



Biopotential Of Compost Derived From Fruit Juice Waste As Soil Conditioner And Growth Promoter In Mung Bean Grown In Alkaline Soils.

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Abstract: The large volume of fruit wastes is presently a challenge for waste operation. The phytotoxicity of declination products of fruit and vegetable waste poses a significant environmental issue that restricts its use. The present study focuses on the microbial declination of juice waste to prepare compost which can be used as soil modifier for alkaline soils and study its impact on the growth parameters of mung bean (*Vigna radiata* L.). The salient finding. The physicochemical properties of the prepared compost were as follows: temperature at $37.07 \pm 0.26^\circ\text{C}$, pH at 7.89 ± 0.35 , organic carbon content at $22.24 \pm 1.56\%$, nitrogen content at $0.808 \pm 0.028\%$, and a C:N ratio of 26.92 ± 2.27 . The effects of compost and bacterial filtrates on seed germination and early plant development were evaluated using *Vigna radiata* in alkaline soil conditions. The results indicated significant improvements in seed length (1.35 ± 0.22 cm), root length (25.71 ± 2.80 cm), plant height (10.71 ± 1.82 cm), and leaf count (6.00 ± 1.00). These outcomes highlight the potential of microbial-enriched fruit waste compost to accelerate decomposition and enhance its effectiveness as a soil conditioner in alkaline soils, thereby improving soil fertility and promoting better crop growth.

Index Terms – Compost, mung dal , fruit waste

I. INTRODUCTION

Since the dawn of time, fruits have been eaten in their natural state or after being reused. At present, the demand for fruits and vegetables has risen for colorful reasons, similar as the expanding population and individualities concluding for healthier food options (1). Out of all the fruits produced, nearly 50 of the crops are reused into juice, the remainder consists of seed, skin, or fruit pulp that's discarded in the process (2) and specifically from citrus juice product, 25 million tons of waste are generated each time. These derivations, representing 20 – 80 of the entire fruit, hold significant significance for environmental factors; nonetheless, the growing focus on their valorization has surfaced in arising exploration fields (3). The large volume of fruit wastes is presently a challenge for waste operation (4). The consumption of fruits generates two orders of waste solid waste, which includes peels, skins, seeds, and monuments, and liquid waste, comprising juice and marshland water (5). These wastes are constantly handled deficiently due to defined access to disposal spots. The childhood of these wastes is astronomically conceded as a significant issue in their composting process and the after use of the compost in land operations (6). To help this, waste can be reused or subordinated to physical, chemical, natural, thermal, or mixed treatments, including options similar as feeding creatures, grinding, composting, anaerobic digestion, and vermicomposting (7). The composting process signifies the regulated breakdown of biodegradable waste through the action of microorganisms (8). The primary benefit of composting lies in the reclamation of nutrients and carbon prisoner through the creation of humic substances. Indispensable technologies (which offer lesser added value for new products) are being pursued to apply the principles of the indirect frugality (9). When dealing with waste generated from fruit libation product, the waste consists of a compositionally different mix, primarily featuring a significant quantum of waste from citrus fruits , making straightforward technological results unfeasible (10). Zema *et al.*(2018). reported their negative impacts on soil microorganisms and, in certain cases, implicit detriment to submarine

ecosystems. The composting of waste generated from citrus fruit processing is complicated by a low pH position, high humidity content, the presence of antimicrobial factors in essential canvases and fungicide remainders (11). Citrus derivations are generally composted alongside other lignocellulosic agrarian and beast wastes (12). Introductory chemicals are constantly added to guarantee pH value adaptation and avoid unwanted turmoil. In connection with meeting the demands for using biodegradable waste, there's a rise in fiscal costs that are not neutralized because of the comparatively low request price (13). Another issue involves possible hazards from the use of composts made from FW, which may arise from ecotoxicity, saltiness, fungicide presence, and colorful other rudiments (14). The phytotoxicity of compost deduced from fruit and vegetable waste poses a significant environmental issue that restricts its use (15). The movement of organic substances into the water phase is told by solubility, opposition, the presence of fresh organic substances, competitive and inhibitory processes among composites, as well as relations involving the factory root system, compost, and microorganisms (16). To overcome these challenges the present study was planned to screen different microbial societies for their declination eventuality in composting juice waste and assessing the compost for their factory growth promoting eventuality in mung bean growth parameters (17).

