MITIGATING WATER STRESS IN SUMMER RICE USING BENEFICIAL ROOT ENDOPHYTIC FUNGUS *Piriformospora indica*

By

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THESIS

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DECLARATION

I, hereby declare that this thesis entitled "**MITIGATING WATER STRESS IN SUMMER RICE USING BENEFICIAL ROOT ENDOPHYTIC FUNGUS *Piriformospora indica***" is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled "MITIGATING WATER STRESS IN SUMMER RICE USING BENEFICIAL ROOT ENDOPHYTIC FUNGUS *Piriformospora indica*" is a record of research work done independently by Ms. Koya Madhuri Mani (2019-11-043) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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KOYA MADHURI MANI

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LIST OF ABBREVATIONS

Abbreviation	**Expansion**
%	Per cent
@	At the rate of
°C	Degree Celsius
AM	Arbuscular Mycorrhizal
B:C	Benefit -cost
CAT	Catalase
CD	Critical difference
cm	Centimeter
cm^3	Cubic centimeter
CMS	Cell membrane stability
CPE	Cumulative pan evaporation
CSI	Chlorophyll stability index
DAS	Days after sowing
DAT	Days after transplanting
DMP	Dry matter production
$d\ Sm^{-1}$	Deci Siemen per meter
EC	Electrical conductivity
et al.	Co-workers/ co- authors
Fig.	Figure
FYM	Farm yard manure

g	Gram
ha	Hectare
IW/CPE	Irrigation water/Cumulative pan evaporation
K	Potassium
KAU	Kerala Agricultural University
kg ha^{-1}	Kilogram per hectare
LAI	Leaf area index
µmole	Micro mole
m^2	Per square meter
M	Meter
mg	Milli gram
Min.	Minimum
mm	Milli meter
MOP	Muriate of potash
N	Nitrogen
NS	Non-significant
P	Phosphorus
PDA	Potato dextrose agar
pH	Negative logarithm of hydrogen ion concentration
PI	Panicle initiation
POP	Package of practices
RBD	Randomized block design
RH	Relative humidity
RLWC	Relative leaf water content
ROS	Reactive oxygen species
₹	Indian rupees
SEm	Standard error mean

SOD	Super oxide dismutase
t ha^{-1}	Tonnes per hectare
TSS	Total soluble sugar
viz.	Namely
WUE	Water use efficiency

INTRODUCTION

1. INTRODUCTION

Climate change has multifaceted interactions with crop production and there is an urgent need to produce sufficient food for the growing population without blaming the climate uncertainty. Research should therefore focus on mitigating the climate change effects like drought, heavy rainfall and rise in temperature so that the yield prospect will not be reduced with changing climate.

Rice is one of the most important staple foods for more than half of the world population, the majority of which are located in Asia. It has been estimated that for every one billion people added to the world's population, 100 million more tonnes of rice (paddy) need to be produced annually (RICE, 2020). In India, rice occupies 23.3 per cent of gross cropped area and 121.46 million tonnes was estimated at record in rice grain production playing an important role in national food supply (GOI, 2020). Rice is grown mostly during *Kharif and Rabi* ensuring adequate water supply. However, for meeting the additional domestic requirement of food grains and feeding livestock, rice cultivation needs to be extended to summer season.

In Kerala, rice is the major food grain produced and intensive efforts are being made by the State Government for augmenting the domestic production. However, rice cultivation has been declining over the years and the land is either kept fallow or getting converted to other upland crops especially during summer. Growing rice during summer should be a practical option for enhancing production levels. Drought or water stress is the prominent reason for drop in paddy acreage as well as yield during the summer season. Crop growth and economic yield are significantly affected by the water stress situation at the critical stages *viz*., maximum tillering, panicle initiation and grain filling in summer rice.

Use of microorganisms that can enhance stress tolerance by plants provide an alternate and ecologically sound way of protecting plants against stress conditions. Endophytic beneficial root fungi are organisms that live in the intercellular or intracellular space of plant tissue resulting in a symbiotic association with the host plant. *Piriformospora indica* is a beneficial root endophytic fungus identified from the root zone area of xerophytic plants in the Thar desert in Rajasthan, India (Verma *et al.*, 1998). It was first reported as a novel endophyte promoting root development. Later, it was reported that plants colonized with *P. indica* were found to be promoted in biomass accumulation, nutrient uptake and abiotic stress tolerance especially drought stress (Sahay and Varma, 1999). This beneficial root endophytic fungus could colonize the roots of large number of plant species like rice, maize, wheat, etc., and was found responsible for the plant growth promotion in unfavourable conditions like water stress, salt stress, nutritional stress, etc. It is known to mitigate the biotic and abiotic stress on the plant growth and development in a sustainable way without causing any harm to the environment and natural resources.

P. indica colonization improved the nitrogen uptake by nitrogen metabolism modification which enhanced the water stress tolerance to plants and was responsible for plant survival in drought condition (Danesh, 2015). *P. indica* could be utilized as a plant promoter, biofertilizer, bioprotector and bioregulator (Gill *et al.*, 2016). Fungal colonization seemed to diminish drought-induced growth hindrance likely through an improved water balance, reflected by the higher leaf water potential and gas exchange (Hosseini *et al.*, 2017). The stimulatory effect of *P. indica* on eco physiological parameters especially intrinsic water use efficiency, photosynthetic rate, stomatal conductance and carboxylation efficiency of rice plants were reported by Bertolazi *et al.* (2019).

In the present scenario of climate change with uncertainty in receipt of rain, moisture stress at critical growth stages can unfavourably affect growth and yield of summer rice. Reports on the potential of *P. indica* to withstand moisture stress in various crops necessitated the need for exploiting its potential for promoting climate resilient agriculture. However, the success of the microbe has to be tested under field condition since the performance depends on the complex interactions between the plants and microbes.

In this background, the present study was undertaken to assess the performance of *P. indica* colonized rice under different levels of moisture stress during summer and to estimate the water use efficiency.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

Rice is the most important staple food crop of India, occupying 23.3 per cent of the gross cropped area and 43 per cent of total food grain production (GOI, 2020). Rice is mostly grown during *Kharif* and *Rabi* ensuring adequate water supply and the general perception about summer rice is that it is drought-prone. Fallowing the land during summer due to paucity of water could be avoided by suitable interventions that can help in mitigating water stress. Studies showed that root endophytes could improve the ability of drought stress tolerance in plants. In this chapter, an attempt has been made to review the effect of beneficial root endophytic fungus (*Piriformospora indica*) under different irrigation scheduling on yield and water stress of rice during summer.

2.1 EFFECT OF IRRIGATION SCHEDULING

Productivity of rice is highly dependent on the water management of the crop during growing season. Once the crop water requirement is known, the most important step is to supply right quantity of water at right time through appropriate method to satisfy the crop water needs this is called irrigation scheduling and such the objective of high yield of good quality, high water use efficiency without any damage to soil productivity and the applying water at reasonable cost. Irrigation scheduling has great impact on crop growth and development including economic product. Severe water stress leads to lower productivity of the crop. Irrigation scheduling shows the impact on varied parameters of crop like plant height, leaf area index, root growth, physiological and yield parameters. Parihar *et al.* (1976) had putforth the approach of IW/CPE (Irrigation Water/Cumulative Pan Evaporation), which is the ratio between irrigation water depth and cumulative pan evaporation minus rain.

2.2 EFFECT OF ROOT ENDOPHYTES

Colonization capability of an organism either prokaryote or eukaryote can be known as endophyte (Saikkonen *et al.,* 2004). It may be different types like mutualism, parasitism etc. and the beneficial one to the plant is mutualism. Beneficial root endophytes could promote the plant growth and its development throughout their crop growth period even in unfavourable situations by enhancing nutrient and water uptake from the soil.

2.3 EFFECT OF BENEFICIAL ROOT ENDOPHYTIC FUNGUS *P. indica*

P. indica was first reported as a novel endophyte promoting root development. Later, plants colonized with *P. indica* had been found to promote biomass accumulation, nutrient uptake and abiotic stress tolerance especially drought stress (Sahay and Varma, 1999). *P. indica* can be utilized as a plant promoter, biofertilizer, bioprotector, and bioregulator (Gill *et al.*, 2016). The stimulatory effect of *P. indica* on ecophysiological parameters, especially intrinsic water use efficiency, photosynthetic rate, stomatal conductance and carboxylation efficiency of rice plants were reported by Bertolazi *et al.* (2019).

2.3.1 Effect of *P. indica* on Growth and Growth Attributes

Piriformospora indica, an axenically cultivable phyto promotional, biotrophic mutualistic root endosymbiont fungi belonging to order sebacinales (basidiomycotina) was reported to mimic capabilities of typical arbuscular mycorrhizal (AM) fungi.

Higher growth and biomass production were observed in *P. indica* colonized maize plants (Kumar *et al.*, 2009). Cruz and Varma (2010) depicted that salt and nutrient-stressed tomato plants have elevated biomass accumulation in presence of fungus *P. indica* and do not show any stress symptoms compared to non-inoculated stressed plants had shown stress symptoms. Anith *et al.* (2011) has observed greater plant height (20.14 cm), number of leaves per plant (9.21), shoot fresh weight (28.96g) and dry weight (3.37g) in *P. indica* colonized black pepper plants whereas, non-inoculated plants recorded lower plant height(18.93 cm), number of leaves per plant (7.66), shoot fresh weight (27.04 g) and dry weight (3.15 g).

Bagde *et al.* (2011) concluded that colonization of beneficial root endophytic fungus *P. indica* in sunflower plants had improved stem height by 19.86 per cent, leaf number by 33.3 per cent, stem diameter by 39.24 per cent, enhancement of leaf length and width by 12.2 and 17.82 per cent respectively over non-inoculated plants. Dolatabadi *et al.* (2011) documented improved growth and growth characteristics (plant height and shoot dry weight) in fungus colonized fennel plants.

A positive response in growth was observed with the colonization of *P. indica* in Arabidopsis, tobacco, and Chinese cabbage in comparison with the non-colonized plants (Johnson *et al.*, 2011).

Husaini *et al.* (2012) reported higher shoot length (4.5 cm), shoot fresh weight (831.75 mg), and growth with colonization of *P. indica* in strawberry whereas, non-colonized plants had lower shoot length (3.75 cm) and shoot fresh weight (617 mg). Alikhani *et al.* (2013) observed a comprehensive growth increment of barley in normal conditions as well as in salt-stressed conditions under co-cultivation of *P. indica* and barley roots. Bagde *et al.* (2010) documented an increase in the number of leaves, root and shoot growth with 136 per cent higher biomass in *P. indica* colonized Aristolochia plants compared to non-colonized plants.

Bagheri *et al.* (2013) documented that *P. indica* colonization could mitigate the salt stress in rice plants. There was a pronounced increase in shoot fresh weight (7.6 g), dry weight (2.5 g) and shoot length (54.3 cm) under high salt stress, whereas, non-inoculated seedlings had a lower shoot fresh weight (3.5 g), shoot dry weight (1.2 g) and shoot length (41cm).

Gosal *et al.* (2013) observed that *P. indica* colonization in sugarcane increased the tiller number per clump, canes and biomass content. Higher leaf number per plant was observed in *P. indica* colonized turmeric plants (Bajaj *et al.*, 2014). Lin *et al.* (2019) demonstrated an experiment on anthurium with *P. indica* colonization and noticed that the fungus had enhanced the growth of plants with a higher leaf area (15.6 cm^2) and plant height (12.8 cm).

The inoculation of beneficial fungus *P. indica* in *Colocasia* plants had promoted growth of the plant in terms of elevated leaf number per plant, leaf length and leaf breadth (Lakshmipriya *et al.*, 2016). Su *et al.* (2017) concluded that *P. indica* could improve plant growth and development by enhancing plant height (4.07%), stem diameter (11.4%) and branch number per plant (26.7%) compared to non-inoculated plants.

A beneficial fungus colonized arabidopsis plants promoted the plant growth, fresh weight and dry weight under normal conditions as well as salt stress conditions (Abdelaziz *et al.*, 2017).

Anith *et al.* (2018) reported colonization of *P. indica* in pepper and sweet potato. Li *et al.* (2020) observed an enhanced growth in terms of leaf number per plant (6.55± 2.16), leaf area per plant, shoot fresh and dry weight with colonization of *P. indica* whereas, lower leaf number per plant (4.07±0.62) and leaf area in non-inoculated plants.

P. indica colonization not only improves post-germination parameters but also improves the germination process. Ghabooli *et al.* (2019) observed improvement in germination process and maintenance of uniformity in germination when colonized with *P. indica* in medicinal plant.

Biotization of *P. indica* with plant roots could also mitigate the frozen effect on plant growth and development and also enhanced fast recovery after frozen (post-thaw recovery). Jiang *et al.* (2020) observed the highest survival rate in biotized *Arabidopsis thaliana*.

2.3.2 Effect of *P. indica* on Yield and Yield Attributes

Beneficial root endophytic fungus *P. indica* co-cultivation enhances the yield and yield attributes in different crops and supports sustainable agriculture.

Waller *et al.* (2005) conducted an experiment in barley with the colonization of *P. indica* under salt stress condition and observed higher yield (59.9 ± 1.76 g/pot) in fungus colonized plants whereas, non-colonized salt stressed plants had yield of 53.9± 3.61 g per pot.

Bagde *et al.* (2011) realized enhanced flower diameter (43.3 %), number of seeds in flower (9.12 %), seed dry weight (45.89 %) and oil content in a seed (51.13 %) with the colonization of *P. indica* in sunflower plants over non-colonized plants. Dolatabadi *et al.* (2011) obtained higher dry weight of 1000 seeds, number of umbels per plant and high oil content in seeds (2.46 % w/w) from the fennel plants colonized with *P. indica* over non-inoculated plants.

Andrade-linares *et al.* (2013) studied the impact of *P. indica* colonization in tomato plants on its economic yield. Colonized plants flowered 12 days earlier than non-colonized plants and enhanced yield attributes and final yield (30 and 70 % higher in first two harvest) than non-colonized plants.

Das *et al.* (2014) reported that aerobic rice with *P. indica* colonization enhanced the tiller number, panicle number, panicle length, grain number per panicle and grain yield. Murphy *et al.* (2014) studied the effects of low temperature stress and *P. indica* colonization on yield of barley and concluded a mean of 22 per cent mean higher grain dry weight over non-colonized low temperature stress plants.

Achatz *et al.* (2015) observed that *P. indica* promoted number of tillers, grains per panicle and yield of barley. Colonization of root endophytic beneficial fungus *P. indica* in medicinal plant coleus enhanced the content of aerial part biomass, inflorescence development and earlier flowering in comparison with the non-colonized control plants (Das *et al.*, 2015).

Bajaj *et al.* (2014) reported higher rhizome yield (12.67 %) with more rhizome weight, volatile oil content and curcumin content with *P. indica* colonization compared to non-colonized plants.

Su *et al.* (2017) recorded enhanced yield and yield attributes *viz.*, pod number per plant (68.71 %), pod length (35.6 %), pod width (23.4 %) and 1000 seed weight (23.83 %) in mustard plants in the presence of fungus colonization compared to non-colonized mustard plants.

Anith *et al.* (2018) observed advanced flowering, spike setting (11.6 spikes at four months after colonization), more fresh weight (315.58 g) and dry weight (80.59 g) of berries in colonized plants, whereas, non-colonized plants showed delayed spike setting (no spikes at four months), lower fresh weight (243.25 g) and dry weight (65.22 g) of berries.

Co-cultivation of *P. indica* with wheat enhanced the grain yield (10 %) by enlarged ears per plant (3.8) and grain number per plant over non-colonized wheat plants with reduced ears per plant (3.2) (Taghinasab *et al.*, 2018). Noorjahan *et al.* (2018) recorded lowest number of days to full bloom (59.55 days), highest number of branches per plant at full bloom (99.9) in *P. indica* colonized marigold plants than non-colonized plants.

Abdelziz *et al.* (2019) observed that in *P. indica* colonized tomato plants yield was greatly enhanced in normal and salt-stressed conditions by 22 and 64 per cent respectively with 26, 33 per cent increment in fresh weight and dry weight.

