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Piriformospora indica-root colonization Improved the Shelf Life and Quality Parameters of Ripe and unripe Fruits of Banana var. Nendran

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ABSTRACT: *Piriformospora indica* is an axenically cultivable fungal root endophyte that contributes multifaceted benefits to plants. The role of *P. indica* in improving quality parameters of ripe and unripe stages of banana (*Musa acuminata*) var. Nendran was investigated. The physical, biochemical and organoleptic status were quantified during the green (unripe) and ripe stages. Both shelf life and beta carotene content were enhanced in the fruits of *P. indica*-colonized plants compared to control. All physical parameters like, bunch weight, fruits per hand, fruit length, fruit weight and fruit diameter were significantly enhanced in bunches obtained from *P. indica*-colonized banana plants. Biochemical parameters *viz*., total sugars, pH, total reducing sugars, beta carotene, protein and carbohydrate contents were also substantially increased in fruits obtained from the fungus colonized plants. In contrast, crude fibre and moisture content were reduced in ripe fruits obtained from the colonized plants compared to their respective control plants. Beta carotene was increased by 93.9 per cent; and pH, total reducing sugars and acidity were increased progressively during ripening of the fruits obtained from the colonized plants. These fruits recorded 34 per cent more total sugars, which indicate the degree of sweetness of the fruit. The carbohydrate, fibre and moisture content were high in unripe banana fruits obtained from the colonized plants compared to control plants. The unripe fruits had 13.2 and 52.15 per cent high carbohydrate and protein contents respectively compared to the respective unripe control fruit. The present study also revealed that *P. indica* could enhance the shelf life of banana fruits by slowing down the ripening process, thereby increasing its marketability. Furthermore, sensory evaluation confirmed the overall acceptability of banana fruits from the endophyte colonized plants compared to fruits from the control plants. Thus *P. indica*-colonized banana plants render fruit quality improvement with enhanced shelf-life of fruits to a reasonable extent.

Keywords: Banana fruit, *Piriformospora indica*, Physical Parameters, Biochemical parameters, organoleptic characters.

INTRODUCTION

Banana (*Musa* spp.), family Musaceae and one of the major fruit crops in the world, have gained importance due to their large-scale cultivation and consumption in recent decades. Banana fruit is enriched with carbohydrates and various macro and micro nutrients, which make it as one of the staple fruit crops that benefit to the human body. Development of good quality bunches/fruits is required to get better market price. The quality attributes *viz*., colour, shape, taste and ripeness have significant impact on banana food industries. Banana is enriched with carbohydrate and starch which have found extensive utilization in the baby food production (Wills *et al*., 1984). The nutritional content, smoothly texture and natural sweetness make them an ideal choice as solid foods to infants. In addition to that, unripe or green bananas are utilized in savoury dishes such as curries and chips. In order to increase their shelf life and adaptability, bananas are further processed into jams, jellies and dried fruit snacks.

India holds the first position of being the largest producer of bananas and nendran (AAB) is the most popular banana variety of Kerala, well suited for both culinary and table purposes, albeit the existing supply of the fruits in the market falls short of meeting the escalating demand (Singh *et al*., 2016). The banana industry faces several significant challenges, including reduced productivity, lack of disease-free planting materials and declining soil fertility, consequently leading to poor growth, yield and quality of banana fruits (Jefwa *et al*., 2012). To bridge the supply and demand gap in the banana industry, there is a requirement for an adequate supply of good quality banana fruits in the market. The enhancement of fruit quality can be achieved through numerous approaches such as augmented fertilizer use, genetic engineering and other cutting-edge techniques whereas, they come at high expense.

At this point, beneficial fungal root endophytes play a major role in enhancing the production and productivity of crop plants. The rhizosphere is the niche of naturally occurring beneficial microbes. Arbuscular mycorrhizal fungi (AMF) are beneficial endophytes colonizing plantain roots and are densely packed with mycelia and arbuscules (Gaidashova*et al*., 2010). AMF enhance the plant performance under stress conditions and encourage plant acceptance in nurseries (Nowak, 1998). Recent studies have looked into how bananas interact with other beneficial microbes such as bacterial communities, Trichoderma species etc. in order to enhance overall growth and development (Kaushal *et al*., 2020).