2. RESEARCH METHODOLOGY

2.1 Description of the Study Area

The trial was carried out and finalized at MIET, Meerut. It's geographically located at 28° 54' 29'' N latitude and 77° 78' 00'' E longitudes, with an altitude of 224.6 m. The study point has an periodic downfall of 586 mm. 1. During the summer, temperatures can soar beyond 45°C, while cooler periods bring a refreshing drop to as low as 20°C. This seasonal variation plays a significant role in shaping the environment of Meerut and cash crops as well as food grains analogous as wheat, bajra, barley, potato, and beats. A number of sugar industriousness are deposited also owing to the fact that large tracts of land grow sugarcane in this region. either, a wide variety of fruits and vegetables also grow in this region (19). In this study, Mung bean (*Vigna radiata* L.) was used as a test crop. It's a lush vegetable and is extremely consumed by people Mung dal (*Vigna radiata* L.) is a fleetly growing legume known for its nitrogen- fixing capability, high protein content, and positive impact on soil fertility (20) Its growth and development are shaped by a range of environmental, soil, and agronomic conditions. A comprehensive understanding of these influences, along with careful monitoring of vital growth parameters, is vital for maximizing yield and icing sustainable civilization in both agrarian and exploration settings (21).

2.2 Collection of fruit waste and bulking agent

Solid wastes from three different fruits: watermelon (*Citrullus lanatus*), pineapple (*Ananas comosus*), sweet lemon (*Citrus limetta*), pomogenerate (*Punica granatum*), papaya (*Carica papaya*), orange (*Citrus X sinensis*) and mix fruits were used as raw material for the compost pile. A significant quantity of fruit waste, gathered in clean bags from one of the campus cafeterias, was combined and shredded into smaller pieces. Additionally, dry leaves and straw, sourced from the campus surroundings, were incorporated as a bulking agent to enhance the structure of the compost.

2.3 Selection of Microbial additives for compost preparation

Composting is defined as an aerobic biochemical and microbial process that transforms organic paraphernalia through hydrolysis into a stable and sanitized end product appertained to have Bacteria, *actinomycetes*, and fungi a part in compost drug.[23] These microbial complements can either be isolated from the microbial communities according to specific degradative functions or developed through culture mixtures analogous as soil, cow soil, and straw etc(24). The named isolates were gram staining and examined under light microscopes and biochemically characterized by brio hydrolysis, oxidase test, carbohydrate fermentation, and color of diffusible color. Inoculations done at 0, 120 and 180 days showed that, lignin declination paced outdoors at the development phase for all the treatments 40 gm inoculum was mixed with raw material to grease the corruption process [25]

3.4 Compost preparation

The waste fusions were composted in polythene bags of size 48 cm wide, and 54 cm long. This size is beneficial for improving oxygen circulation and facilitating the preparation of a substantial amount of compost. The pile was watered and thoroughly mixed every two days to maintain humidity levels around 55%, ensuring optimal microbial activity. Additionally, regular turning of the compost pile aids in aeration, providing essential oxygen to microorganisms that accelerate the decomposition process. (26). Heap temperature was checked every ten days, using a soil thermometer (0°C - 800°C). humidity content, weight loss, and pH values were measured once a week using laboratory outfit. During the development phase, the stacks were turned on a regular and daily base to ameliorate the O_2 position within the mound. Heap humidity was kept under control by adding enough water. By adding the population of aerobic microorganisms, this aeration pets up the composting process (27). The compost pile is allowed to mature for three months, with the duration influenced by environmental conditions and pile size. During this process, the heat generated effectively eliminates harmful pathogens. Eventually, the organic matter breaks down into rich, dark, and crispy compost. [28]

3.5 Measurement of physico-chemical properties of compost

Nitrogen-Phosphorus-Potassium (NPK) value of the resulting compost was determined at the end of the incubation period. A sample of the compost material was oven dried at 105°C for 24 hours after which it was pulverized and sieved ($75\mu\text{m}$). The sample was mixed with 10ml of concentrated hydrochloric acid and heated for 10 minutes. The mixture was cooled, sifted, and examined using a Palintest Photometer 8000 to determine the concentration of various element [29].