2.3.3 Effect of *P. indica* on Physiological Parameters

Proline could resist the abiotic stress by increasing its content in *P. indica* colonized rice plants under stress conditions. Baltruschat *et al.* (2008) conducted an experiment with beneficial root endophytic fungus *P. indica* on barley under salt stress and obtained enhanced antioxidant enzyme activity and improved rate of metabolic activity in leaves. Kumar *et al.* (2009) observed that *P. indica* colonization enhanced the activity of Catalase (CAT), Super oxide dismutase (SOD) in turn reduced the susceptibility to biotic stress by enhanced plant defense system.

Chlorophyll (8.76 mg g^{-1}) enhancement was observed with the colonization of *P. indica* in Chlorophytum plants whereas, non-colonized plants contained lower chlorophyll levels (6.77 mg g^{-1}) (Gosal *et al.*, 2010). Indole acetic acid production was found to be enhanced in *P. indica* colonized barley roots through a key role of *piTam 1* gene by tryptophan feeding (Hilbert *et al.*, 2012).

The aristolochic acid in the leaves of Aristolochia was enhanced with the application of *P. indica* culture filtrate (Bagde *et al.*, 2010). Bagheri *et al.* (2013) assessed the efficiency of *P. indica* under salt stress and reported that proline and relative water content were higher in *P. indica* colonized plants mitigating the effects of salt stress. However, salt stress affected growth and development in noncolonized plants.

P. indica colonized plants had high chl-a, b and carotene pigments in comparison with non-colonized plants under salt stress (Jogawat *et al.*, 2013). High chlorophyll content and sugar content in grains has been obtained with the *P. indica* colonization in aerobic rice plants than non-colonized plants (Das *et al.*, 2014).

Anith *et al.* (2018) conducted an experiment in pepper plants with colonization of *P. indica* and found elevated levels of total chlorophyll content (1.45 mg g^{-1} of fresh tissue) and chlorophyll a (1.15 mg g^{-1} of fresh tissue) over non-colonized plants.

Elevated levels of stomatal conductance (20 % high), CO_2 accumulation (2.75 folds high) and chlorophyll content were found in salt-stressed fungus colonized maize plants. Thus, *P. indica* colonization controlled negative effect of salt stress on maize plants over uncolonized plants (Yun *et al.*, 2018).

High chlorophyll and protein contents were noticed with the biotization of *P. indica* in anthurium plants in contrast to the non-colonized plants (Lin *et al.*, 2019). Inoculation of the *P. indica* in sweet potato resulted in greater values of total soluble sugar (2.82±0.59 mg g^{-1} FW) and soluble protein (7.38±0.27mg g^{-1} FW) over non-colonized plants (Li *et al.*, 2020).

2.3.4 Effect of *P. indica* on Root Observations

Co-cultivation of *P. indica* with plant cuttings showed a positive response with genesis of adventitious roots over non-colonized plants (Druege *et al.*, 2007). Higher nodule formation, root growth and uptake of N, P, K were observed in *P. indica* colonized plants compared to non-colonized plants (Nautiyal *et al.*, 2010).

Anith *et al.* (2011) reported higher root fresh weight (11.04 g) and number (13.14) in *P. indica* colonized black pepper plants whereas, uncolonized plants had lower root number (12.06) and root fresh weight (9.03 g). Bagde *et al.* (2011) conducted a study in sunflower with the colonization of *P. indica* fungus and recorded an increase in root collar diameter (52.7 %), root number (69 %), root length (35 %), and root dry weight (24.27 %) in comparison with non-colonized treatment. Dolatabadi *et al.* (2011) conducted an experiment on fennel plants with *P. indica* colonization and recorded higher root length and dry weight (1.3 g) whereas, non-colonized plants showed root dry weight of 0.98 g.

Husaini *et al.* (2012) reported higher root fresh weight (463.75 mg per plant) and dry weight in *P. indica* colonized strawberry plants. Bagheri *et al.* (2013) determined the efficiency of *P. indica* to combat salt stress in rice and observed a higher root length (10 cm), root fresh weight (3.1 g) and dry weight (1.3 g) under 200mM NaCl salt stress. Non-colonized salt stress plants recorded lower root length (8.73 cm), root fresh weight (1.5 g) and dry weight (0.6 g).

P. indica colonized seedlings had stronger, thicker and brown roots in stressed plants compared to non-colonized stressed plants (Jogawat *et al.*, 2013). Pedrotti *et al.* (2013) noticed that root dry weight, root length, and length of lateral roots were improved by 18, 38 and 64 per cent respectively in *P. indica* colonized Arabidopsis plants in comparison with non-colonized plants.

Das *et al.* (2015) reported that *P. indica* colonisation in coleus plants enhanced root number by 22 per cent and root length by 32 per cent over the absence of fungus in plants. Lin *et al.* (2015) demonstrated an experiment with *P. indica* on anthurium plants and reported that inoculation of *P. indica* in anthurium plants improved root length (14.2 cm) and fresh weight of roots (3.5 g) whereas, non-colonized plants had lowest root length (10.9 cm) and fresh weight of roots (3.2 g).

Rane *et al.* (2015) conducted an experiment in maize with the colonization of *P. indica* and reported that fungus colonization improved root proliferation, dry weight (1.47±0.43 g) and length (38.33±4.93 cm) whereas, non-colonized plants had root length of 35.83±3.05 cm and root dry weight as 1.09±0.35 g.

Co-cultivation of beneficial fungus *P. indica* with the maize roots reported higher root biomass (2.75 g) and root length in petroleum-contaminated soils whereas, non-colonized plants had lower root biomass (2.16 g) and shallow root system (Zamani *et al.*, 2015).

Abdelaziz *et al.* (2017) conducted an experiment in tomato with *P. indica* colonization under salt and normal conditions. The results of investigation suggested that *P. indica* improved root growth and branches in both salt and normal conditions over non-colonized plants. Su *et al.* (2017) demonstrated an experiment in the lab and reported that *P. indica* biotization with brassica enhanced the characters of roots namely root length, root fresh and dry weight by 13.83, 138 and 105.6 per cent respectively in contrast to non-colonized plants.

Noorjahan *et al.* (2018) recorded greater root length (19.21 cm), root volume (39.33 cm^3) and root number per plant (127.33) in *P. indica* colonized marigold plants compared to non-colonized plants.

Yun *et al.* (2018) demonstrated that co-cultivation of *P. indica* with maize improved root volume (64 %), root dry weight (70 %) and root surface area (58 %) under salt stress situations in contrast to the salt-stressed non-colonized maize plants.

Colonization of beneficial fungus *P. indica* in sweet potato enhanced root fresh weight (278 ± 104 mg) and length of lateral roots 1.82 ± 0.41 cm whereas, non-colonized plants had root fresh weight (120 ± 48 mg) and lateral root length (1.1 ± 0.32 cm) (Li *et al.*, 2020).

2.4 EFFECT OF WATER STRESS IN RICE

Rice is a high-water requirement crop for its potential growth and yield. Water stress condition in the standing crop may reduce its growth and development by restricting the photosynthesis and cell division. The main effect of water stress in plant is reducing leaf expansion and area which sequentially reduce the transpiration, photosynthesis and affecting final economic and biological yield.

2.4.1 Effect of Water Stress on Growth Attributes

Maheswari *et al.* (2008) found that irrigation scheduled at IW/CPE ratio 1 has a high leaf area, dry matter production, and crop growth rate (CGR) in comparison with the 0.8 ratios.

Water stress at vegetative stage causes reduction in plant biomass and plant height as photosynthetic rate and dry matter accumulation were affected due to stress (Sarvestani *et al.*, 2008). Cairns *et al.* (2009) conducted a field experiment on effect of water stress on growth of rice and the study suggested that water shortage during the crop growth period between 35 and 60 days after sowing (DAS) could largely reduce the plant height, tiller number per plant over irrigated rice plants.

Rice cultivation in submerged conditions has recorded better growth parameters like tiller number per plant and plant height compared to non-submerged condition, which is a drought stress situation (Mostajeran and Eichi, 2009).

Praba *et al.* (2009) observed that rice plants irrigated at 30 per cent field capacity (FC) particularly during the vegetative stage resulted in lower leaf length elongation with the symptoms of leaf rolling and wilting symptoms which were not observed in control plants. Akram *et al.* (2013) reported that water stress at panicle initiation registered greatest reduction of shoot dry weight and the lowest reduction was recorded by water stress at grain filling stage.

Rice raised under System of rice intensification (SRI) when irrigated 1 and 3 days after draining pond water reached the stage of panicle initiation and flowering 4 days earlier in comparison to irrigation given at 5 days after draining of pond water.

Dry matter accumulation and net photosynthetic rate were found to be higher in former treatments in comparison with latter treatment (Das and Chandra, 2013).

Plant height and number of tillers per unit area were greatly reduced at a moisture stress of 50 per cent FC in comparison to 100 per cent FC at 80 days after transplanting (DAT) (Hussain *et al.,* 2018).

Water stress greatly declined the growth parameters like plant height and leaf area of rice plant. With increase in water stress i.e., from FC to 25 per cent FC greater reduction in plant height and leaf area were observed (Kenawy *et al.*, 2018). Water shortage treatments given to rice by Singh *et al.* (2018) resulted in low plant height, tiller number per plant and low leaf area compared to better growth parameters in control plants.

In another study in summer rice Duvvada *et al.* (2020) recorded the highest number of tillers and CGR in continuous saturation followed by continuous ponding whereas, irrigation to the level of saturation after a hair crack formation resulted in lowest number of tillers and CGR. Hossain *et al.* (2020) opined that irrigating rice at 75 and 50 per cent of saturation observed the lowest plant height, dry matter production and overall plant growth as compared to irrigating at saturation that resulted in better plant growth.

2.4.2 Effect of Water Stress on Yield and Yield Attributes

Kukal *et al.* (2005) in their study with soil matric suction had observed a decline in yield with an increase in soil matric suction. The treatments included scheduling irrigation to rice with tensiometers installed at 15–20 cm soil depth at five levels of soil matric suction viz. 80, 120, 160, 200 and 240±20 cm, in addition to the recommended practice of alternate wetting and drying with an interval of two days after complete infiltration of ponded water. The grain yield of rice remained unaffected up to soil moisture suction of 160±20 cm each year.The yield was found to decrease with increase in soil moisture suction from 200 to 240 +- 20 cm.

Kumar *et al.* (2006) obtained the highest rice grain yield with daily irrigation, whereas the lowest yield was obtained with irrigation at five (or) six days intervals in the summer season. In another study Sarvestani *et al.* (2008) had obtained lower values for yield attributes, namely panicle number, number of filled grains, thousand grain weight, yield and harvest index, when plants had undergone a moisture stress during the reproductive stage.

As reported by Mostajeran and Eichi (2009), the lowest number of grains per panicle and filled grains were obtained in nonsubmerged condition, whereas, submerged condition resulted in most number of filled grains and grains per panicle. According to Praba *et al.* (2009), irrigation at 30 per cent FC during reproductive stage reduced spikelet fertility, grains per panicle and grain weight compared to control.

Pandey *et al.* (2010) conducted a field experiment during the dry season to determine the effect of water stress condition on hybrid rice and summarized that irrigation one day after disappearance of water produced higher yield (6.8 t ha^{-1}), lower sterility percentage, panicle length, effective tillers, grains per panicle and grain weight compared to the yield recorded when irrigated at three days after the disappearance. Irrigated water depth at 9 cm had the highest grain yield (9.9t ha^{-1}) in rice, than the irrigated water depth at 18 cm and 0 cm (Abu and Malgwi, 2011).

Cha-um *et al.* (2012) observed that with enhanced water deficit there was corresponding decline in panicle length, grains per panicle and filled grains. Water stress at panicle initiation stage had greatly reduced panicle number, length, and number of grains per panicle and total grain yield (Akram *et al.*, 2013).

Das and Chandra (2013) obtained higher yields in SRI rice when irrigated at one and three days after draining pond water in comparison to irrigation at five days after draining pond water of SRI rice and conventional rice. Zain *et al.* (2014) reported that drought stress for 15 days during the reproductive stage resulted in 30 per cent reduction in grain yield compared to control, where assured irrigation was there.

A study by Dasgupta *et al.* (2015) concluded that water stress at flowering stage in rice greatly reduced the yield and yield attributes like panicle length, grain number per panicle, filled grain number, and grain weight followed by drought stress given at grain filling stage and tillering stage. Sonit *et al.* (2015) reported that in rice under drip system, irrigation scheduled at IW/CPE of 1.4 produced the highest yield, while irrigation scheduled at 0.6 produced the lowest yield.

In drought studies on rice, Moonmoon *et al.* (2017) reported that imposing drought stress by irrigating at 40 per cent FC during grain filling stage greatly reduced the grain dry weight and thereby grain yield. Sayed and Monem (2017) observed higher number of panicles m^{-2}, panicle weight, and grains per panicle at 30 per cent DASM (Depletion of Available Soil Moisture) than 60 and 85 per cent DASM.

Irrigation scheduled at IW/CPE ratio of 1.0 upto panicle initiation stage and thereafter at 1.2 upto dough stage in rice produced higher yield attributes namely number of panicles per hill, number of filled grains per panicle, test weight, grain yield (4462 kg ha^{-1}) and straw yield (5977 kg ha^{-1}) (Keerthi *et al.*, 2018). In a study conducted by Kenawy *et al.* (2018), lowest number of grains per panicle and 1000 grain weight were recorded when the plants were exposed to a severe water stress treatment 25 per cent FC in comparison to irrigation at FC, where the highest number of grains per panicle and 1000 grain weight was obtained.

Singh *et al.* (2018) observed that water stress treatment for seven days at reproductive stage of rice plants produced the lowest yield attributes and yield in comparison with fully watered plants.

Prasad *et al.* (2019) had observed that drought stress at reproductive stage of rice resulted in a lower grain yield in both drought susceptible and tolerant varieties, but a greater loss in grain yield was reported in drought susceptible varieties. Hossain *et al.* (2020) recorded the highest number of panicles, number of grains per panicle, 1000 grain weight, yield and harvest index in treatments with irrigation at saturation as compared to irrigation at 75 per cent and 50 per cent saturation.

2.4.3 Effect of Water Stress on Physiological Parameters

Low leaf proline content was recorded with the submerged condition and high leaf proline content was observed with non-submerged condition (Mostajeran and Eichi, 2009). Praba *et al.* (2009) studied the effect of drought stress in a field experiment in rice and reported that withholding irrigation for seven days or irrigation at 30 per cent FC had brokendown the stomatal conductance and membrane stability index compared to control.

Pandey *et al.* (2010) opined that application of irrigation water one day after disappearance of ponded water had enhanced the nitrogen content in grain, leaf and stem over irrigation at three days after the disappearance of ponded water.

Majeed *et al.* (2011) reported that with increase in intensity of drought stress the proline content and abscisic acid ABA accumulation were found to be enhanced. The effect of increasing water stress on relative leaf water content (RLWC) was evaluated by Muthurajan *et al.* (2011). They concluded that intermittent drainage at 3 days before heading for 3 days resulted in lowest RLWC with 27 per cent decrement of RLWC in comparison with the well-watered control plants. Water stressed rice plants had lower RLWC, chlorophyll content, stomatal conductance, and elevated levels of proline in flag leaf (Cha um *et al.*, 2012).

Greatest decline in RLWC and photosynthetic active radiation were observed by water deficit condition at panicle initiation stage followed by anthesis and grain filling stage. Water stress condition in grain filling stage resulted in maximum reduction of stomatal conductance and water use efficiency, compared to water stress at anthesis and panicle initiation (Akram *et al.*, 2013). Jabasingh and Babu (2013) studied the relation between proline content and drought stress and reported that proline content has increased with increase in water stress condition. A higher proline content was reported in rice irrigated at seven days interval.

Zain *et al.* (2014) observed a higher peroxidase activity in plants experiencing drought stress for 25 days, followed by periodical water stress for 15 days. The lowest peroxidase activity was observed in plants experiencing drought stress for 15 days at the reproductive stage. Content of malondialdehyde has reduced with increased peroxidase activity and catalase content, which might be responsible for tolerance to water stress.

