to commercial priming products or modern seed enhancement technologies.

However, while the laboratory-scale results are promising, further research is warranted to validate these outcomes under field conditions. Future studies should focus on optimizing extract concentrations, evaluating synergistic effects of combined fruit treatments, and assessing the long-term agronomic impacts on yield and stress tolerance. In addition, exploration of the biochemical mechanisms underlying the observed responses could provide crucial insights for developing standardized formulations.

In conclusion, this research contributes to the growing body of knowledge advocating for sustainable seed enhancement strategies. By demonstrating the potential of locally sourced, fruit-based biostimulants to improve seed performance, it opens new avenues for integrating low-cost, environmentally sound practices into mainstream crop production systems, particularly in vulnerable agroecosystems.

Declarations

Author Contribution

Gerald Enos Shija conceptualized and designed the study, conducted the experiments, collected and analyzed the data, and wrote the manuscript.

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Code availability Not applicable.

Data availability: The datasets generated are all published and raw data generated during the current study are available from the corresponding author on reasonable request.

Clinical trial: Not done.

Conflict of interest: The author declare that they have no competing interests.

Ethics: The plant material used in this study consisted of commercially certified seeds of maize (*Zea mays L*.) and common bean (*Phaseolus vulgaris L*.) purchased from a registered seed supplier (Seed Co Tanzania Limited). As the seeds were cultivated commercial material and not collected from wild or natural habitats, no specific permissions or licenses were required. The study complied with relevant institutional, national, and international guidelines and legislation.