Piriformospora indica, a beneficial fungal root endophyte in the order Sebacinales of Basidiomycotina (Gill *et al*., 2016) colonizes the roots of many plants (Varma *et al*., 1999). *P. indica*-colonized plants impart resistance to both biotic and abiotic stress and improve growth promotion (Oelmuller *et al*., 2009; Johnson *et al*., 2013; Gill *et al*., 2016). Symbiotic association of *P. indica* with crop plants enhanced shoot and root development leading to better vegetative growth (Jacobs *et al*., 2011).

P. indica-colonized TC banana seedlings shortened the time for field transplantation (Li *et al*., 2019; Li *et al*., 2021). In addition to that, the fungus maximizes the production of phenolic compounds and antioxidants in the edible part of the plants (Chandran *et al*., 2021). Moreover, beneficial microorganisms could activate genes responsible for modulating fruit quality parameters (Yan *et al*., 2021). The colonization patterns of *P. indica* and the associated benefits for plants vary considerably across different plant species, resulting in its versatile applications in agriculture (Johnson *et al*., 2014). For instance, review of literature shows that, *P. indica* enhanced fruit quality in tomato (Fakhro *et al*., 2010; Xu *et al*., 2022), pummelo (Yang *et al*., 2020), passion fruits (Yan *et al*., 2021), strawberry (Liu *et al*., 2022) and newhall orange (Cheng *et al*., 2022) by enhanced total soluble sugar (TSS) and antioxidant enzyme activities. Whereas, the studies related to the effect of *P. indica* on overall fruit quality and role on shelf life of banana were yet not addressed. Therefore, the present study investigated the changes in physical, biochemical and organoleptic properties of unripe and ripe stages of fruits harvested from *P. indica*-colonized and non-colonized banana plants.

MATERIAL AND METHODS

A. Plant growth and P. indica co-cultivation

The experiment was conducted in the Instructional Farm, College of Agriculture, Vellayani and Coconut Research Station, Balraramapuram Thiruvananthapuram, Kerala, India, during 2020-2022. The study was carried out with TC banana var. Nendran to assess the effect of *P. indica* on the growth, yield and quality of banana fruits. *P. indica*-colonization in TC banana var. Nendran was carried out with the standardized protocol by Jojy *et al*. (2020). Secondary hardened TC banana plants were grown in grow bags containing *P. indica* multiplied coir pith – dried farm yard manure medium amended with 1 per cent gram flour for 30 days. Later on, these plants were transplanted to the field at a spacing of 2 m × 2 m as per the package of practices of crop plants developed by Kerala Agricultural University (KAU, 2016). The growth of these plants was monitored until fruit harvest. *P. indica*-colonized plants and non-colonized plants (coir pith – dried FYM medium without fungus) were laid out as the two treatments. For the analysis of fruits, five bunches of banana fruits were selected per treatment randomly from 100 plants. Three fruits per D hand (second last) each from both ripened and unripen were taken for analysis from each bunch.

B. Colonization study of P. indica in banana roots

The endophytic colonization of *P. indica* in the roots of the banana was confirmed by compound microscopy. For the study, the colonized roots were washed thoroughly in running tap water and dissected into 1cm sections. The root sections were exposed to a two-minute boiling procedure in a 10 per cent KOH solution, followed by a sterile water wash. The tissues were subsequently acidified with a 1 per cent HCl solution. Later, the root bits were rinsed with sterile water and stained with a 0.5 per cent lactophenol blue solution (Fluka, Menlo Park, USA) for 3 min and the fungal colonisation in roots were observed under a compound microscope (Leica – ICC50 HD, Germany).

C. Plant growth and fruit parameters of banana

Biometric parameters *viz*., pseudostem height, pseudostem girth, green leaf number, leaf length, leaf width and the total number of suckers per plant were recorded from each treatment. After bunch harvest, physical parameters of fruits such as weight of bunch, number of hands per bunch, number of fruits per hand, length of fruits and diameter of the fruits were recorded.