3.6 Microbial analyses of compost and soil

Bacteria, actinomycetes, and fungi played a role in compost processing, with their types and populations varying over time. Compost or soil samples were collected and progressively diluted, while microbial counts were assessed using specific media: Nutrient agar and nitrogen-free agar for bacteria, brio nitrate agar for actinomycetes, and PDA for fungi, utilizing plate count agar [30]. All plates were maintained at temperatures of 25°C and 45°C for 1-2 days to promote bacterial growth, while actinomycetes and fungi were incubated specifically at 25°C . Additionally, phosphate-solubilizing bacteria were assessed using Pikovskaya's medium. A compost suspension was applied to this medium, and the plates were incubated at 30°C for two days [31]. Colonies exhibiting clear zones around bacterial growth were counted, indicating positive phosphate solubilization results [32]

3.7 Soil preparation and plant experiment

Air-dried beach soil, which had been sieved and acid-washed, underwent sterilization twice over two consecutive days before being air-dried again and thoroughly mixed with 20% fruit juice waste compost. Sterile pots were then filled with either 2 kg of sterilized beach soil alone (P1) or 2 kg of the prepared soil mixture (P2–P5). The latter groups were supplemented with N1 (P3), S3 (P4), or a combination of both (P5). Each experimental group consisted of 10 replicates, with five seedlings per pot, which were cultivated at 25°C while soil water potential was maintained near field capacity (33). Including N1 (P3), S3 (P4), and the combination of N1 and S3 (P5). hothouse trial was carried out 5 seedlings were transferred to each plastic pot ($25 \times 25 \text{ cm}^2$), filled with 2 kg of brume- castrated beach soil mixed with 20 fruit juice waste compost. The pots were divided into 5 groups(P), P1 control shops(normal soil without compost), P2 shops grown in normal soil, P3 the shops grown in soil and invested with Azotobacter(20 ml of cell suspense of $8 \times 10^5 \text{ CFU/ ml}$), P4 shops grown in soil with compost and invested with Streptomyces(20 ml of cell suspense of $8 \times 10^5 \text{ CFU/ ml}$), and P5 shops grown in soil with compost and invested with both bacteria(40 ml of a admixture of cell dormancies. After a week, irrigation was applied with 200 ml two times/ week (34). Composed of these accoutrements in mM KH_2PO_4 , 1.0; KNO_3 , 5; $\text{Ca}(\text{NO}_3)_2$, 5, $(\text{NH}_4)_2\text{Mo}_7\text{O}_{24}$, 0.0002, MgSO_4 , 2, Fe EDTA, 0.1, H_3BO_3 , 0.005, MnCl_2 2,0.010, ZnSO_4 4,0.008, CuSO_4 4,0.004.28(35).

2.8 Plant growth and chemical analysis

After a one- month growth period, factory development was estimated through several parameters, including root depth, shoot length, and both fresh and dry biomass measures of roots and shoots. Dry weights were attained by roaster- drying the factory apkins at 70 °C for 48 hours. also, chlorophyll and carotenoid attention in fresh splint samples were quantified using UV-Visible spectrophotometry following color birth with 95 ethanol. Chlorophyll attention($\mu\text{g/ mL}$) were determined using the following equations

$$\text{Chlorophyll a (Chl a)} = (13.36 \times A_{664}) - (5.19 \times A_{649})$$

$$\text{Chlorophyll b (Chl b)} = (27.43 \times A_{649}) - (8.12 \times A_{664})$$

$$\text{Carotenoids} = (1000 \times A_{470} - (2.13 \times \text{Chl a} + 97.63 \times \text{Chl b})) \div 209 \quad [36]$$

These computations handed a comprehensive assessment of color content as pointers of physiological status and photosynthetic eventuality. In addition, shoot samples from each treatment group were harvested, oven-dried, and subjected to biochemical analyses to determine protein and soluble sugar contents, following the standard protocols outlined by Allen et al. [30]. Soluble carbohydrates in shoot tissues were quantified using the Anthrone reagent method, while total soluble protein concentrations were determined using the Lowry assay [37]. For elemental analysis, shoot samples underwent acid digestion, after which phosphorus and nitrogen levels were measured in accordance with the procedures described by Wilde et al. [38]. The concentrations of potassium (K^+) and calcium (Ca^{2+}) were subsequently determined using a Shimadzu Atomic Absorption Spectrophotometer (AA-7800 Series) [39].

2.9 Effects of Juice Waste Compost on the Agronomic Performance

The plant height (PH), number of leaves (NL), leaf area (LA), and fresh weight (FW) was measured during completed at 15 (first harvest) and 45 (second harvest) days after transplanting seedling [40].