Dasgupta *et al.* (2015) studied the effect of water stress at different growth stages and reported that water stress at flowering greatly reduced the RLWC and elevated the leaf proline content. The study concluded that irrigation done after drought stress at flowering couldn't help the plant to recover however, the plants could recover with irrigation after experiencing drought stress at tillering. Khairi *et al.* (2015)

compared alternate wetting and drying to flooding and found that RLWC, chlorophyll, nitrogen, phosphorous, and potassium were the lowest in fields with alternate wetting and drying.

Moonmoon *et al.* (2017) reported that drought stress at grain filling stage decreased the chlorophyll content greatly as compared to control treatment. According to Kenawy *et al.* (2018) rice plants subjected to severe water stress irrigation at 25 per cent FC resulted in highest proline content in comparison with plants under mild and moderate stress. According to Mishra *et al.* (2018) drought conditions induce lowering of RLWC and membrane stability index in rice varieties.

Leaf proline content increased from moderate drought to severe drought condition and a significant decrease of proline content was observed when plants were re-watered for 1 day after severe drought stress (Dien *et al.*, 2019). According to Prasad *et al.* (2019), drought stressed condition in drought susceptible varieties resulted in higher leaf proline and leaf rolling compared to drought tolerant varieties.

Sovannarun *et al.* (2019) observed lowest RLWC and chlorophyll content in rice when irrigation was withheld for seven days compared to well-watered treatment. Low RLWC and water use efficiency in rice have been observed with irrigation at 75 per cent and 50 per cent saturation (Hossain *et al.*, 2020).

Nasrin *et al.* (2020) had reported high proline content, protein content and catalase activity in rice plants under drought stress. They also observed that drought-stressed plants have lower chlorophyll a and b and its ratio along with total chlorophyll content.

2.4.4 Effect of Water Stress on Root Observations

A field study conducted by Kondo *et al.* (2000) to determine the root growth under water stress situations revealed root growth of rice was severely hampered namely, total root length 2138 m m^{-2} under severe stress (no irrigation) conditions as compared to total root length 6981m m^{-2} mild stress (intermittent irrigation).

Cairns *et al.* (2009) experimented on upland rice by withholding water for seven days to impose drought stress and reported that root density (number of roots per hill) had greatly reduced at drought condition (10 ± 12.0) over irrigated condition (20 ± 17.8). Sikutu *et al.* (2010) observed that root length and root shoot ratio decreased with water deficit treatments. Control plants had higher root lengths, whereas water deficit treated plants have lower root lengths.

Dasgupta *et al.* (2015) administered a field experiment by imposing water stress treatment and aimed for recovery of plants with irrigation after drought stress. The result of the research revealed that irrigation after water stress greatly enhanced root biomass over control treatment.

Hazman and Brown (2018) reported that drought stress (restricted irrigation) reduced rooting depth of rice roots by 20 to 26 per cent, whereas, 80 per cent reduction in nodal root number over well-watered plants.

Withholding of irrigation for seven days as water stress condition to rice resulted in the highest root shoot ratio in comparison to the control treatment (Sovannarun *et al.*, 2019). Nasrin *et al.* (2020) conducted a field experiment to evaluate the effects of water stress in rice by imposing water stress conditions (restricting irrigation) for 12, 15, 18 and 21 days. They had observed that drought treatment for 21 days decreased root length by 68 per cent, fresh weight 98.3 per cent, and dry weight 94.7 per cent.

2.5 EFFECT OF *P. indica* ON WATER STRESS

Reports on the potential of *P. indica* to withstand moisture stress in various crops necessitate the need for exploiting its potential for promoting climate-resilient agriculture. It was found that *P. indica* could mitigate the water stress by regulating the root growth of the plant by more acquisition of phosphorus to the plant and also by regulating the internal water status in the cell by producing more osmolytes like proline (Johnson *et al.,* 2014).

2.5.1 Effect of Water Stress and Colonization with *P. indica* on Plant Growth Attributes

Husaini *et al.* (2012) reported that *P. indica* colonized drought stressed strawberry plants exhibited tolerance to drought by higher biomass production and recorded a higher survival rate in comparison to non-colonized drought-stressed plants.

In another study, Tanha *et al.* (2014) realized increased leaf biomass, fresh weight and dry weight in medicinal plant globe artichoke under drought stress colonized with beneficial root endophytic fungus *P. indica.*

Hoessini *et al.* (2017) demonstrated an experiment on wheat with *P. indica* colonization under drought stress with a matric suction of 0, -0.3,-0.5 MPa. Results of the investigation recorded an enhancement in plant height (32 %), leaf area (51 %) and shoot weight (66 %) in colonized plants over uncolonized plants.

Co-culture of *P. indica* with the plant roots could mitigate the effects of water shortage on plant growth and development. Xu *et al.* (2017) observed that *P. indica* colonized plants grew well under normal conditions as well as water stress (20 per cent poly ethylene glycol -600) conditions. Higher growth of the plant, leaf area (33 cm^2) and number of leaves per plant (3.8) were recorded under water stress conditions in the fungus colonized plants.

Ahmavadan and Hajinia (2018) conducted a field experiment to assess the effect of *P. indica* under water stress conditions induced by irrigation at various CPE levels cumulative pan evaporation levels (CPE of 60mm- well watered, 90mm-mild stress, 120mm-severe stress) in millet. The study concluded that fungus colonization improved plant height (27.07%) and flag leaf area (18.64%) in contrast to the non-colonized water-stressed plants.

A mycorrhizal association between *P. indica* and rice under osmotic stress could relieve the adverse effects of stress by improved uptake of functional elements of drought stress like phosphorous and zinc in rice plants (Saddique *et al.*, 2018).

Swetha and Padmavathi (2019) conducted an experiment with *P. indica* colonization on brinjal, where drought stress was induced by restricting irrigation after 60 days of regular watering until start of symptoms of wilting. *P. indica* colonized plants had higher shoot length (37.16 cm), dry weight of shoots (3.76 g) and leaf number (11.33) whereas, drought stressed uncolonized plants exhibited lower shoot length (31.83 cm), shoot dry weight (2.03 g) and leaf number (7.33).

2.5.2 Effect of Water Stress and Colonization with *P. indica* on Yield and Yield Attributes

Sherameti *et al.* (2008) conducted an experiment on *Arabidopsis thaliana* with *P. indica* colonization under drought stress and reported that *P. indica* could combat drought stress and produced flowers and seeds whereas, non-colonized drought stressed seedlings didn't produce flowers and seeds.

Higher grain yield (1794 kg ha^{-1}) and yield attributes *viz.*, panicle number per plant, grain number per panicle and seed dry weight were found in the presence of *P. indica* under water stress conditions in contrast to the absence of fungus under drought stress (Ahmadvand and Hajinia, 2018).

Amini *et al.* (2020) undertook an experiment with *P. indica* inoculation in a moldavian balm plant under water stress conditions (saturation, 70-85, 55-70, 40-55 % FC) and concluded that fungus colonization improved yield and yield components. Dry weight and essential oil content were increased by 40.9 and 37 per cent respectively in all levels of water stress compared with non-inoculated plants.

Tsai *et al.* (2020) conducted a study, where rice seedlings were subjected to drought stress with poly ethylene glycol for four days and noticed that fungal inoculated drought stressed plants flowered 5 days earlier than uncolonized drought stressed plants. Study also reported high panicle number per plant (2.05) and number of filled grains per panicle (96.10), whereas, uncolonized drought stressed plants recorded lower panicle number per plant (1.76) and filled grains per panicle (73.90).

2.5.3 Effect of Water Stress and Colonization with *P. indica* on Physiological Parameters

Husaini *et al.* (2012) reported higher chlorophyll content and RLWC in *P. indica* colonized drought-stressed strawberry plants. *P. indica* colonization improved drought tolerance in wheat by enhanced activity of catalase and decreased the content of MDA, which prevented lipid peroxidation.

Tanha *et al.* (2014) investigated the response of drought stress in globe artichoke with the presence of beneficial root endophytic fungus *P. indica* and signaled that presence of fungus greatly enhanced proline content in leaves of water-stressed plants which could mitigate consequences of stress on plant growth over the non-colonized water-stressed plants. Chlorophyll content decreased in non-colonized drought-stressed plants in comparison to colonized drought-stressed plants (Yaghoubian *et al.*, 2014).

P. indica colonized maize plants under water stress registered higher proline content to mitigate the drought stress with less membrane damage in comparison to the non-colonized stressed plants (Xu *et al.*, 2017)

Fard *et al.* (2017) noticed that upregulation of two miRNAs i.e., miR159 and miR396 led to the physiological changes that improved tolerance of drought stress through the modification of bio water-saving pathway and ABA signaling pathway in *P. indica* colonized rice plants. Hosseini *et al.* (2017) concluded that *P. indica* colonized water-stressed (osmotic potential of 0, -0.3,-0.5 MPa) plants had high leaf water potential (-3.4 MPa), relative water content (74.7) and chlorophyll content (12.44 µg mL^{-1}) in contrast to the non-colonized water-stressed plants.

Ahmavadan and Hajinia (2018) concluded that *P. indica* could improve chlorophyll level under severe water stress situations in contrast to the fungus non-inoculated water-stressed plants. *P. indica* colonized plants under drought stress showed higher chlorophyll content (0.07g L^{-1}) and proline (20.9 µg mL^{-1}) thereby, improved water uptake from water deficit soil and escaped adverse effects of water stress (Sweta and Padmavathi 2019).

Amini *et al.* (2020) reported that the presence of fungus in medicinal plant could improve the chemical components of essential oil content by 70 per cent under high drought stress over non-colonized plants.

2.5.4 Effect of Water Stress and Colonization with *P. indica* on Root Observations

Tanha *et al.* (2014) investigated the response of drought stress in globe artichoke with the presence of beneficial root endophytic fungus *P. indica* and reported that fungal colonization enhanced root volume, root fresh weight, and root length under water stress situations over non-colonized drought-stressed plants.

The effect of water stress condition on *P. indica* inoculated maize plants under water stress condition indicated higher root fresh weight and dry weight over non-colonized plants drought stressed plants (Xu *et al.*, 2017).

Hosseini *et al.* (2017) studied the effect of *P. indica* under drought stress and found that fungus colonized drought stress plants had larger root volume (36 %) and root length (16 %) in contrast to non-colonized drought-stressed plants. Hosseini *et al.* (2018) conducted an experiment on maize with water stress conditions in terms of water potential levels *viz.*, -0.1, -0.2, -0.3, -0.4 MPa, with *P. indica* co-cultivation. The study revealed that fungal colonization could reduce stress on plant root development which might be by osmotic balance or cell wall modification with improved root elongation rate and deeper root penetration.

Water-stressed *P. indica* colonized brinjal plants had higher root length (26.33 cm) and root dry weight (2.1 g) whereas, non-colonized plants showed lower root length (16.66 cm) and root dry weight (1.43 g) under water-stressed plants (Swetha and Padmavathi, 2019).

The above cited literature reveals the beneficial effect of colonization with endophytic fungus *P. indica* in managing drought stress in various crops, specifically in rice. However, the research works pertaining to the effect of *P. indica* colonization in mitigating water stress under field condition are meager. The present investigation was hence attempted to study the effect of *P. indica* in mitigating the drought stress experienced by rice plants in summer under tropical condition.

MATERIALS AND METHODS

3. MATERIALS AND METHODS

The experiment entitled 'Mitigating water stress in summer rice using beneficial root endophytic fungus *Piriformospora indica*' was conducted at the College of Agriculture, Vellayani, Kerala. The objective of the study was to assess the performance of *P. indica* colonized rice under different levels of moisture stress during summer. The materials and methods followed are briefly discussed below.

3.1 EXPERIMENTAL SITE

The experiment was laid out in the reclaimed low land areas in block D of Instructional Farm attached to College of Agriculture, Vellayani, Thiruvananthapuram, Kerala. The site is located at 8° 43' N latitude, 76° 98' E longitude and at an altitude of 20.0 meters above mean sea level.

3.1.1 Soil

Soil of the experimental site belongs to the soil order Oxisol with sandy clay loam texture. Composite soil sample was taken prior to the experiment from the field and tested for its physico-chemical properties. The physico-chemical composition of the soil of the experimental field is presented in Table 1.

3.1.2 Climate and Season

The experiment was conducted during summer season of 2021. The data on mean maximum and minimum temperatures, relative humidity and rainfall were collected from the Class B Agromet Observatory of Department of Agricultural Meteorology, College of Agriculture, Vellayani. Weather data during the cropping season (March-June 2021) is depicted in Fig. 1, 2 and documented in Appendix 1.

The mean maximum temperature ranged between 30.5°C to 34.3°C and mean minimum temperature ranged between 20.4°C to 26.4°C, mean maximum relative humidity ranged between 87.30 to 96 per cent, and mean minimum relative humidity ranged between 65 to 88.1 per cent. The total annual rainfall received during cropping season was 860.7 mm.

3.1.3 Cropping History

The experimental site was lying fallow during the previous season.

Table 1. Physico-chemical properties of the soil

Sl.no	Property	Value	Rating	Reference
1.	Fine sand (%)	29.20	Sandy Clay Loam	Bouyoucos Hydrometer method (Bouyoucos, 1962)
	Coarse sand (%)	18.60		
2.	Silt (%)	24.40		
3.	Clay (%)	26.40		
4.	pH (1: 2.5)	5.00	Acidic	Jackson (1973)
5.	Electrical Conductivity (dS m^{-1})	0.50	Safe	Jackson (1973)
6.	Organic Carbon (%)	0.60	Medium	Walkley and Black (1934)
7.	Available N (kg ha^{-1})	140.46	Low	Subbaih and Asija (1956)
8.	Available P (kg ha^{-1})	198.24	High	Bray and Kurtz (1945)
9.	Available K (kg ha^{-1})	332.53	Medium	Jackson (1973)

3.2 MATERIALS

3.2.1 Crop and Variety

Prathyasa (MO 21), released from Rice Research Station (RRS) Moncompu of Kerala Agricultural University was used for the study. It is a non-lodging, photo insensitive and semi-tall variety with a duration of 105-110 days. The grains are red, long and bold with an average grain and straw yield of 5.0 and 6.5 t ha^{-1} respectively. It is moderately resistant to gall midge, brown plant hopper, sheath blight and sheath rot.

3.2.2 Source of Seed

Seeds of variety *Prathyasa* were collected from Rice Research Station, Moncompu.