D. Biochemical parameters of fruit

Biochemical parameters *viz*., total sugars (Lane and Eyon,1943), total reducing sugars (Sudarmadji *et al*.,1997), protein (Lowry *et al*., 1954), total carotenoid (Lichtenthaler, 1987), starch content (Sadasivam and Manickam 2008) and proximate parameters *viz*., moisture and fibre content (Sudarmadji*et al*., 1997; SNI, 2006) were assessed in ripe and unripe banana fruits from each treatment. Furthermore, the pH was determined by dissolving approximately 1 g of banana pulp in 10 ml of distilled water (IAL, 2008). The sugar-to-acid and pulp-to-peel ratio were calculated from the observed data.

E. Organoleptic Test

An organoleptic test employing human sensory tools was performed to assess the physical attributes of a product, thereby providing insight into its consumer acceptance. The test encompassed the evaluation of six parameters *viz*., colour, aroma, appearance, texture, taste and overall acceptability. In the present study, organoleptic tests were performed on banana fruit samples with the participation of 16 panellists, utilising a rating scale of 1 to 5. Subsequently, the obtained organoleptic test values were computed using the hedonic test formula.

Average Quality Score $X = \sum Xi/n$

Where, X – average quality score; Xi – quality score of organoleptic test by panellist I; n - number of panellists. A higher hedonic scale indicates a greater rate of panellist acceptance or preference.

F. Data analysis

The generated data was subjected to statistical analysis using GRAPES version 2.0, College of Agriculture, Vellayani, (Gopinath *et al*., 2021). The growth parameters of the two treatments were compared with student's t-test and fruit quality parameters were assessed by one-way analysis (ANOVA) at 0.05 per cent significance.

RESULTS

A. P. indica increased growth parameters of banana seedlings

The role of *P. indica* on the performance of TC banana var. Nendran was assessed at 60 days after *P. indica*-colonization in the seedlings of a secondary hardened plant. During the initial days of the growth, there was no significant difference in the biometric parameters of the colonized and non-colonized plants. All the biometric parameters at 60 days after colonization were significantly higher in the colonized seedlings than the control. *P. indica* colonized plants increased shoot length by 30 to 42 per cent in comparison to the non-colonized seedlings. There was significant difference in leaf width among these treatments. The leaf width of 60 days old *P. indica*-colonized banana plants were 27.95 per cent higher than that of the control plants (Table 1 and Fig. 1).

The effect of *P. indica*-colonization was prominently observed as the plant growth progressed. *P. indica*-colonized plants were observed to have a significantly higher overall biomass compared to the control plants throughout the growth stage. The colonized-plants exhibited 86.7 per cent more root biomass in comparison to control. *P. indica* also enhanced root biomass (Table 2 and Fig. 1) and increased the number of root hairs for nutrient absorption from soil. The *P. indica*-colonized plant roots were recorded with 2.5 times more secondary and 3.5 times more tertiary roots than control plants. The initial enhancement in number of secondary and tertiary roots in the colonized plants might be enabling the quick establishment of the TC banana plants in the field and also for the nutrient absorption.

B. P. indica enhanced physical parameters and shelf life of banana fruits

P. indica-colonized banana plants developed a long finger/fruit compared to the untreated control. More importantly, the harvested fruits exhibited a substantial increase in size, as evidenced by their higher transverse and longitudinal diameters (Fig. 2C; Table 3). This enlargement in fruit dimensions led to a remarkable increase of more than 10 per cent in the fruit weight (Fig. 2C&D; Table 3). *P. indica*-colonized banana plants produced significantly higher bunch (Fig. 2A) which was 32 per cent heavier than the control plants.

Table 1: *P. indica* enhanced shoot parameters of TC banana var. Nendran at 60 days after colonization.