Consent to Participate: Not applicable

Consent to Publish: Not applicable

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Figures

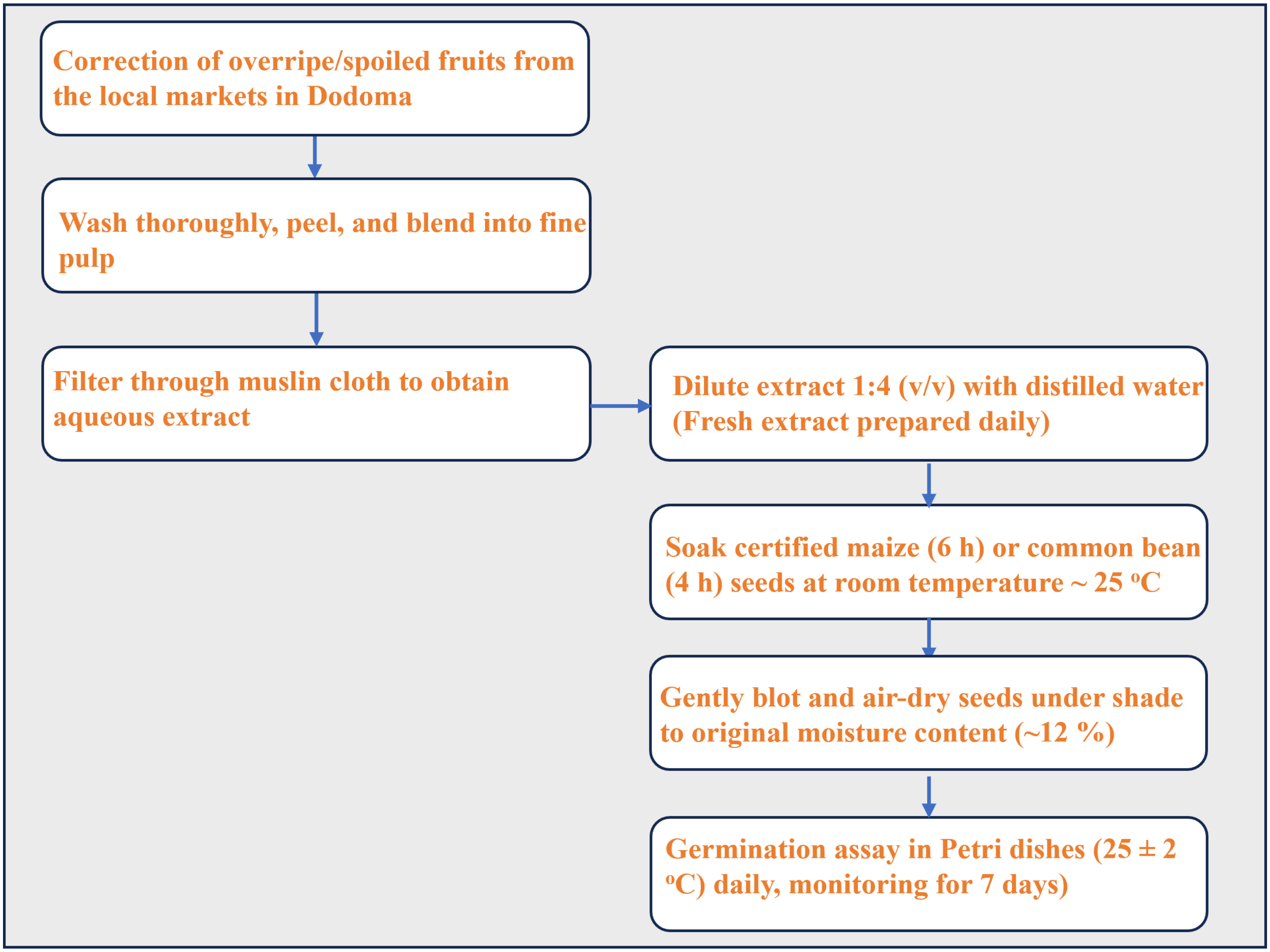

Figure 1

Schematic illustration of the seed priming process using fruit waste extracts

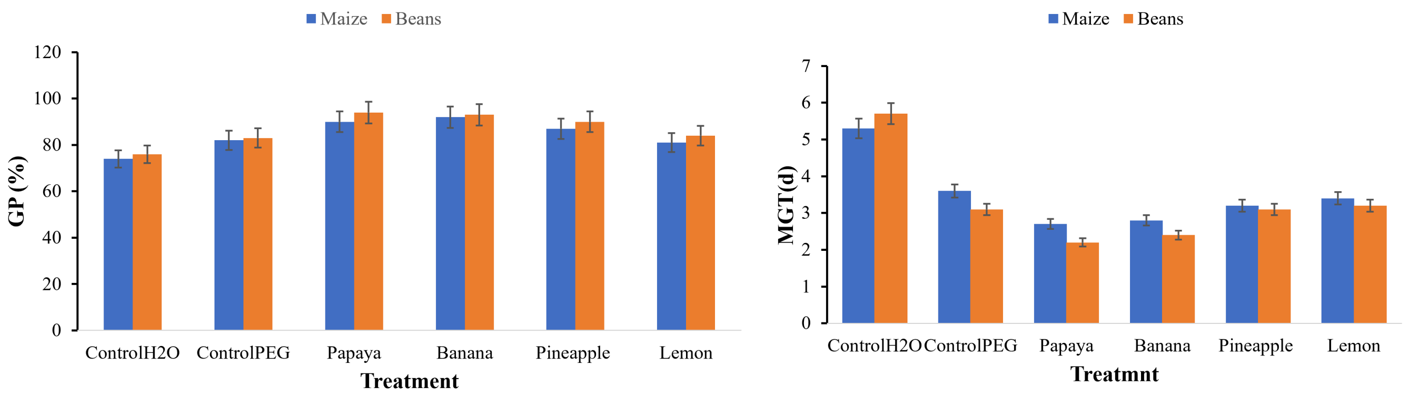

Figure 2

Germination and Seedling Growth Parameters of Maize and Common Bean as Influenced by Fruit-Based Seed Priming Treatments