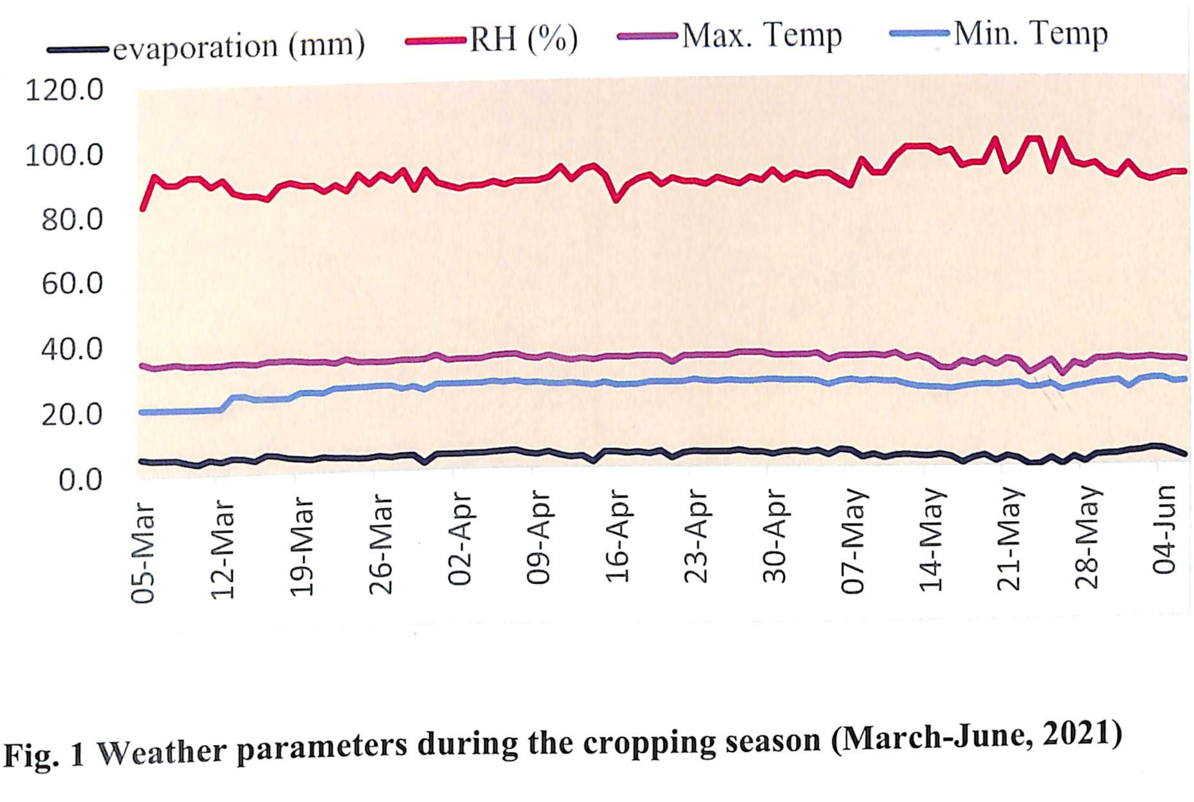


Fig. 1 Weather parameters during the cropping season (March-June, 2021)

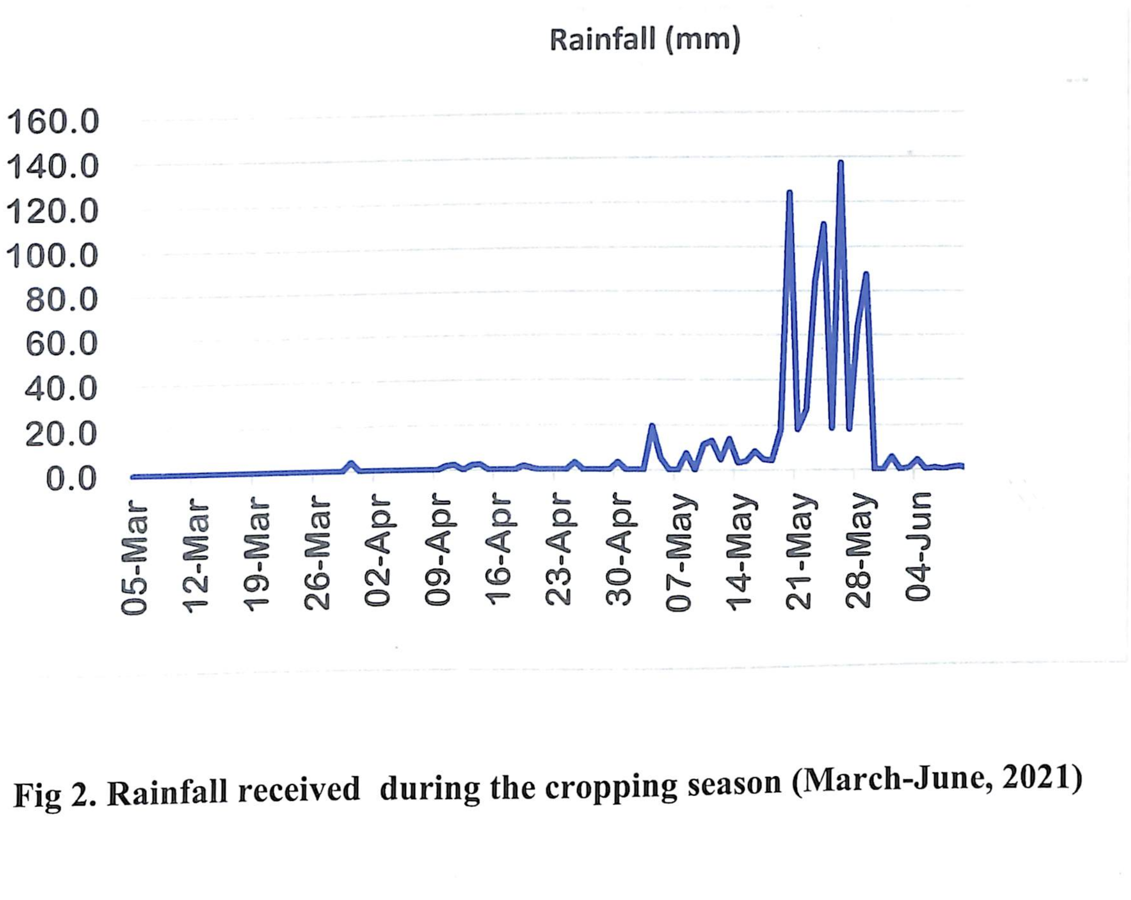


Fig 2. Rainfall received during the cropping season (March-June, 2021)

3.2.3 Manures and Fertilizers

Farmyard manure (FYM) containing 0.50 per cent N, 0.20 per cent P_2O_5 and 0.40 per cent K_2O was used as source of organic manure. The chemical fertilizers used for the study were urea (46 %N), rajphos (20 % P_2O_5) and muriate of potash (60 % K_2O).

3.2.4 Irrigation

Irrigation was scheduled as per treatments and the required quantity of water was measured using water meter.

3.2.5 Collection of Culture of *Piriformospora indica*

Culture of beneficial root endophyte *Piriformospora indica* was collected from the Department of Plant Pathology, College of Agriculture, Vellayani. In order to maintain the viability of the fungus, monthly subculturing of *P. indica* in sterile Potato dextrose agar (PDA) medium in petri plates was done. The broth was made with PDA solution in conical flask by addition of *P. indica* culture bits (2-3) and allowed to grow for three weeks.

3.3 METHODS

3.3.1 Design and Layout

Design	:	RBD
Treatments	:	2 x 3 x 2
Replications	:	3
Season	:	Summer 2021
Variety	:	Prathyasa
Plot size	:	4 m x 5 m
Spacing	:	15 cm × 10 cm

3.3.2 Treatments

Factor A : Colonizing with *P. indica* (P)

p_1 : *P. indica* colonized rice

p_2 : non colonized rice

Factor B: Irrigation interval (I)

i_1 : at 30 mm CPE

i_2 : at 35 mm CPE

i_3 : at 40 mm CPE

Factor C: Depth of irrigation(D)

d_1 : to a depth of 1.5 cm

d_2 : to a depth of 3 cm

Treatment combinations

$p_1i_1d_1$ $p_1i_2d_1$ $p_1i_3d_1$ $p_1i_1d_2$ $p_1i_2d_2$ $p_1i_3d_2$

$p_2i_1d_1$ $p_2i_2d_1$ $p_2i_3d_1$ $p_2i_1d_2$ $p_2i_2d_2$ p_2i_3

3.3.3 Layout of the Field Experiment

Layout of the field experiment is furnished in Fig.3

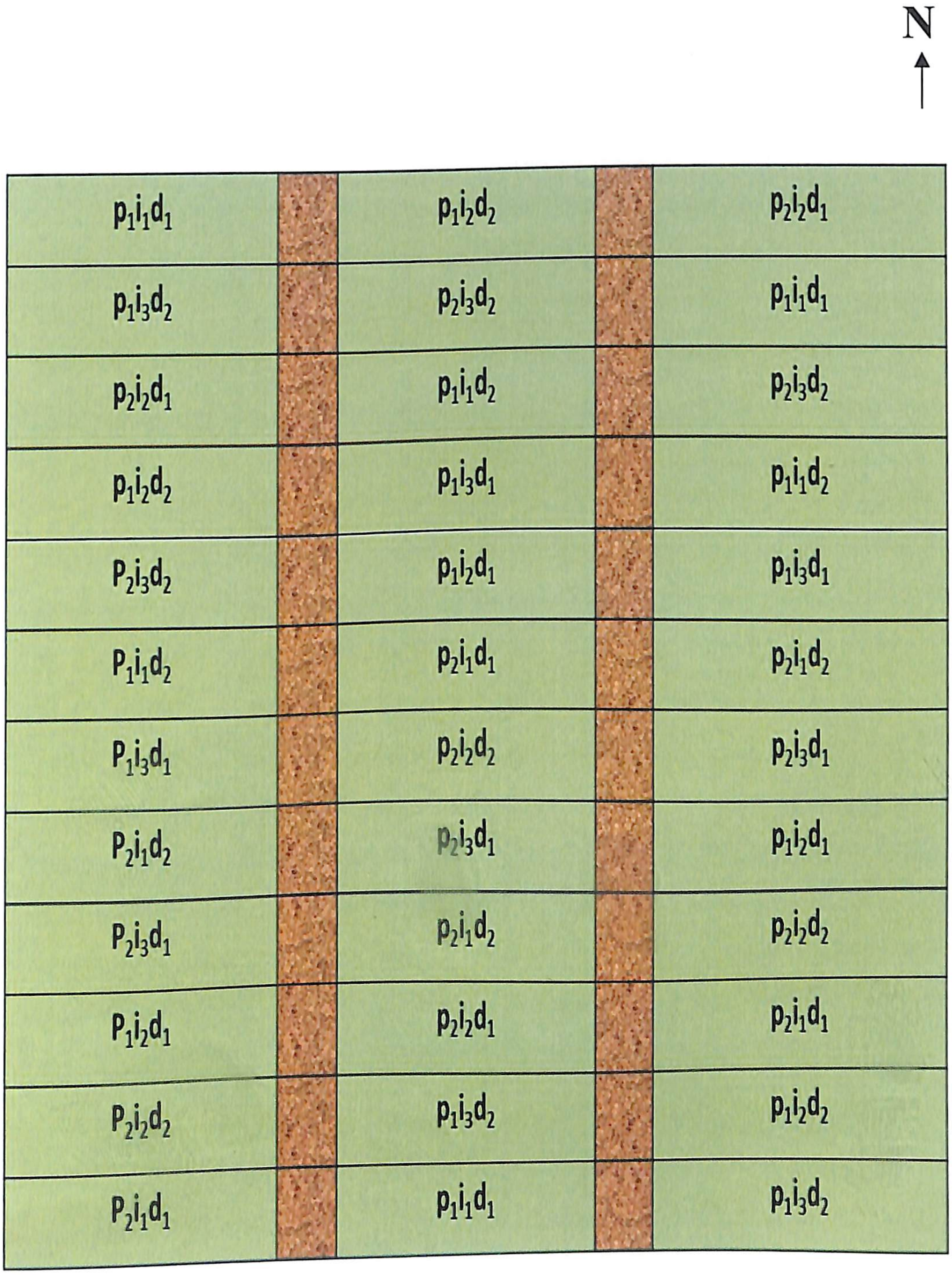


Fig 3. Layout of the experimental field

3.3.4 Crop Management

The crop was grown and managed in line with the cultivation practices as per the recommendations of Package of Practices (KAU, 2016).

3.3.4.1 Land Preparation

The reclaimed low land area was ploughed using a power tiller and leveled. Plots of 20 m^2 were made with bunds of width 50 cm on all four sides. In between each block, drainage channels of 0.75 m width were maintained. Lime was applied to the field prior to the experiment at 600 kg ha^{-1}.

3.3.4.2 Co-cultivation of P. indica with Rice Seedlings

Rooting medium comprising 500 g coir pith compost, 500 g cowdung powder and 20 g basin flour in polypropylene covers was sterilized in autoclave at 121°C for 21 minutes (min.). It was then transferred to clean, dried and sterilized plastic trays. Fungal broth (40 mL) was added to these trays filled with medium under laminar air flow and kept in incubator for five days for white fungal mat formation. Seeds were sterilized by soaking in 0.1 per cent HgCl solution for one min and later soaked in distilled water for 12 hours. Sterilized and pre-soaked paddy seeds were spread on the surface of the rooting media with sufficient white mycelial formation. The roots were examined for colonization under microscope from five days after sowing (DAS) (Johnson *et al.*, 2011). Simultaneously control / non-colonized seeds sterilized and soaked in distilled water for 12 hours were sown in rooting media trays without fungus.

3.3.4.3 Assessment of Root Colonization with Fungus

Root colonization was observed by taking ten random root bits from the co cultivated rice seedlings. The collected roots were dipped in 10 per cent KOH overnight, followed by five consecutive washing with water. Later the washed root bits were treated with 1 per cent HCl for four minutes. The treated roots were mounted on a sterile glass slide using the stain lactophenol cotton blue (Johnson *et al.*, 2011). Detailed examination of the colonized roots was done under the microscope.

3.3.4.4 Seeds and Sowing

The seeds kept for germination in *P. indica* culturing trays for colonisation of the fungus were treated as colonized seedlings and seeds kept in the same media without the fungus were treated as non-colonized seedlings. After 14 days, both the set of seedlings were transplanted to the field as colonized and non-colonized plants under a spacing of 15 cm x 10 cm.

3.3.4.5 Application of Manures and Fertilizers

Farmyard manure at 5 t ha^{-1} was added to all the plots uniformly. Recommended nutrient dose of N: P_2O_5: K_2O @ 70: 35: 35 kg ha^{-1} was adopted in the experimental field. Nitrogen was applied in 3 equal split doses *i.e.*, at basal, active tillering and panicle initiation stage, entire phosphorus was applied as basal and potassium was applied in two split doses at basal and panicle initiation (PI) stage.

3.3.4.6 Irrigation

The transplanted colonized and non-colonized rice seedlings were uniformly irrigated for 10 days after transplanting (DAT). The data on daily evaporation collected from Department of Agricultural Meteorology, College of Agriculture, Vellayani was used for scheduling the frequency of irrigation and water meter was used to measure the quantity of irrigation water to be diverted to each plot as per treatments.

3.3.4.7 Weed Management

Two hand weedings were done at 15 and 30 DAT.

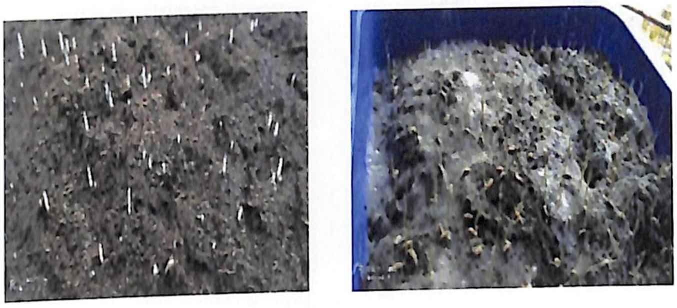
3.3.4.8 Plant Protection

No disease incidence was observed during the cropping season. However, rice bug infestation noticed during flowering and milk stage was controlled by spraying malathion (4 mL L^{-1}).

3.3.4.9 Harvest

The crop was harvested after 115 DAS when the grains were at hard dough stage and dry. The plants from net plot area were harvested manually excluding the

White fungal mat formation on rooting media



Germinating seeds on colonized rooting media

Seedlings at 7 DAS

Seedlings at 14 DAS

At 10 DAT

At tillering stage

At flowering stage

Plate 3. Stages of field experimentation

Plate 4. General view of experimental field

border rows, threshed separately followed by winnowing. The produce was cleaned, sun dried, weighed and dry weight expressed as kg ha^{-1}

3.4. OBSERVATIONS

3. 4. 1. Observations on Growth Characters

Five randomly selected plants from the net plot area avoiding the border rows were tagged as observation plants. The observations on the growth, yield attributes and yield were recorded on these plants.

3.4. 1. 1. Plant Height

The plant height was taken from the base of the stem to the tip of the top most leaf at 15, 30, 45, 60 DAT and at harvest. It was recorded from the five observation plants selected randomly from each plot, mean value was worked out and expressed in cm.

3. 4. 1. 2. Number of Tillers m^{-2}

The tiller number was counted from one m^2 within the net plot area selected at random at 15, 30, 45, 60 DAT and harvest and mean values were worked out and recorded.

3. 4. 1. 3. Leaf Area Index

Six sample hills were selected from the net plot area, tagged and the maximum length (l) and width (w) of third leaf from top were measured at 15, 30, 45, 60 DAT and harvest. The total number of leaves were counted for each sample hill and multiplied with the mean value. (Area of one leaf = l x w x k).