Treatments	Shoot length (cm)	Girth (cm)	Number of leaves	Leaf length (cm)	Leaf width (cm)	Fresh weight of shoot (g)
Control	52.89 ± 0.17	6.78 ± 0.73	8.35 ± 0.49	33.02 ± 0.18	16.33 ± 0.14	68.88 ± 0.40
P. indica	68.90 ± 0.15	9.84 ± 0.09	10.47 ± 0.51	43.08 ± 0.34	20.90 ± 0.34	92.73 ± 0.26
% change	30.27	45.01	25.35	30.44	27.95	34.62

Values are mean of 16 replications ± standard deviation of three independent experiments

Table 2: *P. indica* enhanced root parameters of TC banana var. Nendran at 60 days after colonization.

Treatments	Root length (cm)	Number of major roots	Number of secondary roots	Number of tertiary roots	Fresh weight of root (g)
Control	52.88 ± 0.26	11.35 ± 0.49	79.75 ± 0.68	163.53 ± 1.55	11.09 ± 0.11
P. indica	57.04 ± 0.17	18.59 ± 0.51	129.76 ± 2.25	210.35 ± 0.61	20.72 ± 1.09
% change	7.85	63.73	62.71	76.98	86.74

Values are mean of 16 replications ± standard deviation of three independent experiments

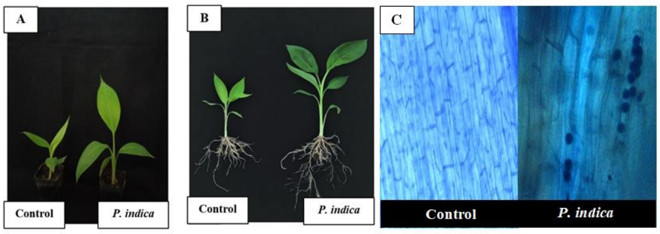

Fig. 1. *P. indica*-colonization enhanced growth promotion in TC banana plants. (A) *P. indica*-colonized and non-colonized control TC banana plantlets at 60 days after colonization. (B) Shoot and root biomass of *P. indica*-colonized and non-colonized control TC banana plantlets at 60 days of colonization (DAC). (C) Compound microscopic image of *P. indica*-colonization in roots of TC banana plants after 60 DAC.

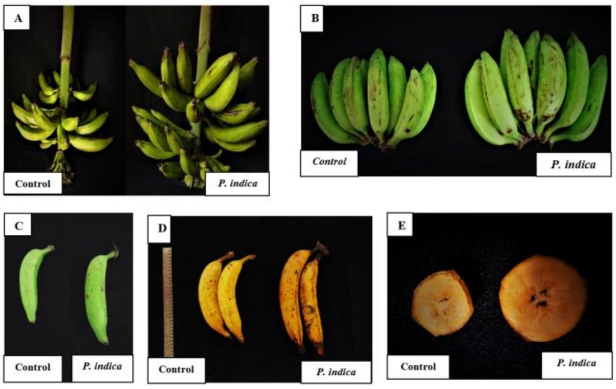

Fig. 2. *P. indica* enhanced fruit yield in banana var. Nendran. (A) Whole bunch of banana; (B) Hands of banana; (C) & (D) Unripe and ripe fingers/fruits of banana (E) Horizontal cut of banana fruit

The number of hands per bunch (Fig. 2B) and number of fingers per hand (Fig. 2C) in *P. indica*-colonized plants showed only 12 per cent and 6 per cent increase respectively compared to control. The average weight of the second hand of the bunch (D hand) and average weight of the finger in a hand showed, 40 and 43 per cent increase in *P. indica*-colonized plants. In this study, all the physical parameters of banana fruit showed enhancement except the number of fruits per hand. The average length and girth of a finger was also improved by about 19.5 and 28.8 per cent respectively in *P. indica* colonized plants compared to control (Fig. 2D).

Table 3: Comparative analysis of physical parameters of banana fruit with or without *P. indica*.