2.10 Statistical analysis

The statistical program SPSS was used to gather and evaluate data for every parameter. A one-way analysis of variance (ANOVA) was performed on the data to assess the difference in treatment mean values ($P < 0.05$) [41].

3. RESULTS AND DISCUSSION

Here are the results of methodology used

3.1 Selection of Microbial additives for compost preparation

Amylase-producing microorganisms hydrolyze starch into simpler sugars, a process visually confirmed by the formation of clear zones surrounding the NAM-6 and NAM-3 isolates on starch agar plates. This indicates extracellular amylase activity, consistent with the observations of [42], who reported efficient starch degradation by *Bacillus* species isolated from soil. Citrate utilization was assessed using Simmons citrate agar, where a distinct color change from green to blue in isolates SDA4 and PDA4 signaled alkaline byproduct formation, indicative of citrate permease activity [43]. This enzymatic capability is characteristic of specific taxa within the Enterobacteriaceae family, as documented by [44]. Furthermore, isolate PD4 exhibited pectin degradation capabilities, suggesting the production of pectinase—an enzyme integral. This enzymatic process facilitates the breakdown of pectin in plant cell walls and is extensively utilized in food processing industries. Comparable enzymatic activity has been observed in *Bacillus* and *Aspergillus* species, as documented in [45]. Fermentation profiling revealed that isolates SDA4 and NAM-7 were capable of metabolizing the supplied carbohydrate substrate, likely glucose or lactose, with the production of acid and possibly gas. Such fermentation tests are critical for bacterial identification and have been previously employed in characterizing lactic acid bacteria, as described by [46]. The biochemical profiling indicates that citrate utilization is the most commonly observed trait among the isolates. Carbohydrate fermentation and pectinase production were moderately detected, while amylase activity was comparatively less prevalent. These findings highlight the potential of certain isolates in facilitating the breakdown of organic matter converting raw material into useful compost [47] [Fig 3.1].

3.2 Compost preparation

The composting process of fruit juice waste was monitored weekly, capturing its physical changes over 12 weeks. The observed transformations highlight microbial activity and compost maturation.

Weeks 1–5: The organic material remained fresh, with clearly identifiable components. The waste was moist, and microbial colonization had begun. Its light brown color indicated a high sugar content, characteristic of fruit waste. This stage aligns with the mesophilic phase, during which easily decomposable compounds begin to degrade [48]

Weeks 5–7: Significant changes were observed as the material darkened and lost its original structure depicting the decomposition of cellulose and hemicellulose. This stage aligns with the thermophilic phase, marked by elevated microbial activity and heat, which accelerates decomposition [49].

•**Weeks 9–12:** The compost attained a dark, soil-like texture, with the original fruit waste

The progression demonstrates successful microbial degradation, leading to well-developed compost. The study successfully results that fruit juice waste can be converted into mature compost in approximately 12 weeks under aerobic conditions. The degradation is evident visually, transitioning from fresh organic material to stable compost. These observations are in agreement with previous research and validate composting as a viable method for organic fruit waste management [51] [Fig 3.3].

3.3 Measurement of physico-chemical properties of compost

The temperature and pH fluctuations observed over the 12-week composting period highlight the transition from active decomposition to maturation.

Temperature Profile: An initial rise to 31–34°C by week 2 marks the thermophilic phase, driven by intense microbial breakdown of organic matter. By week 5, temperatures gradually decline, indicating the cooling phase as decomposition slows. Between weeks 9 and 12, temperatures stabilize at 28–30°C, signaling the maturation phase and reduced microbial activity. These trends align with composting dynamics described by [52] and [53]

pH Profile: The pH changes reflect key biochemical transformations. At week 2, a moderate pH of 6.5–7.5 suggests the formation of organic acids during early decomposition. By week 5, pH increases to 7.5–8.5, corresponding to protein degradation and ammonification. By week 9, stabilization at 8.5–9.5 indicates compost maturity and chemical stability, consistent with findings from [54] and [55].

These physico-chemical parameters confirm that the fruit juice waste composting process follows standard composting phases, culminating in a well-matured, stable compost product suitable for agricultural use [56]. [Fig 3.4].