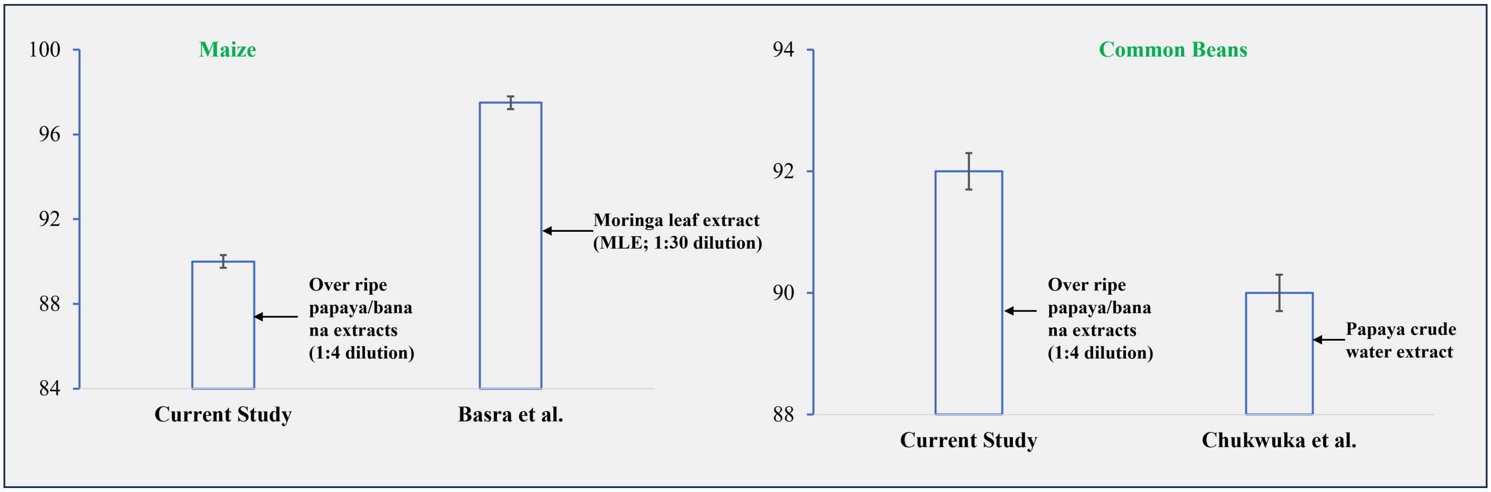

Figure 3

Comparative effects on germination percentage and mean germination time across the current fruit extract treatments and selected benchmarks from literature highlighting the competitive efficacy of overripe fruit-derived biostimulants.

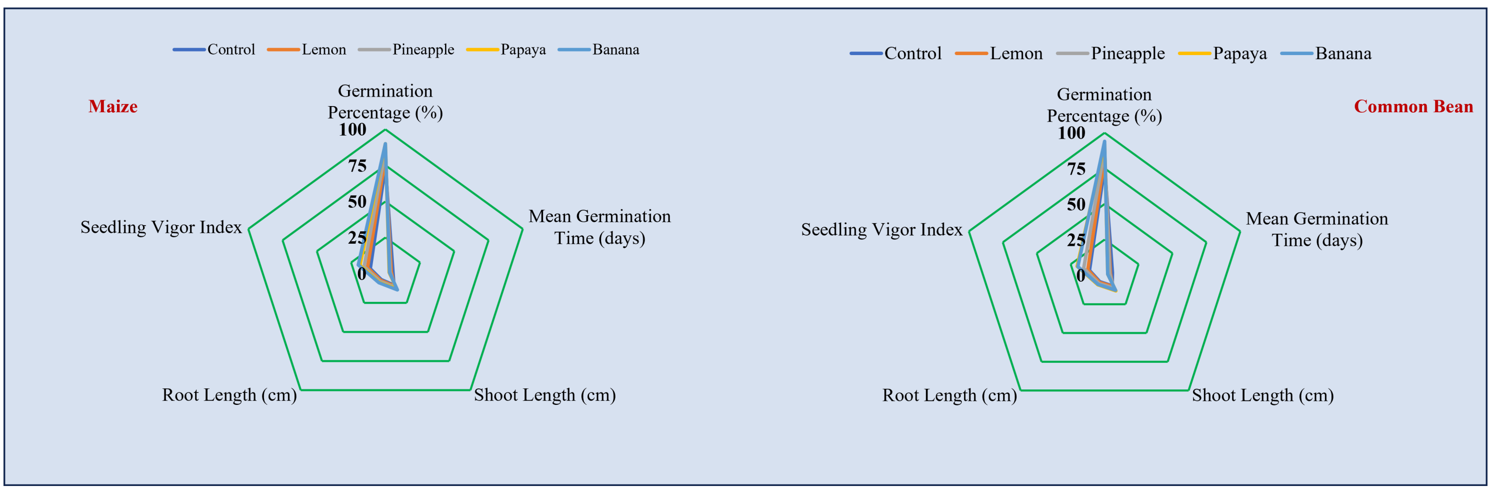

Figure 4

Radar chart illustrating the relative performance (normalized to the highest value) of fruit-derived priming agents versus control across five key parameters in maize and common bean