Yoshida *et al.* (1976) suggested the formula for LAI

$$\text{LAI} = \frac{\text{Leaf area of 6 sample hills}}{\text{6 x Land area occupied}}$$

k – Constant (0.67 at seedling and harvest and 0.75 at all other stages of crop)

l – Maximum length of 3rd leaf blade from the top (cm)

w – Maximum width of the 3rd leaf blade (cm)

3. 4. 1. 4. Dry Matter Production (DMP)

At harvest the observational plants were uprooted, washed, sun dried and oven dried at 70 ± 5°C to constant weight and expressed in kg ha^{-1}.

3.4.2 Yield Attributes and Yield

3.4.2.1 Number of Productive Tillers per Square Metre

The number of panicles were counted from one m^2 from net plot area at harvest and mean values were calculated and expressed as productive tillers m^{-2}.

3.4.2.2 Filled Grain's per Panicle

The number of filled grains from five panicles randomly selected from the net plot area were counted, mean value worked out and expressed as filled grains per panicle.

3.4.2.3 Sterility Percentage

Filled and unfilled grains were counted from five panicles randomly selected from the net plot area. It was calculated using the formula

$$\text{Sterility percentage} = \frac{\text{Number of unfilled grains per panicle}}{\text{Total number of grains in a panicle}} \times 100$$

3.4.2.4 Thousand Grain Weight

Fully filled, bold one thousand grains were collected from the harvested grains, weighed and expressed in grams.

3.4.2.5 Grain Yield

From the net plot area, rice plants in one m^2 area were harvested, threshed and winnowed separately. The grains were sun-dried to a moisture content of 13 per cent, weighed and expressed in kg ha^{-1}.

3.4.2.6 Straw Yield

After threshing, the harvested straw obtained from each net plot area was sun dried to a constant value, weighed and expressed in kg ha^{-1}.

3.4.2.7 Harvest Index (HI)

It was calculated by the formula suggested by Donald and Hamblin (1976).

$$\text{HI} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100$$

3.4.3 Observations on Root Parameters

For taking the root observations, plants were raised simultaneously in pots of size 30 cm height and 24 cm diameter. The drainage holes in the pots were sealed and filled with soil from the experimental field. Two seedlings were maintained in each pot with four sample plants per treatment.

3.4.3.1 Rooting Depth

The entire soil mass inside the pot was taken out by overturning carefully. The mud attached to the roots was slowly removed from the sides till the roots are visible. The depth to which the root has penetrated was recorded at 15, 30, 45, 60 DAT and harvest, mean value worked out and expressed in cm.

3.4.3.2 Root Volume

Root volume was measured by water displacement method (Mishra and Ahmed, 1989). Test plants were taken out from the pots at 15, 30, 45, 60 DAT and harvest by emptying the pots at the respective stage. Roots were cleaned and immersed in a measuring cylinder containing known volume of water and quantity of water displaced was expressed in cm^3 per plant.

3.4.3.3 Root Shoot Ratio

Test plants were taken out from the pots at 15, 30, 45, 60 DAT and harvest by emptying the pots at the respective stage. The root dry weight and shoot dry weight were recorded separately and the root to shoot ratio was worked out.

3.4.3.4 Root Dry Weight

Test plants were taken out from the pots carefully at 15, 30, 45, 60 DAT and harvest without any damage to the root, cleaned thoroughly and dried in a hot air oven at 70 ± 5° C until constant weight and expressed in g.

3.4.3.5 Average Root Length

Test samples were taken out from the pots at 15, 30, 45, 60 DAT and harvest carefully without any damage to the root and cleaned thoroughly. Counted the total number of roots, measured the length of each root and the mean value expressed in cm.

3.4.4 Physiological Parameters

3.4.4.1 Proline

Fully emerged third leaf from the top was taken from field at PI and flowering stage for the estimation of proline using the method explained by Bates *et al.* (1973). It was expressed as μ mol g^{-1} of fresh weight.

$$\mu \text{ moles of proline per g tissue} = \frac{\mu g \frac{\text{proline}}{\text{ml}} \text{x ml toulene}}{115.5} \text{x} \frac{5}{\text{g sample}}$$

3.4.4.2 Relative Leaf Water Content (RLWC)

Fully emerged third leaf from the top was taken from field at PI and flowering stage for the estimation of RLWC. A known weight of the sample was taken, and immersed in distilled water for 2 hours. After that, leaves were kept on blotting paper to absorb water present on the leaf surface, weighed and recorded as turgid weight. These samples were oven dried at 70°c for 48 hrs, weighed and the dry weight was recorded.

RLWC was estimated using the following formula (Slatyer and Barrs, 1965). It was expressed in percentage.

$$\text{RLWC} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Turgid weight} - \text{Dry weight}} \text{x } 100$$

3.4.4.3 Cell Membrane Stability (CMS)

Cell membrane stability was estimated using the method described by Blum and Ebercorn (1981). Fresh leaf samples were taken and washed with deionized water to remove electrolytes on the sample surface. Samples were kept in a vial incubated under dark for 24 hrs. Then, initial conductance was taken by conductivity meter. After that, vials were autoclaved for 15 min to destroy cell membrane and to release electrolytes from sample tissue. After cooling, conductivity was recorded as final conductance. It was expressed in percentage.

$$\text{CMS} = \frac{1-(\text{T1} \div \text{T2})}{1-(\text{C1} \div \text{C2})} \text{x } 100$$

Where, T1 and T2 indicates stress samples at initial and final conductance respectively. C1 and C2 are control samples at initial and final conductance readings respectively.

3.4.4.4 Chlorophyll Stability Index (CSI)

Chlorophyll stability index was estimated by using the formula given by Hiscox and Israelstam (1979). It was expressed in percentage. Fresh leaf samples of each treatment were taken and kept in two glass tubes. One was taken as control without any heat treatment and another one as stress condition subjected to heat at 56°C for 30 min. Chlorophyll content was taken at both conditions in spectrophotometer at 660 nm wavelength.

$$\text{CSI} = \frac{\text{Total chlorophyll under stress}}{\text{Total chlorophyll under control}} \text{x } 100$$

3.4.5 Water Use Efficiency (WUE)

Water use efficiency was estimated after calculating the water requirement and economic yield. Water requirement was taken as the sum of total quantity of water supplied through irrigation and effective rainfall. It was expressed as kg $\text{ha}^{-1}\text{mm}^{-1}$.

$$\text{WUE} = \frac{\text{Economic yield}}{\text{Water requirement}}$$

3.4.6 Soil Analysis

Composite soil samples were taken after the experiment from each plot to a depth of 15 cm for major nutrient analysis. Soil sample was shade dried, cleaned and sieved through 0.5 mm sieve for organic carbon estimation and 2 mm for NPK. Soil organic carbon was expressed in per cent and available NPK was expressed in kg ha^{-1}.

3.4.7 NPK uptake

After harvest plant samples were collected, oven dried at 70 ± 5°C, powdered and digested for analysing the NPK content. The nutrient uptake of the crop was computed and expressed in kg ha^{-1}.

Nutrient uptake = Nutrient content (%) x Total dry matter production (kg ha^{-1})

3.4.8 Observations on Major Weeds

Major weed species observed in the field upto 45 DAT were recorded.

3.4.9 Pest and Disease Incidence

The crop was monitered for observing the pest and disease infection if any.

3.4.10 Economic Analysis

3.4.10.1 Gross Income

It was calculated on the basis of grain, straw yield and their existing market prices. The gross income was calculated by using the formula

Gross income = Grain yield (t ha^{-1}) x Market price (₹ t^{-1})
+ Straw yield (t ha^{-1}) x Market price (₹ t^{-1})

3.4.10.2 Net Income

Net income (₹ ha^{-1}) = Gross income (₹ha^{-1}) - Cost of cultivation (₹ ha^{-1})

3.4.10.3 B:C ratio

The benefit-cost ratio was worked out using the following formula

$$\text{B:C Ratio} = \frac{\text{Gross income (₹ ha}^{-1}\text{)}}{\text{Cost of cultivation (₹ ha}^{-1}\text{)}}$$

3.4.11 Statistical Analysis

Data generated were statistically analysed by using Analysis of Variance (ANOVA) technique suggested by Panse and Sukhatme (1985) as applied to Randomised Block Design. The significance was tested using F test (Snedecor and Cochran, 1967). Critical difference was worked out at 5 per cent level of probability, wherever the treatment differences were found significant.

RESULTS

4. RESULTS

Moisture stress at critical growth stages can unfavourably affect growth and yield of summer rice. The present study entitled 'Mitigating water stress in summer rice using beneficial root endophytic fungus *Piriformospora indica*' was carried out in the low land paddy fields of College of Agriculture, Vellayani during summer, 2021.

The data recorded were statistically analysed to assess the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and their interaction on growth, yield, root and physiological parameters of rice. The results obtained are comprehended here under.

4.1 GROWTH AND GROWTH ATTRIBUTES

4.1.1 Plant Height

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and their interaction on plant height at 15, 30, 45, 60 DAT (days after transplanting) and harvest are presented in a Table 2a, 2b and 2c.

Results showed that colonizing with *P. indica,* irrigation interval and depth of irrigation had significant influence on plant height of rice. *P. indica* colonized rice plants were significantly taller with plant height of 34.64, 55.56, 67.02, 87.75 and 90.91 cm at 15, 30, 45, 60 DAT and harvest respectively. Irrigation interval i_1 (30 mm CPE) led to significantly taller plants with height of 55.74, 68.57, 86.90 and 90.15 cm at 30, 45, 60 DAT and harvest respectively followed by the irrigation interval i_2 and i_3. Depth of irrigation significantly influenced plant height of rice. Significantly superior plant height (58.28, 75.85, 93.58 and 96.36) was recorded at 3 cm depth followed by d_1 (1.5 cm) at 30, 45, 60 DAT and harvest.

Among first order interactions, P x I interaction showed significant variation in plant height at all stages of growth, except at 30 DAT. Irrigation of *P. indica* colonized rice plants at irrigation interval i_1 (30 mm CPE) resulted in significantly superior plant height of 71.66 cm at 45 DAT. Interaction p_1i_1 brought about superior plant height of 90.16 and 93.08 cm at 60 DAT and harvest respectively which was on par with p_1i_2.

The lowest plant height of 61.43, 81.4 and 84.5 cm was recorded with p_2i_2 (non-colonized rice plants at irrigation interval 35 mm CPE) at 45, 60 DAT and harvest respectively. Interaction P x D evinced significant influence on plant height only at 30 DAT.

The effect of interaction I x D, also significantly influenced the plant height at 15, 45, 60 DAT and harvest. Interaction i_3d_1 recorded superior plant height of 34.6 cm at 15 DAT. Irrigation at 30 mm CPE to a depth of 3 cm (i_1d_2) resulted in superior plant height of 76.78 cm at 45 DAT which was on par with i_2d_2 (75.93) and i_3d_2 (74.83). At 60 DAT and harvest, i_2d_2 recorded significantly taller plants of 96.56 and 98.86 respectively which were on par with i_3d_2 (irrigation at 40 mm CPE to a depth of 3 cm). The lowest plant height of 50.38, 71.41 and 74.61 at 45, 60 DAT and harvest respectively were recorded with i_3d_1 (irrigation at 40 mm CPE to a depth of 1.5 cm).

Among second order interactions, $p_1i_2d_2$ (*P. indica* colonized irrigated at 35 mm CPE to a depth of 3 cm) resulted in significantly superior plant height of 103.7 and 105.76 at 60 DAT and harvest followed by $p_2i_3d_2$ (96.3 and 98.92) at 60 DAT and harvest. At 45 DAT, $p_1i_2d_2$ observed superior plant height (80.1) on par with $p_1i_1d_2$ (77.56).

Table 2a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on plant height, cm

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1 (*P. indica* colonized rice)	34.64	55.56	67.02	87.75	90.91
p_2 (non-colonized rice)	32.70	52.47	63.21	82.51	85.66
SEm (±)	0.02	0.30	0.62	0.76	0.73
CD (0.05)	0.067	0.881	1.824	2.238	2.161
Irrigation interval (I)					
i_1 (30 mm CPE)	33.40	55.74	68.57	86.90	90.15
i_2 (35 mm CPE)	34.20	53.80	64.16	85.75	88.95
i_3 (40 mm CPE)	33.41	52.51	62.60	82.74	85.76
SEm (±)	0.02	0.36	0.76	0.93	0.90
CD (0.05)	0.082	1.079	2.234	2.740	2.647
Depth of irrigation (D)					
d_1 (1.5 cm)	33.73	49.75	54.38	76.67	80.21
d_2 (3 cm)	33.61	58.28	75.85	93.58	96.36
SEm (±)	0.02	0.30	0.62	0.76	0.73
CD (0.05)	0.067	0.881	1.824	2.238	2.161

Table 2b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on plant height, cm

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	34.21	56.90	71.66	90.16	93.08
p_1i_2	35.30	55.00	66.90	90.11	93.40
p_1i_3	34.41	54.80	62.50	82.96	86.25
p_2i_1	32.60	54.58	65.48	83.63	87.21
p_2i_2	33.10	52.60	61.43	81.40	84.50
p_2i_3	32.41	50.23	62.71	82.51	85.27
SEm (±)	0.04	0.52	1.07	1.32	1.27
CD (0.05)	0.116	NS	3.159	3.875	3.743
P×D interaction					
p_1d_1	34.69	50.80	57.17	79.15	82.90
p_1d_2	34.59	60.33	76.86	96.34	98.92
p_2d_1	32.77	48.71	51.58	74.20	77.52
p_2d_2	32.63	56.23	74.83	90.83	93.80
SEm (±)	0.03	0.42	0.87	1.07	1.04
CD (0.05)	NS	1.246	NS	NS	NS
I×D interaction					
i_1d_1	33.23	51.30	60.36	83.66	86.98
i_2d_1	33.57	49.43	52.40	74.95	79.03
i_3d_1	34.60	48.53	50.38	71.41	74.61
i_1d_2	33.80	60.18	76.78	90.13	93.31
i_2d_2	33.36	58.16	75.93	96.56	98.86
i_3d_2	33.46	56.50	74.83	94.06	96.91
SEm (±)	0.04	0.52	1.07	1.32	1.27
CD (0.05)	0.116	NS	3.159	3.875	3.743

Table 2c. Effects of P×I×D interaction on plant height, cm

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	33.77	51.50	65.76	86.83	90.06
$p_1i_2d_1$	35.60	50.23	53.70	76.53	81.03
$p_1 i_3d_1$	34.70	50.66	52.06	74.10	77.60
$p_1 i_1d_2$	34.64	62.30	77.56	93.50	96.10
$p_1 i_2d_2$	35.00	59.76	80.10	103.70	105.76
$p_1 i_3d_2$	34.13	58.93	72.93	91.83	94.90
$p_2 i_1d_1$	32.70	51.10	54.96	80.50	83.90
$p_2 i_2d_1$	33.60	48.63	51.10	73.36	77.03
$p_2 i_3d_1$	32.03	46.40	48.70	68.73	71.63
$p_2 i_1d_2$	32.50	58.06	76.00	86.76	90.53
$p_2 i_2d_2$	32.60	56.56	71.76	89.43	91.96
$p_2 i_3d_2$	32.80	54.06	76.73	96.30	98.92
SEm (±)	0.05	0.73	1.52	1.86	1.80
CD (0.05)	0.164	NS	4.468	5.481	5.293

4.1.2. Number of Tillers m^{-2}

Variations in the number of tillers m^{-2} are furnished in the Table 3a, 3b and 3c.

P. indica colonization had significantly influenced the number of tillers m^{-2} at 30, 45, 60 DAT and harvest. Colonized plants showed significantly superior number of tillers m^{-2} (140.38, 208.38, 254.44 and 260.38) at 30, 45, 60 DAT and harvest. There was 19.68, 10.64, 16 and 15.69 per cent increase in tiller production in colonized plants compared to non-colonized plants at 30, 45, 60 DAT and harvest respectively. Irrigation interval significantly influenced the tiller production of rice plants. Irrigation interval i_1 (30 mm CPE) caused significantly higher number of tillers m^{-2} (145.41, 218.41, 261.16 and 267) at 30, 45, 60 DAT and harvest respectively followed by i_2 (35 mm CPE) and i_3 (40 mm CPE). Depth of irrigation also significantly influenced number of tillers in rice. Plants irrigated to a depth of 3 cm produced significantly higher number of tillers (162.22, 237.88, 277.44 and 282.83) at 30, 45, 60 DAT and harvest.