3.4 Microbial analyses of compost and soil

Microbial profiling of compost and soil samples has revealed a diverse range of enzymatic and metabolic activities, as illustrated in the bar chart. Cellulase and amylase activities were found to be relatively low, indicating limited cellulose and starch degradation—likely due to early composting stages or a low abundance of specialized degraders. In contrast, pectinase activity was slightly higher, suggesting active breakdown of plant cell walls. Strong microbial activity in Simmons citrate and carbohydrate fermentation tests highlights the dominance of microbes capable of metabolizing citrate and a variety of sugars, aligning with the expected stages of compost maturation [57]. Additionally, robust responses in carbohydrate catabolism and indole production suggest metabolic adaptability and potential nitrogen cycling. A higher prevalence of Methyl Red (MR) reactions compared to Voges-Proskauer (VP) indicates a preference for mixed acid fermentation pathways [58]. Microbial growth at pH 8.5, with a subsequent decline at pH levels of 9.5 and 11.5, reflects tolerance to moderate alkalinity and diminished activity in extreme pH conditions [59]. Minimal gelatinase activity points to a low abundance or inactivity of proteolytic bacteria. Overall, the findings suggest a functionally diverse microbial community, particularly active in carbohydrate metabolism—an essential factor in composting and soil nutrient cycling [60]. The enzymatic activities observed—cellulase and amylase production—confirm the isolates' role in organic matter decomposition and nutrient cycling [61]. Positive Simmon's citrate and carbohydrate catabolism tests demonstrate their ability to utilize diverse carbon sources,

enhancing survival and function in the rhizosphere [62]. Methyl red and VP test results indicate mixed acid fermentation pathways important for soil microbial balance [63]. Growth at alkaline pH (8.5–9.5) aligns with reports of beneficial microbes thriving in such conditions, aiding plant growth in alkaline soils [64]. Low gelatinase activity suggests limited extracellular protease secretion, potentially affecting soil protein interactions [65]. These traits support the isolates' potential for sustainable agriculture to improve crop productivity and soil health [Fig 3.5]. Positive indole test results indicate the presence of tryptophanase, which converts tryptophan into indole, pyruvate, and ammonia—key components of nitrogen metabolism. Indole production, typical of genera like *Escherichia*, *Proteus*, and *Klebsiella* [66] supports nutrient cycling and plant growth. The pH tolerance of isolates N5 and S10 highlights their ability to grow in diverse soil conditions, enhancing their suitability for agriculture and bioremediation. pH-tolerant microbes are especially effective in stressed or degraded soils [67]. Together, indole production and pH tolerance are vital traits of plant growth-promoting rhizobacteria (PGPR). Indole compounds such as indole-3-acetic acid (IAA) directly enhance root development and plant health [68]. [Fig 3.6].

3.8 Plant growth and chemical analysis

To evaluate the effect of fruit waste compost on *Vigna radiata* L. (Mung bean), parameters such as number of leaves, height. This parameter is important as we have to see the effect of compost on plant growth. The stages of mung bean (*Vigna radiata*) seed germination and seedling growth under different [69]. The superior growth observed with isolates P006 and S010 indicates their possession of key plant growth-promoting traits (PGPTs), such as IAA production, phosphate solubilization, and ACC deaminase activity—common mechanisms of PGPR that enhance nutrient uptake, hormonal balance, and stress tolerance [70]. The exceptional root development in P006-treated plants likely results from elevated IAA levels, which stimulate root elongation and branching [71]. Similarly, the improved shoot height and leaf number seen with S010 suggest enhanced photosynthesis and biomass accumulation [72]. Variation in growth responses among isolates reflects the diverse metabolic potential of rhizobacteria and their interaction with plant genotypes and environmental conditions [73]. [Fig 3.7]. To evaluate the effect of fruit waste compost on *Vigna radiata* L. (Mung bean), parameters such as number of leaves, height. This parameter is important as we have to see the effect of compost on plant growth [74]. The bar chart illustrates the effects of different bacterial isolates (N003, N005, N006, S004, S010, P009, and P006) on various plant growth parameters, including seed length, shoot height, leaf count, and root length. Among all isolates, P006 exhibited the most pronounced growth promotion, with the highest root length (35 cm), shoot height (20 cm), and leaf count (10). Isolate S010 also showed significant growth-promoting effects, particularly in shoot height (15 cm) and root length (30 cm). In contrast, isolates like P009 and N005 displayed relatively modest performance across all parameters [75] [Fig 3.7].