Sr. No.	Physical Parameters	Control	*P. indica*	% change	T (0.05)	T (0.01)
1.	Weight of bunch (kg)	7.75 ± 0.48	10.30 ± 1.21	32.90	2.13	2.95
2.	Number of hands per bunch	4.13 ± 0.50	4.63 ± 0.50	12.10		
3.	Number of fingers per hand	8.94 ± 0.85	9.50 ± 0.52	6.26		
4.	Total number of fingers per bunch	33.31 ± 4.21	38.69 ± 2.06	16.15		
5.	Weight of D hand of bunch (kg)	2.63 ± 0.30	3.69 ± 0.28	40.30		
6.	Average weight of fingers (g)	256.21 ± 39.12	366.40 ± 18.62	43.00		
7.	Average length of finger (cm)	21.66 ± 1.06	25.88 ± 1.11	19.48		
8.	Average girth of finger (cm)	10.45 ± 0.41	13.46 ± 0.59	28.80		
9.	Days taken for ripening	5.25 ± 0.68	7.81 ± 0.83	48.76		
10.	Shelf life (in days)	12.06 ± 1.84	16.56 ± 1.09	37.31		

Values are mean of 16 replications ± standard deviation of three independent experiments

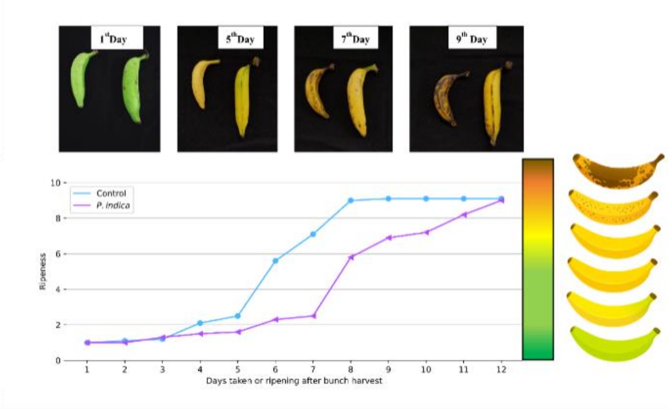

Fig. 3. Comparative analysis of progressive ripening rate and shelf life of banana fruits from plants with or without *P. indica*.

Shelf life of bananas is a major concern for banana growers. It is grouped under highly perishable fruits. The fruits taken from *P. indica*-colonized plants ripened after a week at room temperature, whereas fruit from control plants ripened within five days. Similar trend was also observed in fruit shelf life (maturity to rotting) (Fig. 3). Fruits from *P. indica*-colonized plants were observed to have a shelf life of more than two week, whereas fruit from control plants were completely rotten by 12th day of storage under room temperature. The delay in ripening characteristics of fruits from *P. indica*-colonized plants enhanced the marketability of banana fruits

C. P. indica improved biochemical parameters of fruit

Fruits from *P. indica*-colonized plants had enhanced TSS value in many crops (Fakhro *et al*., 2010; Yan *et al*., 2021; Cheng *et al*., 2022). The present study confirmed the beneficial and positive effect of *P. indica* on all biochemical parameters of fruits like peel weight, pulp-to-peel ratio, sugar-to-acid ratio, beta carotene, moisture content, protein, pH, carbohydrate, total sugars, reducing sugars and crude fibre.

The pulp-to-peel ratio showed significant variation in the green and ripe stages of the banana fruits. Fruits from *P. indica*-colonized plants had reduced pulp-to-peel ratio and the per cent reduction was 12.27 in the green stage; whereas it was enhanced by 1.8 per cent in the ripe stage in comparison to the respective control. Further, during the ripening, fruit weight was reduced by 1-5 per cent in both the cases (fruits from control and *P. indica*-colonized plants). At the green stage (unripe), *P. indica* reduced peel-to-pulp ratio (by 1.3%), whereas, at the ripe stage, the ratio was highest for fruits from *P. indica*-colonized plants (3.3 %) compared to the respective control. Furthermore, the increase in the pulp-to-peel ratio can be attributed to the translocation of water from the peel to the pulp, facilitated by the osmotic gradient created by the higher sugars concentration in the pulp compared to the peel (Aquino *et al*., 2017). Similarly, the sugars-to-acid ratio was recorded maximum in ripe fruits obtained from *P. indica*-colonized plant (34.10 ± 1.89) compared to fruits from control plant (30.48 ± 2.88). The sugars-to-acid ratio plays a vital role in determining the taste profile of fruits.