Among the first order interactions, effect of P x I, P x D and I x D were found significant with respect to the tiller number m^{-2}. In P x I interaction, p_1i_1 registered significantly superior tiller number (154.16, 226.83, 275 and 281.66) at 30, 45, 60 DAT and harvest respectively. The lowest number of tillers was recorded in p_2i_3 at all the stages of observation. In the case of P x D interaction, p_1d_2 exhibited significantly superior number of tillers (174.44, 244.55, 287.77 and 293.44) at 30, 45, 60 DAT and harvest respectively followed by p_2d_2. Non-colonized rice plants irrigated to a depth of 1.5 cm (p_2d_1) produced the lowest number of tillers (85.77, 145.55, 171.55 and 177.88 at 30, 45, 60 DAT and harvest respectively). The interaction I x D significantly influenced the number of tillers at 30, 45, 60 DAT and harvest. Plants irrigated at 30 mm CPE to a depth of 3 cm (i_1d_2) produced significantly superior number of tillers m^{-2} (181.66, 259.33, 300.66 and 306.16) at 30, 45, 60 DAT and harvest respectively followed by i_2d_2.

The effect of P x I x D interaction was found to be significant with respect to number of tillers m^{-2}. *P. indica* colonized rice plants irrigated at 30 mm CPE to a depth of 3 cm registered significantly superior number of tillers m^{-2} (191.66, 267, 310 and 316) at 30, 45, 60 DAT and harvest respectively followed by $p_2i_1d_2$ (171.66, 251.66, 291.33 and 296.33). The lowest number of tillers m^{-2} was recorded with $p_2i_3d_1$ (70.66, 118.33, 130 and 138) at all stages of observation except at 15 DAT.

Table 3a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on tiller number m^{-2}

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P.indica* (P)					
p_1(*P.indica* colonized rice)	71.66	140.38	208.38	254.44	260.38
p_2(non-colonized rice)	69.72	117.88	188.33	219.33	225.05
SEm (±)	1.71	1.92	1.67	2.07	2.05
CD (0.05)	NS	5.636	4.908	6.079	6.002
Irrigation interval (I)					
i_1 (30 mm CPE)	73.75	145.42	218.42	261.16	267.00
i_2 (35 mm CPE)	70.83	126.67	197.08	240.33	245.91
i_3 (40 mm CPE)	66.66	115.33	179.58	209.16	215.25
SEm (±)	2.09	2.35	2.05	2.54	2.51
CD (0.05)	NS	6.902	6.011	7.446	7.350
Depth of irrigation (D)					
d_1 (1.5 cm)	70.28	96.06	158.89	196.33	202.61
d_2 (3 cm)	71.11	162.22	237.88	277.44	282.83
SEm (±)	1.71	1.92	1.67	2.07	2.046
CD (0.05)	NS	5.636	4.908	6.079	6.002

Table 3b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on tiller number m^{-2}

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	74.17	154.17	226.83	275.00	281.66
p_1i_2	72.50	138.33	206.67	260.00	265.83
p_1i_3	68.33	128.67	191.67	228.33	233.66
p_2i_1	73.33	136.67	210.00	247.33	252.33
p_2i_2	69.17	115.00	187.50	220.66	226.00
p_2i_3	66.67	102.00	167.50	190.00	196.83
SEm (±)	2.96	3.33	2.90	3.59	3.54
CD (0.05)	NS	9.761	8.501	10.530	10.395
P×D interaction					
p_1d_1	71.67	106.33	172.22	221.11	227.33
p_1d_2	71.67	174.44	244.56	287.77	293.44
p_2d_1	68.80	85.78	145.56	171.55	177.88
p_2d_2	70.56	150.00	231.11	267.11	272.22
SEm (±)	2.42	2.72	2.37	2.93	2.89
CD (0.05)	NS	7.970	6.941	8.598	8.487
I×D interaction					
i_1d_1	75.00	109.17	177.50	221.66	227.83
i_2d_1	70.00	96.67	161.67	207.33	213.66
i_3d_1	65.83	82.33	137.50	160.00	166.33
i_1d_2	72.50	181.67	259.33	300.66	306.16
i_2d_2	71.67	156.67	232.50	273.33	278.16
i_3d_2	69.17	148.33	221.67	258.33	264.16
SEm (±)	2.96	3.33	2.90	3.59	3.54
CD (0.05)	NS	9.761	8.501	10.530	10.395

Table 3c. Effects of P×I×D interaction on tiller number m^{-2}

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	75.00	116.67	186.67	240.00	247.33
$p_1i_2d_1$	73.33	108.33	173.33	233.33	240.00
$p_1i_3d_1$	66.67	94.00	156.67	190.00	194.66
$p_1i_1d_2$	73.33	191.67	267.00	310.00	316.00
$p_1i_2d_2$	71.67	168.33	240.00	286.66	291.66
$p_1i_3d_2$	70.00	163.33	226.67	266.66	272.66
$p_2i_1d_1$	75.00	101.67	168.33	203.33	208.33
$p_2i_2d_1$	66.67	85.00	150.00	181.33	187.33
$p_2i_3d_1$	65.00	70.67	118.33	130.00	138.00
$p_2i_1d_2$	71.67	171.67	251.67	291.33	296.33
$p_2i_2d_2$	71.67	145.00	225.00	260.00	264.66
$p_2i_3d_2$	68.33	133.33	216.67	250.00	255.66
SEm (±)	4.19	4.71	4.10	5.07	5.01
CD (0.05)	NS	13.804	12.023	14.892	14.701

4.1.3 Leaf Area Index

Influence of colonization with *P. indica*, irrigation interval, depth of irrigation and its interaction on leaf area index (LAI) of rice at 15, 30, 45, 60 DAT and harvest are presented in Table 4a, 4b and 4c.

Perusal of the data revealed the significant influence of colonizing *P. indica* on LAI at all the stages of observation. LAI was found to be significantly superior at all growth stages for colonized plants, the values being 0.91, 1.42, 2.93, 3.83 and 2.19 at different growth stages followed by non-colonized plants. The variation in LAI due to irrigation interval adopted was significant at 15, 30, 45, 60 DAT and harvest. Irrigation interval (i_1) produced significantly higher LAI (0.9, 1.39, 2.98 and 3.83) at 15, 30, 45 and 60 DAT compared to i_2 and i_3. The effect of depth of irrigation on LAI was found to be significant at all growth stages. Plants irrigated to a depth of 3 cm (d_2) produced significantly superior LAI compared to those irrigated at 1.5 cm depth (d_1).

Among two factor interactions, P x I interaction showed significant influence on LAI at all stages of observation, except at 15 DAT. Colonized plants irrigated at 30 mm CPE recorded significantly superior LAI (1.56, 3.16 and 3.99) at 30, 45 and 60 DAT. Other treatments viz., p_1i_2 (2.88), p_2i_1 (2.80), p_1i_3 (2.76) and p_2i_2 (2.64) were superior to p_2i_3 (2.55) at 45 DAT. Interaction p_1i_2 (3.81), p_1i_3 (3.68), p_2i_1 (3.66) and p_2i_2 (3.36) were superior to p_2i_3 (3.22) at 60 DAT. Effect of P x D interaction showed significant influence on LAI at all stages of observation. Colonized plants irrigated to a depth of 3 cm (p_1d_2) recorded maximum LAI of 0.92, 1.64, 3.28 and 4.38 at 15, 30, 45 and 60 DAT respectively and were significantly superior. The least LAI was recorded by p_2d_1 (non-colonized plants irrigated to a depth of 1.5 cm) at all stages of observation.

The effect of I x D interaction on LAI was significant at 30, 45, 60 DAT and harvest. Irrigation at 30 mm CPE to a depth of 3 cm (i_1d_2) evinced significantly superior LAI of 1.62, 3.39 and 4.32 at 30, 45 and 60 DAT respectively followed by i_2d_2 (irrigation at 35 mm CPE to a depth of 3 cm) that had LAI (1.41, 3.08 and 3.99) at 30, 45 and 60 DAT respectively, which were on par with i_3d_2 at 30 and 45 DAT.

Effect of P x I x D was significant at all stages of observation, except at 15 DAT. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) led to the maximum LAI of 1.80, 3.54 and 4.54 at 30, 45 and 60 DAT, which were significantly superior to the rest. At the same irrigation interval and depth, non-colonized plants ($p_2i_1d_2$) produced LAI of 4.1 at 60 DAT, which was 10.73 per cent lower than colonized plants. The lowest LAI of 0.90, 2.17 and 2.87 were recorded with $p_2i_3d_1$ (non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm) at 30, 45 and 60 DAT respectively. At the same interval and depth, colonized plants ($p_1i_3d_1$) recorded LAI of 3.13 at 60 DAT, which was 9.05 per cent higher than non-colonized plants under severe stress situation.

Table 4a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on leaf area index

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1(*P. indica* colonized rice)	0.91	1.42	2.93	3.83	2.19
p_2(non-colonized rice)	0.84	1.13	2.67	3.42	2.03
SEm (±)	0.01	0.01	0.01	0.01	0.04
CD (0.05)	0.033	0.027	0.032	0.042	0.122
Irrigation interval (I)					
i_1 (30mm CPE)	0.90	1.39	2.98	3.83	2.03
i_2 (35mm CPE)	0.87	1.25	2.76	3.59	2.14
i_3 (40mm CPE)	0.85	1.18	2.65	3.45	2.15
SEm (±)	0.01	0.01	0.01	0.02	0.05
CD (0.05)	0.040	0.034	0.039	0.051	0.149
Depth of irrigation (D)					
d_1 (1.5cm)	0.85	1.08	2.43	3.17	1.99
d_2 (3cm)	0.90	1.47	3.17	4.07	2.23
SEm (±)	0.01	0.01	0.01	0.01	0.04
CD (0.05)	0.033	0.027	0.032	0.042	0.122

Table 4b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on leaf area index

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	0.93	1.56	3.16	3.99	2.15
p_1i_2	0.91	1.40	2.88	3.81	2.20
p_1i_3	0.88	1.32	2.76	3.68	2.20
p_2i_1	0.87	1.23	2.80	3.66	1.91
p_2i_2	0.84	1.10	2.64	3.36	2.09
p_2i_3	0.82	1.04	2.55	3.22	2.09
SEm (±)	0.02	0.02	0.02	0.02	0.07
CD (0.05)	NS	0.047	0.055	0.072	0.211
P×D interaction					
p_1d_1	0.90	1.21	2.59	3.28	2.15
p_1d_2	0.92	1.64	3.28	4.38	2.22
p_2d_1	0.82	0.96	2.28	3.06	1.83
p_2d_2	0.87	1.29	3.06	3.77	2.23
SEm (±)	0.02	0.01	0.01	0.02	0.06
CD (0.05)	0.046	0.039	0.045	0.059	0.172
I×D interaction					
i_1d_1	0.88	1.17	2.57	3.33	1.97
i_2d_1	0.86	1.09	2.44	3.18	1.94
i_3d_1	0.83	0.99	2.28	3.00	2.06
i_1d_2	0.92	1.62	3.39	4.32	2.09
i_2d_2	0.89	1.41	3.08	3.99	2.35
i_3d_2	0.87	1.37	3.03	3.90	2.23
SEm (±)	0.02	0.02	0.02	0.02	0.07
CD (0.05)	NS	0.047	0.055	0.072	0.211

Table 4c. Effects of P×I×D interaction on leaf area index

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	0.92	1.32	2.78	3.44	2.24
$p_1i_2d_1$	0.91	1.22	2.59	3.27	2.04
$p_1i_3d_1$	0.87	1.09	2.39	3.13	2.17
$p_1i_1d_2$	0.95	1.80	3.54	4.54	2.07
$p_1i_2d_2$	0.91	1.58	3.16	4.35	2.36
$p_1i_3d_2$	0.90	1.55	3.13	4.24	2.24
$p_2i_1d_1$	0.84	1.02	2.37	3.23	1.70
$p_2i_2d_1$	0.81	0.97	2.29	3.09	1.84
$p_2i_3d_1$	0.80	0.90	2.17	2.87	1.95
$p_2i_1d_2$	0.90	1.45	3.24	4.10	2.12
$p_2i_2d_2$	0.88	1.24	3.00	3.63	2.34
$p_2i_3d_2$	0.85	1.19	2.93	3.57	2.23
SEm (±)	0.03	0.02	0.03	0.03	0.10
CD (0.05)	NS	0.067	0.096	0.102	0.298

4.1.4 Dry Matter Production at Harvest

Table 5a, 5b, 5c present the effects of colonization with *P. indica*, irrigation interval and depth of irrigation on dry matter production (DMP) in rice.

The data revealed that main and interaction effects of all the factors were significant on DMP at harvest. *P. indica* colonization (3630.94 kg ha^{-1}) was significantly superior to non-colonized plants (3161.56 kg ha^{-1}). Irrigation at 30 mm CPE produced significantly superior DMP of 3789.24 kg ha^{-1} compared to the plants irrigated 35 mm (3322.22 kg ha^{-1}) and 40 mm CPE (3077.29 kg ha^{-1}). Depth of irrigation did also significantly influence the DMP at harvest. Irrigation to a depth of 3 cm (d_2) resulted in significantly higher DMP (3880.19 kg ha^{-1}) over d_1.

Among the first order interactions, P x I registered significant variation in DMP at harvest. The combination of p_1i_1 (colonization with plants irrigated at 30 mm CPE) was significantly superior (4090.89 kg ha^{-1}), followed by p_1i_2 (3512.63 kg ha^{-1}) which was on par with p_2i_1 (3487.58 kg ha^{-1}). Effect of P x D interaction showed significant variation with superiority of p_1d_2 (4034.47 kg ha^{-1}), followed by p_2d_2 (3725.91 kg ha^{-1}). The least DMP (2597.20 kg ha^{-1}) was recorded in p_2d_1 (non-colonized plants irrigated to a depth of 1.5 cm). Effect of I x D interaction on DMP was significant with i_1d_2 (irrigation at 30 mm CPE to a depth of 3 cm) having the highest value (4260.07 kg ha^{-1}), followed by i_2d_2 (3772.68 kg ha^{-1}). The lowest DMP (2546.69 kg ha^{-1}) was recorded in i_3d_1.

P x I x D also exhibited significant variation in DMP with $p_1i_1d_2$ resulting in significantly superior value (4559.26 kg ha^{-1}), followed by $p_2i_1d_2$ (3960.21 kg ha^{-1}) which was on par with $p_1i_2d_2$. There was 15.12 per cent enhancement in DMP in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants at the same irrigation frequency. Other treatments, $p_1i_2d_2$ (3852.17), $p_2i_2d_2$ (3693.07), $p_1i_3d_2$ (3691.31), $p_1i_1d_1$ (3621.86), $p_2i_3d_2$ (3524.46), $p_1i_2d_1$ (3173.09), $p_2i_1d_1$ (3014.95), $p_1i_3d_1$ (2887.30) and $p_2i_2d_1$ (2570.56) were superior to $p_2i_3d_1$ (2206.08).