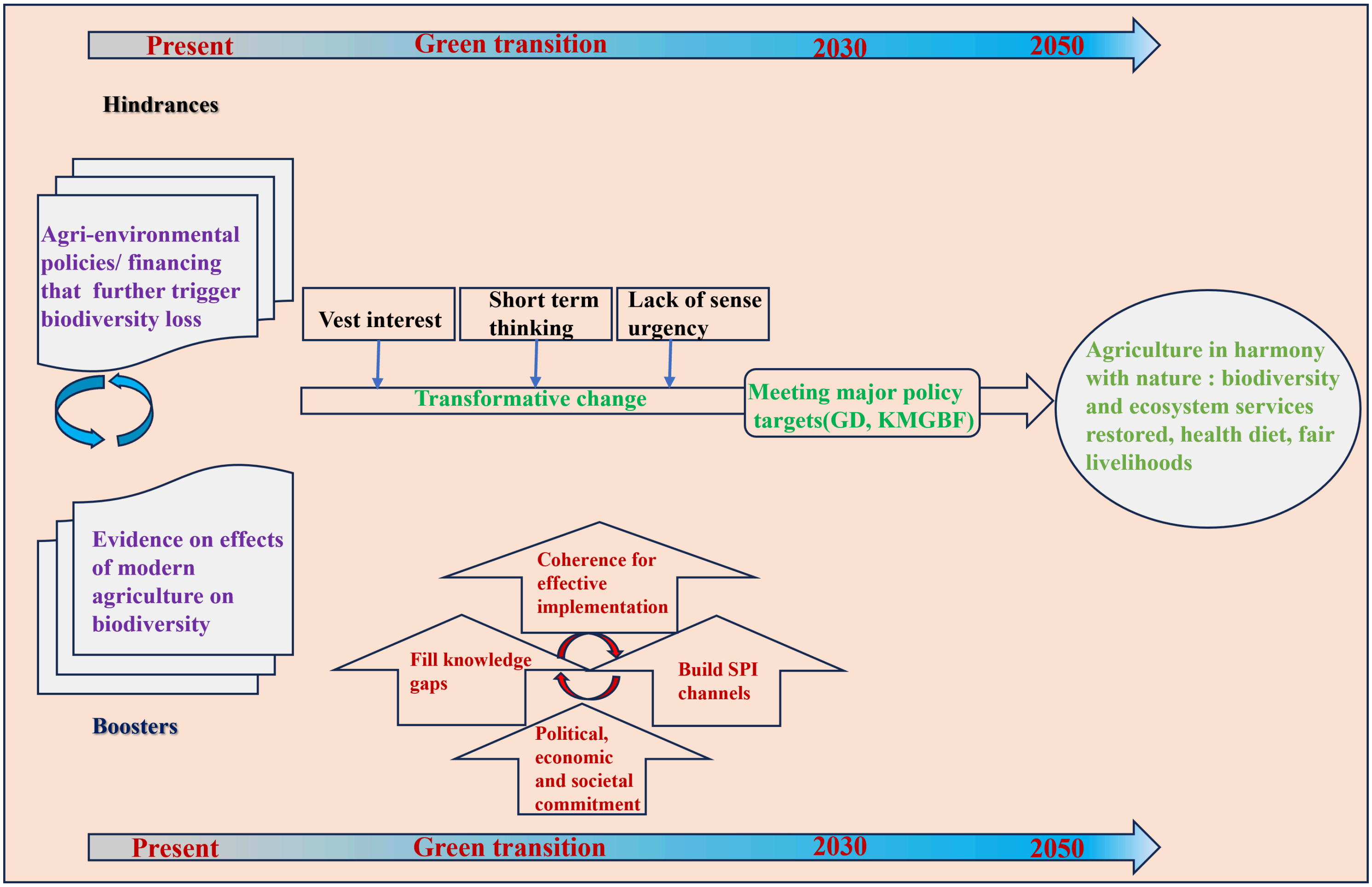

Figure 5

Proposed research roadmap for fruit waste-derived biostimulants in seed priming: from laboratory validation to field application and circular economy integration