Table 4: Effect of *P. indica* on peel to pulp ratio and sugars to acid ratio on ripe and unripe banana fruits.

Treatments	Pulp weight (g)	Peel weight (g)	Pulp-peel ratio	Sugars-acid ratio
Unripened banana fruits from control plants	197.75 ± 8.34	63.75 ± 3.77	3.11 ± 0.25	9.32 ± 0.76
Unripened banana fruits from *P. indica*-colonized plants	249.25 ± 6.95	81.25 ± 5.74	3.07 ± 0.11	4.82 ± 0.34
Ripened banana fruits from control plants	188.50 ± 15.41	57.75 ± 3.30	3.29 ± 0.49	30.48 ± 2.88
Ripened banana fruits from *P. indica*-colonized plants	245.75 ± 16.39	72.25 ± 3.86	3.40 ± 0.19	34.10 ± 1.89

Values are mean of 5 replications ± standard deviation of three independent experiments

The data reveals that maximum total sugars (23.1 %) (Fig. 4A) and total reducing sugars (14.2 %) (Fig. 4C) were recorded in ripe banana fruits obtained from *P. indica*-colonized plants. At the same time, the total sugar value of ripened banana fruits from *P. indica*-colonized plants was 34.4 per cent more than that of fruits from control plants. Although the pH levels of both unripe and ripe bananas varied significantly, the colonization of *P. indica* did not appear to have significant influence on fruit pH in either stage (Fig. 4B).

As per the study, the major proximate component moisture was 54.40 per cent for the unripe fruits and 62.34 per cent for ripe fruits from the control plants. Among different treatments, fruit obtained from *P. indica*-colonized banana showed a significant reduction of moisture content in both unripe (10.2 %) and ripe fruits (8.5%) compared to the control (Fig. 4D).

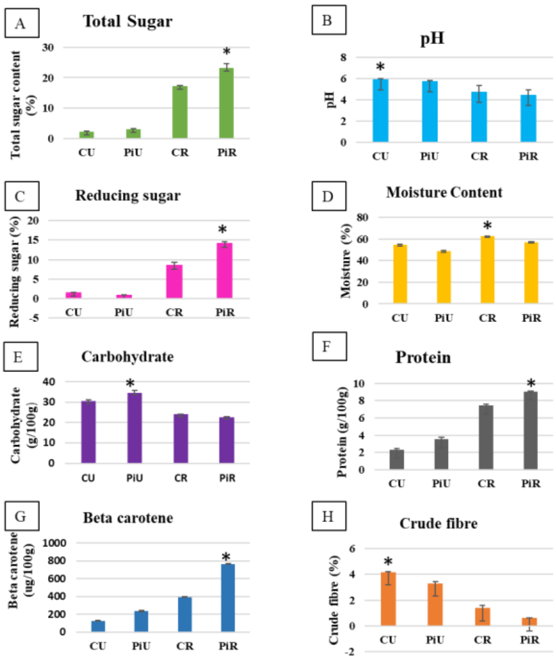

Fig. 4. Proximate analysis of banana at two different stages of fruit, unripe and ripe fruits. CU - Control unripe fruits; PiU - Unripe fruits from *P. indica*-colonized plant; CR - Control ripe fruits; PiR- Ripe fruits from *P. indica*-colonized plant. Fruits were collected from D hand with replications 5. (A) Total sugars; (B) pH; (C) Reducing sugars; (D) Moisture percentage; (E) Carbohydrate; (F) Protein; (G) Beta carotene and (H) Crude fibre. Bars represent standard deviations (SDs). Asterisks denotes significant differences, as determined by ANOVA (* P ≤ 0.005).

A significant difference ($P < 0.05$) in crude carbohydrate (Fig 4E) content was observed between ripe and unripe fruits. The unripe fruits obtained from *P. indica*-colonized banana plants (PiU) recorded a 13.2 per cent increase in carbohydrate content compared to unripe banana fruits obtained from control plants (CU). Whereas, while ripening, the fruits obtained from *P. indica*-colonized plant showed reduced (6.02 %) carbohydrate content compared to fruits from control plants (CR). During ripening of banana fruits, the carbohydrate content decreases while the sugar content increases due to the conversion of starch to sugars.