Table 5a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on dry matter production

Treatments	Dry matter production (kg ha^{-1})
Colonizing with *P. indica* (P)	
p_1 (*P. indica* colonized rice)	3630.94
p_2 (non-colonized rice)	3161.56
SEm (±)	16.48
CD (0.05)	48.368
Irrigation interval (I)	
i_1 (30 mm CPE)	3789.24
i_2 (35 mm CPE)	3322.22
i_3 (40 mm CPE)	3077.29
SEm (±)	20.19
CD (0.05)	59.238
Depth of irrigation (D)	
d_1 (1.5 cm)	2912.31
d_2 (3 cm)	3880.19
SEm (±)	16.48
CD (0.05)	48.368

Table 5b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on dry matter production

Interactions	Dry matter production (kg ha^{-1})
P × I interaction	
p_1i_1	4090.89
p_1i_2	3512.63
p_1i_3	3289.30
p_2i_1	3487.58
p_2i_2	3131.82
p_2i_3	2865.27
SEm (±)	28.55
CD (0.05)	83.775
P × D interaction	
p_1d_1	3227.42
p_1d_2	4034.47
p_2d_1	2597.20
p_2d_2	3725.91
SEm (±)	23.31
CD (0.05)	68.402
I × D interaction	
i_1d_1	3318.41
i_2d_1	2871.30
i_3d_1	2546.69
i_1d_2	4260.07
i_2d_2	3772.68
i_3d_2	3607.88
SEm (±)	28.55
CD (0.05)	83.775

Table 5c. Effect of P x I x D interaction on dry matter production

Treatment combinations	Dry matter production (kg ha^{-1})
$p_1i_1d_1$	3621.86
$p_1i_2d_1$	3173.09
$p_1i_3d_1$	2887.30
$p_1i_1d_2$	4559.26
$p_1i_2d_2$	3852.17
$p_1i_3d_2$	3691.31
$p_2i_1d_1$	3014.95
$p_2i_2d_1$	2570.56
$p_2i_3d_1$	2206.08
$p_2i_1d_2$	3960.21
$p_2i_2d_2$	3693.07
$p_2i_3d_2$	3524.56
SEm (±)	40.38
CD (0.05)	118.476

Table 5b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on dry matter production

Interactions	Dry matter production (kg ha^{-1})
P × I interaction	
p_1i_1	4090.89
p_1i_2	3512.63
p_1i_3	3289.30
p_2i_1	3487.58
p_2i_2	3131.82
p_2i_3	2865.27
SEm (±)	28.55
CD (0.05)	83.775
P × D interaction	
p_1d_1	3227.42
p_1d_2	4034.47
p_2d_1	2597.20
p_2d_2	3725.91
SEm (±)	23.31
CD (0.05)	68.402
I × D interaction	
i_1d_1	3318.41
i_2d_1	2871.30
i_3d_1	2546.69
i_1d_2	4260.07
i_2d_2	3772.68
i_3d_2	3607.88
SEm (±)	28.55
CD (0.05)	83.775

Table 5c. Effect of P x I x D interaction on dry matter production

Treatment combinations	Dry matter production (kg ha^{-1})
$p_1i_1d_1$	3621.86
$p_1i_2d_1$	3173.09
$p_1i_3d_1$	2887.30
$p_1i_1d_2$	4559.26
$p_1i_2d_2$	3852.17
$p_1i_3d_2$	3691.31
$p_2i_1d_1$	3014.95
$p_2i_2d_1$	2570.56
$p_2i_3d_1$	2206.08
$p_2i_1d_2$	3960.21
$p_2i_2d_2$	3693.07
$p_2i_3d_2$	3524.56
SEm (±)	40.38
CD (0.05)	118.476

4.2 YIELD AND YIELD ATTRIBUTES

4.2.1 Productive Tillers m^{-2}

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and their interaction on productive tillers m^{-2} are presented in Table 6a, 6b and 6c.

Results showed that *P. indica* colonization resulted in significantly superior number of productive tillers m^{-2} (222.84) compared to non-colonized plants (149.16). Irrigation interval could also significantly influence the productive tillers of rice. Irrigation at 30 mm CPE (i_1) reported significantly superior number of productive tillers m^{-2} (210.10), followed by irrigation at 35 mm CPE (191.25) and 40 mm CPE (156.66). Depth of irrigation also did significantly influence the productive tiller number m^{-2}. Significantly superior number of productive tillers m^{-2} (223.88) was produced at irrigation to a depth of 3 cm followed by irrigation given to a depth of 1.5cm (148.12).

Among the first order interactions, P x I interaction could significantly influence the number of productive tillers m^{-2} in rice. *P. indica* colonized plants irrigated at 30 mm CPE brought about significantly superior number of productive tillers m^{-2} (250.20). Interaction P x D significantly influenced the number of productive tillers m^{-2}. *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) produced significantly superior number of productive tillers m^{-2} (256.11), followed by non-colonized plants irrigated to a depth of 1.5 cm (191.66). The least number of productive tillers m^{-2} (106.66) was recorded in non-colonized plants irrigated to a depth of 1.5 cm (p_2d_1).

The number of productive tillers m^{-2} was significantly influenced by second order interaction (I x D). Irrigation at 30 mm CPE to a depth of 3 cm (i_1d_2) evinced significantly higher number of productive tillers m^{-2} (239.16), which was on par with i_2d_2 (224.16). Significantly the lowest number of productive tillers m^{-2} (105.00) was reported in i_3d_1 (irrigation at 40 mm CPE to a depth of 1.5 cm).

Among the second order interactions, treatment combination $p_1i_1d_2$ was found to be significantly superior with 275.00 productive tillers m^{-2}, followed by $p_1i_2d_2$ with 251.66 productive tillers m^{-2}, which was on par with $p_1i_3d_2$ (241.66), followed by $p_1i_1d_1$

(225.40), $p_1i_2d_1$ (210.00), $p_2i_1d_2$ (203.33). There was 35.24 per cent enhancement in productive tillers in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants irrigated at same interval and depth.

4.2.2 Filled Grains Per Panicle

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and their interaction on filled grains per panicle are presented in Table 6a, 6b and 6c.

The data revealed that the main effects of all the factors significantly influenced filled grains per panicle. Significantly superior filled grains per panicle (81.11) was recorded in *P. indica* colonized plants, followed by non-colonized plants (69.66). Irrigation at 30 mm CPE produced significantly higher filled grains per panicle (84.58), followed by i_2 (73.83) and i_3 (67.75). Irrigation to a depth of 3 cm depth caused superior filled grains per panicle (89.88).

Among the first order interactions, effect of P x I, P x D and I x D were significant. In the case of P x I interaction, significantly superior filled grains per panicle was observed in p_1i_1 (92.00), followed by p_1i_2 (78.83). In case of P x D interaction, significantly superior filled grains per panicle were produced in p_1d_2 (97.00), followed by p_2d_2 (82.77). In the case of I x D, significantly higher filled grains per panicle (100.83) was recorded in i_1d_2, followed by i_2d_2 (87.66). The lowest number of filled grains per panicle (54.33) was recorded in i_3d_1 (irrigation at 40 mm CPE to a depth of 1.5 cm).

Among the second order interactions, treatment combination $p_1i_1d_2$ produced significantly higher filled grains per panicle (111.33), which was 23.24 per cent higher over non-colonized plants at the same irrigation frequency. The least number of filled grains per panicle was recorded in $p_2i_3d_1$ (49.66).

Table 6a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on productive tillers m^{-2}, filled grains per panicle, sterility percentage and thousand grain weight.

Treatments	Productive tillers m^{-2}	Filled grains per panicle	Sterility percentage	Thousand grain weight (g)
Colonizing with *P. indica*				
p_1(*P.indica* colonized rice)	222.84	81.11	13.37	22.54
p_2 (non-colonized rice)	149.16	69.66	16.48	22.55
SEm (±)	2.97	0.60	0.14	0.03
CD (0.05)	8.717	1.769	0.406	NS
Irrigation interval (I)				
i_1 (30 mm CPE)	210.10	84.58	13.01	22.94
i_2 (35 mm CPE)	191.25	73.83	14.90	22.36
i_3 (40 mm CPE)	156.66	67.75	16.86	22.33
SEm (±)	3.64	0.74	0.17	0.04
CD (0.05)	10.676	2.166	0.498	0.133
Depth of irrigation (D)				
d_1 (1.5 cm)	148.12	60.88	18.22	21.73
d_2 (3 cm)	223.88	89.88	11.63	23.36
SEm (±)	2.97	0.60	0.14	0.04
CD (0.05)	8.717	1.769	0.406	0.108

Table 6b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation productive tillers m^{-2}, filled grains per panicle, sterility percentage and thousand grain weight.

Interactions	Productive tillers m^{-2}	Filled grains per panicle	Sterility percentage	Thousand grain weight (g)
P x I interaction				
p_1i_1	250.20	92.00	11.71	22.95
p_1i_2	230.83	78.83	13.35	22.38
p_1i_3	187.50	72.50	15.05	22.28
p_2i_1	170.00	77.16	14.32	22.94
p_2i_2	151.66	68.83	16.47	22.34
p_2i_3	125.83	63.00	18.66	22.38
SEm (±)	5.147	1.044	0.24	0.064
CD(0.05)	15.099	3.063	0.704	NS
P x D interaction				
p_1d_1	189.57	65.22	16.44	21.69
p_1d_2	256.11	97.00	10.30	23.39
p_2d_1	106.66	56.55	20.00	21.77
p_2d_2	191.66	82.77	12.96	23.34
SEm (±)	4.202	0.853	0.20	0.052
CD(0.05)	12.328	2.501	0.575	NS
I x D interaction				
i_1d_1	181.03	68.33	15.93	22.19
i_2d_1	158.33	60.00	17.97	21.53
i_3d_1	105.00	54.33	20.77	21.46
i_1d_2	239.16	100.83	10.10	23.70
i_2d_2	224.16	87.66	11.85	23.19
i_3d_2	208.33	81.16	12.95	23.20
SEm (±)	5.147	1.044	0.24	0.064
CD (0.05)	15.099	3.063	0.704	NS

Table 6c. Effect of P x I x D interaction on productive tillers m^{-2}, filled grains per panicle, sterility percentage and thousand grain weight.

Treatment combinations	Productive tillers m^{-2}	Filled grains per panicle	Sterility percentage	Thousand grain weight (g)
$p_1i_1d_1$	225.40	72.66	14.62	22.17
$p_1i_2d_1$	210.00	64.00	16.06	21.56
$p_1i_3d_1$	133.33	59.00	18.64	21.33
$p_1i_1d_2$	275.00	111.33	8.80	23.74
$p_1i_2d_2$	251.66	93.66	10.63	23.21
$p_1i_3d_2$	241.66	86.00	11.46	23.23
$p_2i_1d_1$	136.66	64.00	17.25	22.21
$p_2i_2d_1$	106.66	56.00	19.87	21.50
$p_2i_3d_1$	76.66	49.66	22.88	21.60
$p_2i_1d_2$	203.33	90.33	11.38	23.67
$p_2i_2d_2$	196.66	81.66	13.06	23.17
$p_2i_3d_2$	175.00	76.33	14.43	23.17
SEm (±)	7.28	1.47	0.34	0.09
CD (0.05)	21.353	4.332	0.995	NS

4.2.3 Sterility Percentage

Influence of colonization with *P. indica*, irrigation interval, depth of irrigation and their interaction on sterility percentage are presented in Table 6a, 6b and 6c.

Perusal of the data revealed the significant influence of *P. indica* colonization on sterility percentage. The lowest sterility percentage (13.37) was recorded in *P. indica* colonized plants. The sterility percentage was the lowest (13.01) in i_1 followed by i_2 (14.90). Rice plants irrigated to a depth of 3 cm had significantly lower sterility percentage (11.63) compared to plants irrigated to a depth of 1.5 cm (18.22).

Among the two factor interactions, the effect of P x I, P x D and I x D were significant. In the case of P x I interaction, p_1i_1 had a lower sterility percentage (11.71) and the highest sterility percentage (18.66) was observed in p_2i_3. *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) led to the lowest sterility percentage (10.30), followed by p_2d_2 (12.96). Irrigation at 30 mm CPE to a depth of 3 cm (i_1d_2) had the lowest sterility percentage of 10.09, followed by i_2d_2 (11.84). The highest percentage of sterility (20.76) was recorded in i_3d_1 (irrigation at 40 mm CPE to a depth of 1.5 cm)

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P x I x D interaction significantly influenced the sterility percentage of rice. Colonized plants irrigated at 30 mm CPE to a depth of 3 cm exhibited the lowest sterility percentage (8.80) followed by $p_1i_2d_2$ (10.63). Higher sterility percentage of 22.88 was recorded in non-colonized rice plants irrigated at 40 mm CPE to a depth of 1.5 cm ($p_2i_3d_1$).

4.2.4 Thousand Grain Weight

Tables 6a, 6b and 6c represent the influence of *P. indica*, irrigation interval and depth of irrigation on thousand grain weight of rice. Colonization with *P. indica* showed no significant influence on thousand grain weight of rice. However, irrigation interval and depth of irrigation had significant effect on it. Irrigation at 30 mm CPE marked significantly superior thousand grain weight (22.94), followed by i_2 (22.36), which was on par with i_3 (22.33). Maximum thousand grain weight of 23.36 was recorded in irrigation depth of 3 cm, followed by d_1 (21.73).

Two factor interactions and three factor interactions could not influence thousand grain weight of rice.

4.2.5 Grain Yield

Table. 7a, 7b, and 7c represent the effects of *P. indica*, irrigation interval and depth of irrigation on grain yield of rice.

The results showed that colonizing with *P. indica*, irrigation interval and depth of irrigation had significant influence on grain yield of rice. Plants colonized with *P. indica* produced significantly superior grain yield (2056.71 kg ha^{-1}) over non- colonized rice (1755.61 kg ha^{-1}). Grain yield was found to be significantly superior in plants irrigated at 30 mm CPE (2165.82 kg ha^{-1}), followed by i_2 (1851.14 kg ha^{-1}). The lowest grain yield was recorded in i_3 (1701.52 kg ha^{-1}). The influence of depth of irrigation showed significant effect when irrigated to a depth of 3 cm compared to 1.5 cm depth.

Among the first order interactions, P x I interaction exerted significant effect on grain yield. Maximum grain yield (2366.01 kg ha^{-1}) was recorded in *P. indica* colonized rice irrigated at 30 mm CPE (p_1i_1). In general, non-colonized plants recorded a lower yield with any of the irrigation interval tested. The lowest grain yield (1564.60 kg ha^{-1}) was recorded in p_2i_3. It was found that colonization with *P. indica* increased grain yield by 20.37 per cent when irrigated at 30 mm CPE.

P x D interaction also registered significant variation in grain yield. *P. indica* colonized plants irrigated to a depth of 3 cm was significantly superior with a grain yield of 2332.55 kg ha^{-1}. The next best yield was recorded in non-colonized plants irrigated to a depth of 3 cm (2128.01 kg ha^{-1}). At the same irrigation depth of 3 cm, *P. indica* colonized plants evinced 9.6 per cent increase in yield over non-colonized plants. Colonized plants produced a higher yield of 1780.86 kg ha^{-1}, while the non-colonized plants irrigated to a depth of 1.5 cm had the lowest yield of 1383.22 kg ha^{-1}.

I x D interaction exerted significant influence on grain yield of rice. The highest grain yield of 2501.65 kg ha^{-1} was recorded in i_1d_2 and was significantly higher than rest of the treatments. The lowest grain yield (1354.58 kg ha^{-1}) was produced in plants irrigated at 40 mm CPE to a depth of 1.5 cm and was significantly inferior.

Among the second order interactions, $p_1i_1d_2$ produced significantly superior yield (2698.56 kg ha^{-1}), followed by $p_2i_1d_2$ (2304.73 kg ha^{-1}). At the same irrigation interval and depth (30 mm CPE and 1.5 cm), there was 17 per cent yield variation between colonized and non-colonized plants. Among the colonized plants, $p_1i_2d_2$ recorded grain yield of 2188.43 kg ha^{-1} and was on par with $p_1i_3d_2$. The lowest yield 1142.93 kg ha^{-1} was recorded in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm.

Table 7a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on grain yield, straw yield and harvest index.

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
Colonizing with *P. indica*			
p_1 (*P. indica* colonized rice)	2056.71	2393.70	0.46
p_2 (non-colonized rice)	1755.61	2132.50	0.45
SEm (±)	16.50	17.46	0.01
CD (0.05)	48.405	51.238	NS
Irrigation interval (I)			
i_1 (30 mm CPE)	2165.82	2471.47	0.46
i_2 (35 mm CPE)	1851.14	2232.25	0.45
i_3 (40 mm CPE)	1701.52	2085.57	0.45
SEm (±)	20.21	21.39	0.01
CD (0.05)	59.284	62.753	NS
Depth of irrigation (D)			
d_1 (1.5 cm)	1582.04	2012.35	0.44
d_2 (3 cm)	2230.28	2513.85	0.47
SEm (±)	16.50	17.46	0.01
CD (0.05)	48.405	51.238	NS

Table 7b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on grain yield, straw yield and harvest index.