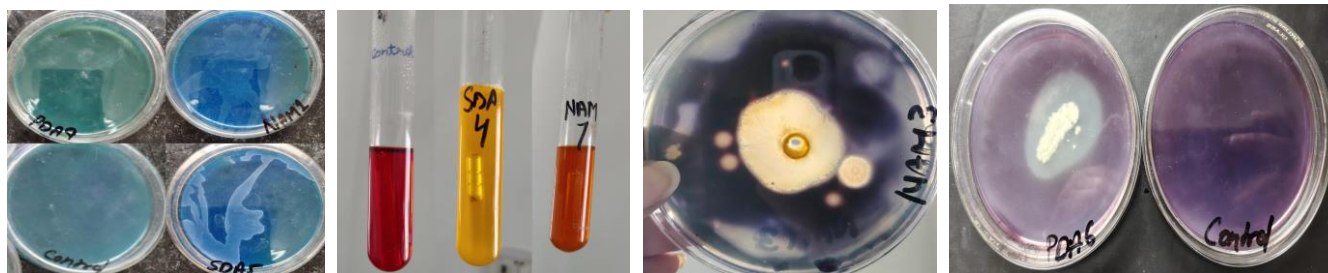


FIG 3.1: Biochemical characterization of bacterial isolates. (1) Amylase test – Clear zone after iodine staining indicates starch hydrolysis. (2) Simmon citrate test – Green to blue color change indicates citrate utilization. (3) Protease test – Clear zone shows casein hydrolysis. (4) Carbohydrate fermentation test – Yellow color and gas in Durham tube indicate acid and gas production. (All tests incubated at 37°C for 24–48 h under aerobic conditions.)

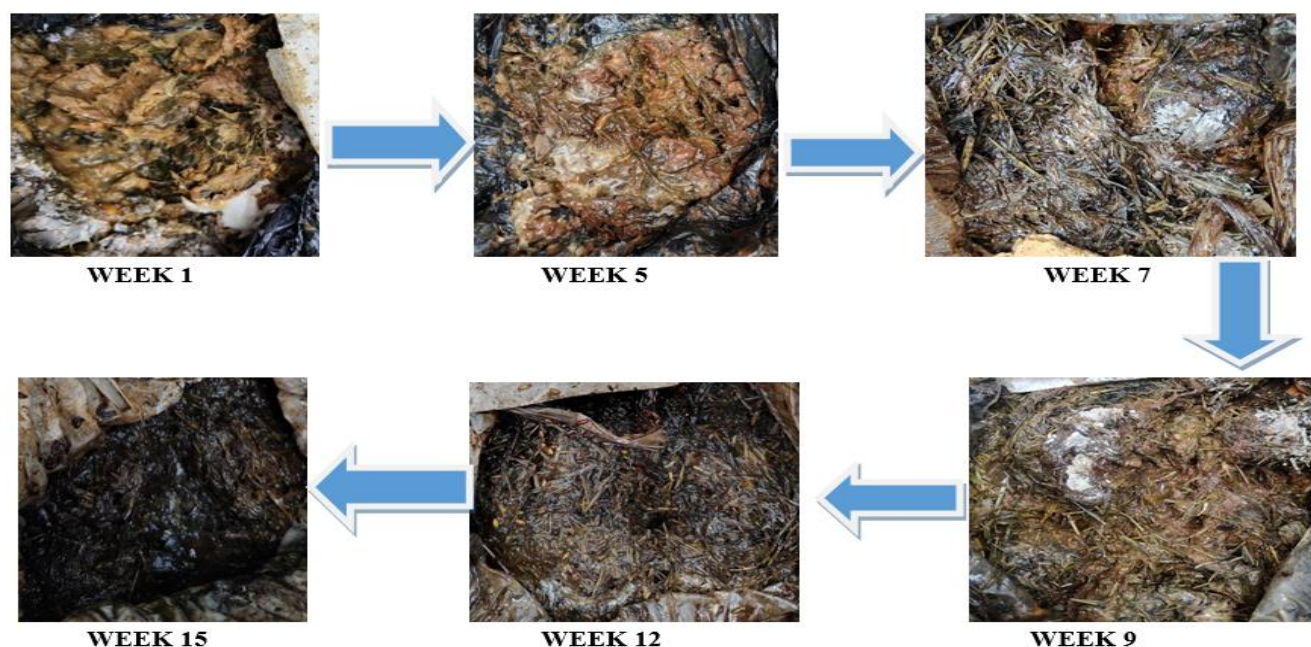


Figure 3.3: Visual progression of fruit waste composting over a 15-week period.