Beta carotene, protein and crude fibre are essential components of fruits. Protein content in unripe and ripe banana fruits obtained from *P. indica*-colonized plants was 52 per cent and 21.6 per cent higher respectively compared to the respective control (Fig. 4F). The concentration of beta carotene increased while ripening progresses in banana fruit. Ripe banana fruits obtained from *P. indica*-colonized plants were observed with orange to red flesh, whereas ripe fruits from control plants were found with yellowish to orange flesh (Fig. 2D and 2E). The beta carotene is the essential source of vitamin A and it imparts colour to the fruits during ripening. Beta carotene level in ripe fruits from *P. indica*-colonized banana plants was 93.9 per cent higher compared to ripe fruits from control plants (Fig 4G). Ripe fruit obtained from *P. indica*-colonized plant recorded 2.5 times reduced crude fibre content compared to control. The fibre content increases in banana fruit till maturity and as the ripening progresses, the fibre content will gradually decrease. Similarly, unripe banana fruits from *P. indica*-colonized plant were found to be with 20 per cent reduced fibre content than fruits from control plants (Fig. 4H).

D. P. indica enhanced the overall acceptability of banana fruits

Higher the hedonic value represents the good acceptance of the fruit. Overall acceptability was good for fruit from *P. indica*-colonized banana plants compared to the control plant. Banana fruits obtained from *P. indica*-colonized plants showed 8.48 and 8.00 hedonic value for colour and taste respectively (Fig. 5), which was 13.9 per cent and 9.4 per cent higher than the fruits from control plants compared to colour and taste of control fruits.

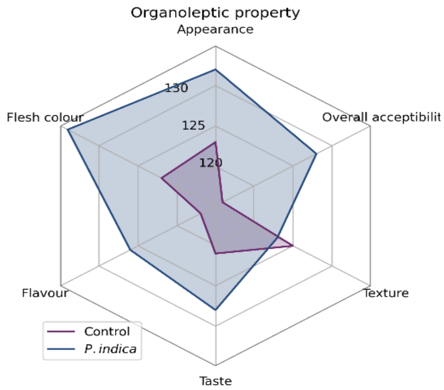

Fig. 5. Radar chart of sensory evaluation of banana fruits from *P. indica*-colonized and control plants.

The peel of fruits obtained from *P. indica*-colonized plant showed golden yellow with reddish spots at ripen stage whereas control fruit peel appeared as usual yellow to pale. The fruit pulp from the *P. indica*-colonized plant was light orange to reddish orange in hue, compared to the control fruit's yellow to orange coloration. Beta carotene level in fruits supported the above data.

DISCUSSION

P. indica-colonization improved physical parameters of harvested produces in many agriculture and horticulture crops (Varma *et al*., 2012). *P. indica*-colonized fruit crops *viz*., passion fruit (Yan *et al*., 2021), strawberry (Liu *et al*., 2022) and new hall orange (Cheng *et al*., 2022) showed a positive result in various physical parameters studied and the same trend was observed in vegetable crops like tomato (Wang *et al*., 2015; Sam, 2021), Okra (Chippy 2020), vegetable cowpea or yard long bean (Chandran *et al*., 2021). *P. indica*-colonization also influenced the fruit quality parameters. *P. indica*-colonisation results in the promotion of fruit pulp-to-peel ratio leading to the production of heavier and larger fruits (Table 3). Although this result has been verified for many beneficial plant-microbe interactions, the proposed study demonstrated that under field conditions, one-time inoculation / colonization of the beneficial fungal root endophyte, *P. indica* is adequate to enhance plant growth, yield and fruit quality of banana plants for the entire crop period.

Wang *et al*. (2015) reported that *P. indica*-colonization improves tomato fruit quality. The result was further supported by analyzing the soluble sugars and protein contents of the fruits (Xu *et al*., 2022). The sweeter taste of the fruit is probably due to the combined effect of reduced moisture and accumulation of various soluble compounds in response to *P. indica*-colonization. In the present study, thicker peels of banana fruits due to the fungus colonization provide better protection against early rotting of fruits after ripening, enhanced shelf life and subjectively more attractive fruits. It further indicates that *P. indica*-colonization in banana plants is convenient approach to enhance fruit quality in alignment with market demands.

The moisture content of fruits serves as a measure of water activity, in turn indicates the stability and vulnerability of fruit to microbial infection (Edem and Miranda 2011). In general, unripe banana fruits have low moisture content, longer shelf life than ripe fruit and high insoluble polysaccharides that might have slow down the growth of microorganisms. Banana fruits from *P. indica*-colonized plants showed prolonged shelf life compared to untreated fruit. Low moisture content in ripe fruit also contributes to longer shelf life of banana fruits. All the biochemical parameters except crude fibre and carbohydrate contents were decreased during ripening. Insoluble carbohydrates, starch and polysaccharides are converted into soluble sugars, thus increased the sweetness of the ripe plantain (Ezeigbo and Ezeigbo 2018). Moreover, it was observed that significant changes occur in the starch during the ripening of bananas (Lii *et al*., 1982). The chemical composition of bananas undergoes alterations at different maturation stages, where starch degradation occurs and sucrose content increases (Cordenunsi-Lysenko *et al*., 2019). The conversion of starch to sucrose during ripening is responsible for the sweetening of the pulp as well as supplies energy for metabolic activities; which develops further quality parameters *viz*., pulp colour, volatile compounds and pulp texture in ripe bananas, determine the market quality of fruits (Shiga *et al*., 2011).

The *P. indica*-colonized plants were enriched with mineral nutrients compared to those from non-colonized plants (Johnson *et al*., 2014), which is responsible for the enhanced fruit quality. Potassium is a significant nutrient in soil and it facilitates the movement of sugars throughout the plant and accumulates starch in fruits (Kumar *et al*., 2006). It has been demonstrated that *P. indica* aids in the transport of potassium to the host plant and encourages its absorption from the soil by creating intricate networks of hyphae that expand the surface area for nutrient absorption (Su *et al*., 2017). This symbiotic association enables the plant to efficiently absorb potassium and other essential elements. Consequently, the plant exhibits improved fruit size, shape, colour and freshness, all of which are vital factors in the market.

The consistent bright orange colour of fruit pulp of the colonized plant (Fig. 3E) is due to the enriched beta carotene level compared to the pulp from the control plants. Similar effect was observed in case of peel. The fruit peel of the fungus-colonized plant showed reddish dots, whereas fruits from the control plants showed pale yellow peel (Fig 3D). Enriched antioxidants reduce the cell death and keep the fruits fresh for longer time. Ascorbic acid is well known antioxidant which may contribute to the longer freshness of the fruits (Edem and Miranda 2011). High levels of reduced and non-reduced sugars in the fruits of *P. indica*-colonized plants may be attributed to an enhanced primary metabolism during the initial stages of fruit development.

The significant variations in the proximate and mineral composition of the fruit during ripening suggest the changes in the nutrient properties of banana fruits. Other factors that could influence variations in the nutritional composition of plantain including variety, soil properties and microbial activities which may directly or indirectly influence the composition of the fruit.

CONCLUSIONS

P. indica-colonization exhibited significant growth promoting effects in banana plants. *P. indica* significantly enhanced the number of roots, facilitated nutrient uptake and increased banana yield. The present work concluded that the one-time application of *P. indica* inoculum in the rhizosphere under agricultural conditions is sufficient to enhance the growth and development of banana plants during the entire crop period which results in higher yield and better fruit quality. Both ripe and unripe banana fruits of *P. indica*-colonized plants recorded significantly enhanced total sugars, protein and carbohydrate contents, while experiencing decreased moisture and fibre contents. The increased total sugars and decreased moisture content in fruits are attributed to its enhanced sweetness. Along with the physical and quality parameters, *P. indica* improved the overall acceptability of banana fruits by promoting early maturity and delayed ripening.

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Conflict of Interest. None.

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