Sequential images illustrate the decomposition stages of fruit waste during composting at Weeks 1, 5, 7, 9, 12, and 15. Observable changes include the breakdown of organic matter, reduction in volume, colour darkening, and microbial colonization—indicating active microbial activity and organic matter degradation throughout the composting process.

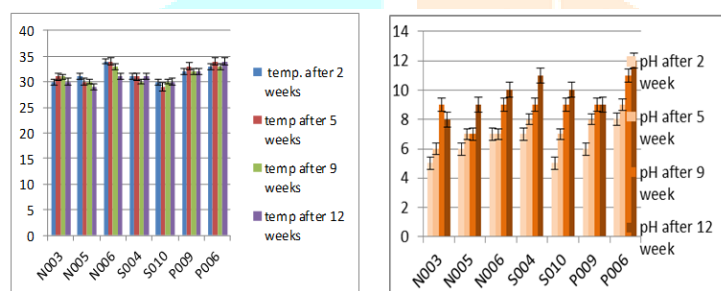


Figure 3.4: Temporal variation in temperature and pH during fruit waste composting across different microbial treatments.

The left panel shows changes in compost temperature at 2, 5, 9, and 12 weeks, while the right panel presents corresponding pH measurements at 2, 5, and 9 weeks for treatments labeled N003 to P006. Temperature and pH shifts reflect microbial metabolic activity and compost maturation over time.

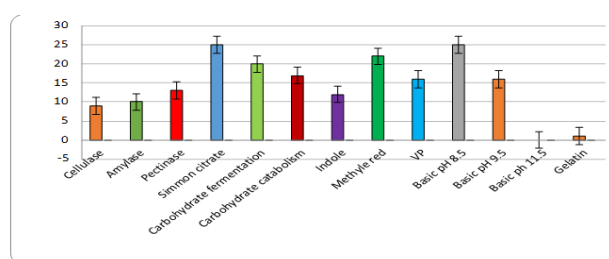


Figure 3.5: Biochemical and physiological profiling of bacterial isolates.

Bar graph depicting the number of isolates showing positive responses for various enzymatic activities (cellulase, amylase, pectinase), metabolic capabilities (Simmon's citrate utilization, carbohydrate fermentation and catabolism), fermentation pathways (indole, methyl red, Voges-Proskauer [VP] tests), and tolerance to different alkaline pH levels (8.5, 9.5, and 11.5). Gelatinase activity was also evaluated to assess protease secretion. These traits reflect the functional diversity and ecological adaptability of the isolates in soil environments.



Figure 3.6: Indole production and alkaline pH tolerance of bacterial isolates.

The left panel shows indole production by different bacterial isolates in tryptophan broth, indicated by the development of a pink ring after addition of Kovac's reagent. The right panels demonstrate the growth of selected isolates (N5 and S10) in nutrient broth adjusted to pH 8.5, 9.5, and 11.5, confirming their ability to tolerate and grow under alkaline conditions. These traits highlight the potential application of isolates in promoting plant growth under stress conditions such as alkaline soils.

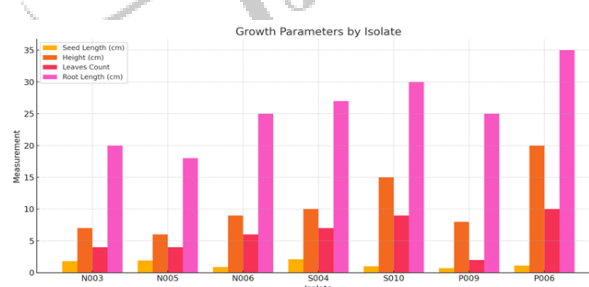


Figure 3.7: Comparative analysis of plant growth parameters influenced by different bacterial isolates.

Bar graph showing the effect of bacterial isolates (N003, N005, N006, S004, S010, P009, and P006) on seedling growth parameters, including seed length, shoot height, leaf count, and root length. Isolate P006 exhibited the highest enhancement in root length (35 cm), shoot height (20 cm), and leaf number (10), indicating its strong potential as a plant growth-promoting rhizobacteria (PGPR) candidate.

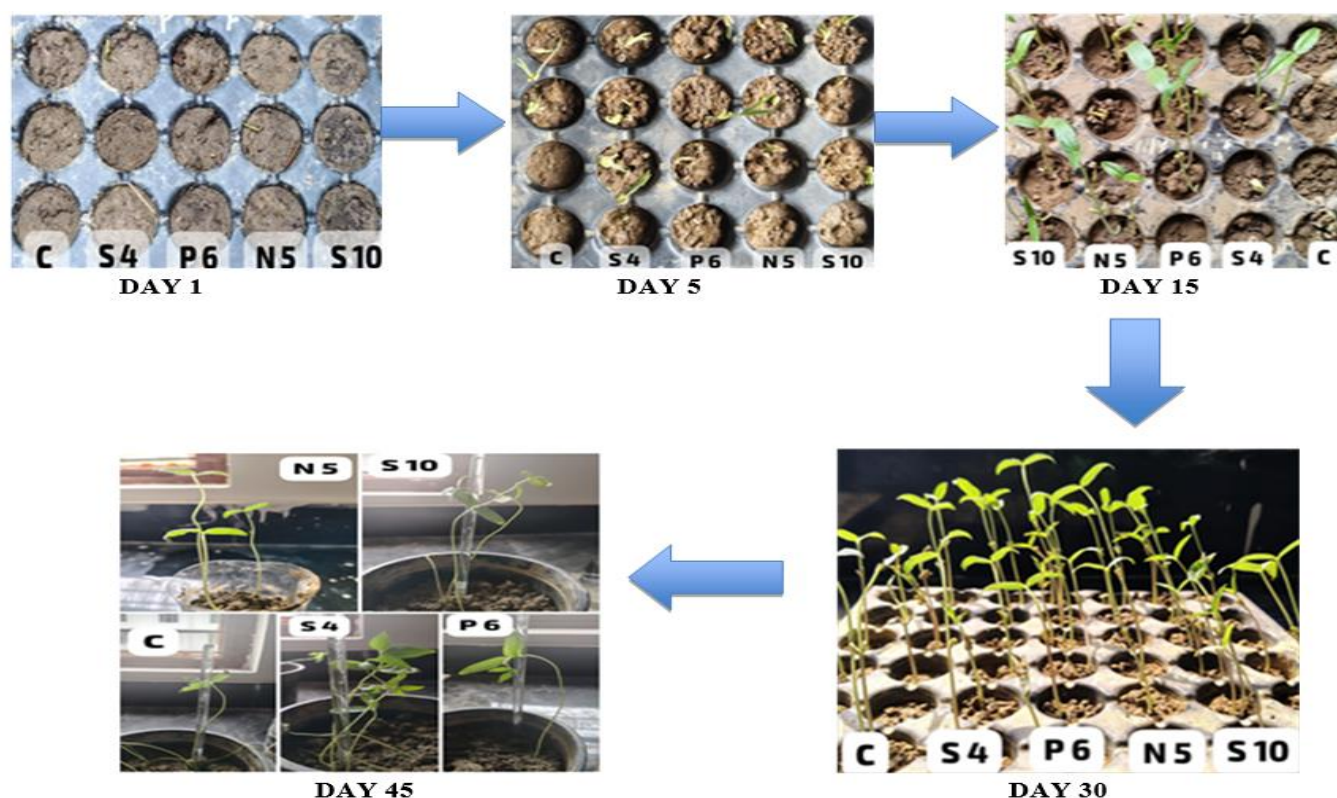


Figure 3.7: Growth progression of seedlings under different compost treatments over a 45-day period. Images depict germination and vegetative growth of seedlings on Days 1, 5, 15, 30, and 45 under various compost-amended treatments (C, S4, P6, N5, S10). Visual comparisons highlight differences in emergence rate, shoot development, and overall plant vigor among the treatments, indicating the influence of compost type on early plant growth.

Conclusion

Increasing awareness of the environmental and ecological consequences of agricultural activities has emphasized the need for sustainable farming practices. Fertilizer suitability is evaluated based on agronomic parameters. The results demonstrate that compost treatments significantly enhanced seedling germination and vegetative development compared to the control. Among the treatments, P6 and S10 showed the highest growth promotion, with S4 also supporting robust seedling development. This confirms that compost amendments—particularly those labeled P6 and S10—can effectively improve early plant growth, likely due to improved nutrient availability and soil structure. Further work is required with increased number of samples and different varieties and species to formulate an efficient soil conditioner for commercialization of biowaste as a valuable soil amendment in sustainable agriculture.

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