Interactions	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
P x I interaction			
p_1i_1	2366.01	2630.00	0.47
p_1i_2	1965.58	2348.80	0.45
p_1i_3	1838.45	2202.30	0.45
p_2i_1	1965.55	2312.95	0.45
p_2i_2	1736.70	2115.70	0.45
p_2i_3	1564.60	1968.85	0.44
SEm (±)	28.58	30.25	0.01
CD (0.05)	83.841	NS	NS
P x D interaction			
p_1d_1	1780.86	2192.16	0.44
p_1d_2	2332.55	2595.23	0.47
p_2d_1	1383.22	1832.53	0.43
p_2d_2	2128.01	2432.46	0.46
SEm (±)	23.33	24.70	0.01
CD (0.05)	68.456	72.461	NS
I x D interaction			
i_1d_1	1830.00	2255.50	0.44
i_2d_1	1561.55	1982.40	0.44
i_3d_1	1354.58	1799.15	0.42
i_1d_2	2501.65	2687.45	0.48
i_2d_2	2140.73	2482.10	0.46
i_3d_2	2048.46	2372.00	0.46
SEm (±)	28.58	30.25	0.01
CD (0.05)	83.410	NS	NS

Table 7c. Effects of P×I×D interaction on grain yield, straw yield and harvest index

Treatment combinations	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
$p_1i_1d_1$	2033.63	2411.86	0.45
$p_1i_2d_1$	1742.73	2166.60	0.44
$p_1i_3d_1$	1566.23	1998.04	0.43
$p_1i_1d_2$	2698.56	2948.13	0.47
$p_1i_2d_2$	2188.43	2531.00	0.46
$p_1i_3d_2$	2110.66	2406.56	0.46
$p_2i_1d_1$	1626.36	2099.13	0.43
$p_2i_2d_1$	1380.36	1798.20	0.43
$p_2i_3d_1$	1142.93	1600.26	0.41
$p_2i_1d_2$	2304.73	2526.76	0.47
$p_2i_2d_2$	2093.03	2433.20	0.46
$p_2i_3d_2$	1986.26	2337.43	0.45
SEm (±)	40.42	42.78	0.01
CD (0.05)	118.569	125.506	NS

4.2.6 Straw Yield

Results on the effect of colonizing with *P. indica,* irrigation interval, depth of irrigation and their interaction on straw yield are furnished in Table 7a, 7b and 7c.

Individual effects of *P. indica* colonization, irrigation interval and depth of irrigation had significant influence on straw yield. Significantly superior straw yield (2393.70 kg ha^{-1}) was recorded with the colonization of *P. indica*. Irrigation interval i_1 (30 mm CPE) produced superior straw yield (2471.47 kg ha^{-1}) followed by i_2 (2232.25 kg ha^{-1}) and i_3 (2085.57 kg ha^{-1}). Depth d_2 (at 3 cm) could produce superior straw yield (2513.85 kg ha^{-1}), followed by d_1 (2012.35 kg ha^{-1}).

Among the interactions, P x I and I x D could not significantly influence the straw yield of rice. Among the P x D interaction, *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) produced significantly superior straw yield (2595.23 kg ha^{-1}), followed by p_2d_2. The lowest straw yield (1832.53 kg ha^{-1}) was recorded in p_2d_1.

The effect of P x I x D could significantly influence the straw yield of rice. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) produced significantly higher straw yield (2848.13 kg ha^{-1}), followed by $p_1i_2d_2$ (2531 kg ha^{-1}) which was on par with $p_2i_1d_2$, $p_1i_3d_2$, $p_2i_2d_2$ and $p_2i_3d_2$. Straw yield was enhanced by 12.71 per cent in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3cm over non-colonized plants at same irrigation frequency.

4.2.7 Harvest Index

Table 7a, 7b and 7c present the effect of *P. indica*, irrigation interval and depth of irrigation on harvest index. *P. indica* colonization, irrigation interval and depth of irrigation did not influence the harvest index of rice.

The effect of P x I, P x D, I x D and P x I x D were not significant on harvest index of rice.

4.3 ROOT OBSERVATIONS

4.3.1 Rooting Depth

Influence of *P. indica* colonization, irrigation interval and depth of irrigation on rooting depth are furnished in Table 8a, 8b and 8c.

All the main factors exerted significant influence on the rooting depth of rice plant at all stages of observation. *P. indica* colonized plants produced significantly superior rooting depth of 8.32, 14.79, 22.11, 25.11 and 26.06 cm at 15, 30, 45, 60 DAT and harvest respectively. Irrigation given at 35 mm CPE produced superior rooting depth of 14.25 and 21.67 at 30 and 45 DAT respectively which was followed by i_1 (30 mm CPE) and i_3 (40 mm CPE). At 60 DAT and harvest maximum rooting depth (24.41 and 25.94 respectively) was recorded at i_1 (30 mm CPE). Regarding depth of irrigation, plants irrigated at 3 cm exhibited the highest rooting depth (8.35, 16.35, 25.52, 28.28 and 29.24 cm) at all growth stages.

Among the first order interactions, *P. indica* colonized plants irrigated at 30 mm CPE observed the highest rooting depth at 60 DAT and harvest (25.99 and 27.23) followed by p_1i_2. Non-colonized plants irrigated at 40 mm CPE produced the lowest rooting depth (21.63 and 22.89 cm) at 60 DAT and harvest respectively. The effects of I x D were found to be significant on rooting depth of rice at all stages of observation. *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) produced superior rooting depth of 17.75, 27.03, 29.14 and 29.77 cm at 30, 45, 60 DAT and harvest respectively followed by p_2d_2 (non-colonized plants irrigated to a depth of 3 cm).

Rice plants irrigated at 35 mm CPE to a depth of 3 cm produced significantly superior rooting depth viz., 17.85, 27.52, 29.66 and 30.00 cm at 30, 45, 60 DAT and harvest respectively, followed by irrigation given at 40 mm CPE to a depth of 3 cm. The lowest rooting depth of 9.64, 13.69, 17.13 and 18.46 cm at 30, 45, 60 DAT and harvest respectively were recorded with irrigated at 40 mm CPE to a depth of 1.5 cm.

Among the second order interactions, *P. indica* colonized rice plants irrigated at 35 mm CPE to a depth of 3 cm recorded significantly superior rooting depth viz., 19.4 and 28.98 cm at 30 and 45 DAT. There was 19.01 per cent higher rooting depth in colonized plants irrigated at 35 mm CPE to a depth of 3 cm over non-colonized plants at same irrigation schedule at 30 DAT. There was 15.53, 26.13 and 21.93 per cent enhancement of rooting depth in *P. indica* colonized plants over non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm at 30, 60 DAT and harvest respectively.

Table 8a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on rooting depth, cm

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1(*P. indica* colonized rice)	8.32	14.79	22.11	25.11	26.06
p_2(non-colonized rice)	8.00	12.47	19.29	22.70	24.11
SEm (±)	0.04	0.07	0.06	0.09	0.09
CD (0.05)	0.108	0.214	0.166	0.269	0.274
Irrigation interval (I)					
i_1 (30 mm CPE)	8.32	13.40	20.43	24.41	25.94
i_2 (35 mm CPE)	8.20	14.25	21.67	24.39	25.30
i_3 (40 mm CPE)	7.96	13.23	19.98	22.92	24.01
SEm (±)	0.04	0.09	0.07	0.11	0.11
CD (0.05)	0.133	0.262	0.204	0.330	0.336
Depth of irrigation (D)					
d_1 (1.5 cm)	7.97	10.91	15.87	19.53	20.93
d_2 (3 cm)	8.35	16.35	25.52	28.28	29.24
SEm (±)	0.04	0.07	0.06	0.09	0.09
CD (0.05)	0.108	0.214	0.166	0.269	0.274

Table 8b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on rooting depth, cm

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	8.46	14.46	21.73	25.99	27.23
p_1i_2	8.35	15.54	23.05	25.12	25.81
p_1i_3	8.16	14.37	21.53	24.21	25.14
p_2i_1	8.18	12.35	19.14	22.83	24.66
p_2i_2	8.06	12.96	20.30	23.66	24.79
p_2i_3	7.76	12.10	18.43	21.63	22.89
SEm (±)	0.06	0.13	0.10	0.16	0.16
CD (0.05)	NS	0.371	0.288	0.467	0.475
P×D interaction					
p_1d_1	8.17	11.83	17.18	21.08	22.35
p_1d_2	8.47	17.75	27.03	29.14	29.77
p_2d_1	7.77	9.99	14.57	17.99	19.51
p_2d_2	8.23	14.95	24.01	27.42	28.71
SEm (±)	0.05	0.10	0.08	0.13	0.13
CD (0.05)	NS	0.303	0.235	0.381	0.388
I×D interaction					
i_1d_1	8.18	12.45	18.10	22.36	23.72
i_2d_1	8.06	10.65	15.83	19.11	20.60
i_3d_1	7.68	9.64	13.69	17.13	18.46
i_1d_2	8.46	14.36	22.77	26.46	28.17
i_2d_2	8.35	17.85	27.52	29.66	30.00
i_3d_2	8.25	16.83	26.28	28.71	29.57
SEm (±)	0.06	0.13	0.10	0.16	0.16
CD (0.05)	0.188	0.371	0.288	0.467	0.475

Table 8c. Effects of P×I×D interaction on rooting depth, cm

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	8.36	13.48	19.17	23.76	25.14
$p_1i_2d_1$	8.20	11.68	17.12	20.37	21.62
$p_1i_3d_1$	7.96	10.34	15.24	19.11	20.29
$p_1i_1d_2$	8.56	15.43	24.29	28.22	29.33
$p_1i_2d_2$	8.50	19.40	28.98	29.86	30.00
$p_1i_3d_2$	8.36	18.41	27.83	29.32	30.00
$p_2i_1d_1$	8.00	11.41	17.03	20.96	22.31
$p_2i_2d_1$	7.93	9.63	14.54	17.85	19.58
$p_2i_3d_1$	7.40	8.95	12.13	15.15	16.64
$p_2i_1d_2$	8.36	13.30	21.24	24.70	27.01
$p_2i_2d_2$	8.20	16.30	26.06	29.46	30.00
$p_2i_3d_2$	8.13	15.25	24.74	28.10	29.14
SEm (±)	0.09	0.18	0.14	0.22	0.23
CD (0.05)	0.265	0.525	0.408	0.660	0.672

4.3.2. Root Volume

Variations in root volume with respect to colonization with *P. indica*, irrigation interval and depth of irrigation are presented in Table 9a, 9b and 9c.

It was noticed that *P. indica* colonization, irrigation interval and depth of irrigation had significant effect on root volume of rice at all stages of observation. Colonized plants produced significantly superior root volume at all growth stages compared to non-colonized plants. Irrigation at 30 mm CPE had superior root volume at all stages of observation compared to 35 mm and 40 mm CPE. Depth at 3 cm showed significantly higher root volume at all growth stages compared to irrigation given at 1.5 cm.

Among the first order interactions, the effect of P x I significantly influenced the root volume at all growth stages of observation. Colonized plants irrigated at 30 mm CPE exhibited significantly superior root volume of 13.15, 21.86, 35.42 and 37.16 cm^3 at 30, 45, 60 DAT and harvest respectively followed by p_1i_2. The effect of P x D was significant at all growth stages, except at 15 DAT. *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) recorded superior root volume (14.23, 23.74, 44.19 and 45.54 cm^3 at 30, 45, 60 DAT and harvest respectively), followed by p_2d_2. The lowest root volume was registered with non-colonized rice plants irrigated to a depth of 1.5 cm (3, 6.22, 10.11 and 11.14 cm^3 at 30, 45, 60 DAT and harvest respectively).

The effect of I x D interaction was significantly superior with irrigation at 30 mm CPE to a depth of 3 cm on root volume. At 15, 30, 45, 60 DAT and harvest the recorded root volume was 1.6, 16.68, 28.75, 46.14 and 48.00 cm^3 respectively.

Second order interactions, P x I x D significantly influenced the root volume at 15, 30, 45, 60 DAT and harvest. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm caused significantly superior root volume (18.86, 32.16, 50.57 and 52.56 cm^3 at 30, 45, 60 DAT and harvest respectively). This was followed by *P. indica* colonized plants irrigated at 35 mm CPE to a depth of 3 cm ($p_1i_2d_2$) (44.64 and 45.80 cm^3) at 60 DAT and harvest respectively and $p_2i_1d_2$ (14.50 cm^3) at 30 DAT. *P. indica* colonized rice plants irrigated at 30 mm CPE to a depth of 3 cm, showed 39.84, 30.06, 21.21 and 21.02 per cent enhancement of root volume at 15, 30, 60 DAT and harvest over noncolonized plants at the same irrigation schedule. *P. indica* colonized plants under severe stress (*i.e.*, irrigation at 40 mm CPE to a depth of 1.5 cm) recorded 39.21, 101.68, 44.12 and 39.06 per cent higher root volume over non-colonized plants at the same irrigation interval and depth at 15, 30, 60 DAT and harvest respectively.

Table 9a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on root volume, cm^3

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p$_1$ (*P. indica* colonized rice)	1.19	9.51	16.24	29.14	30.40
p$_2$ (non-colonized rice)	0.97	7.08	11.86	20.52	21.82
SEm (±)	0.02	0.08	0.16	0.16	0.17
CD (0.05)	0.072	0.243	0.467	0.466	0.508
Irrigation interval (I)					
i$_1$ (30 mm CPE)	1.29	11.56	19.55	31.75	33.30
i$_2$ (35 mm CPE)	0.99	7.50	12.69	23.61	24.74
i$_3$ (40 mm CPE)	0.97	5.82	9.91	19.13	20.30
SEm (±)	0.03	0.10	0.19	0.19	0.21
CD (0.05)	0.088	0.297	0.562	0.570	0.622
Depth of irrigation (D)					
d$_1$ (1.5 cm)	0.74	3.89	7.48	12.10	13.20
d$_2$ (3 cm)	1.42	12.69	20.62	37.56	39.02
SEm (±)	0.02	0.08	0.16	0.16	0.17
CD (0.05)	0.072	0.243	0.467	0.466	0.508

Table 9b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on root volume, cm^3

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	1.46	13.15	21.86	35.42	37.16
p_1i_2	1.06	8.56	15.03	28.53	29.70
p_1i_3	1.04	6.81	11.83	23.47	24.35
p_2i_1	1.11	9.98	17.25	28.07	29.43
p_2i_2	0.91	6.43	10.35	18.69	19.78
p_2i_3	0.90	4.83	8.00	14.79	16.26
SEm (±)	0.04	0.14	0.28	0.27	0.30
CD (0.05)	0.124	0.420	0.809	0.807	0.880
P×D interaction					
p_1d_1	0.86	4.78	8.74	14.09	15.26
p_1d_2	0.62	14.23	23.74	44.19	45.54
p_2d_1	1.52	3.00	6.22	10.11	11.14
p_2d_2	1.33	11.15	17.51	30.93	32.51
SEm (±)	0.03	0.11	0.22	0.22	0.24
CD (0.05)	NS	0.343	0.661	0.659	0.719
I×D interaction					
i_1d_1	0.98	6.45	10.36	17.35	18.60
i_2d_1	0.63	3.45	7.23	10.84	12.05
i_3d_1	0.60	1.79	4.85	8.11	8.96
i_1d_2	1.60	16.68	28.75	46.14	48.00
i_2d_2	1.35	11.55	18.15	36.39	37.43
i_3d_2	1.33	9.85	14.98	30.16	31.65
SEm (±)	0.04	0.14	0.28	0.27	0.30
CD (0.05)	0.124	0.420	0.809	0.807	0.880

Table 9c. Effects of P×I×D interaction on root volume, cm^3

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	1.06	7.43	11.56	20.28	21.76
$p_1i_2d_1$	0.80	4.53	8.43	12.43	13.60
$p_1i_3d_1$	0.71	2.40	6.23	9.57	10.43
$p_1i_1d_2$	1.86	18.86	32.16	50.57	52.56
$p_1i_2d_2$	1.33	12.60	21.63	44.64	45.80
$p_1i_3d_2$	1.36	11.23	17.43	37.38	38.26
$p_2i_1d_1$	0.90	5.46	9.16	14.43	15.43
$p_2i_2d_1$	0.46	2.36	6.03	9.25	10.50
$p_2i_3d_1$	0.50	1.19	3.46	6.64	7.50
$p_2i_1d_2$	1.33	14.50	25.33	41.72	43.43
$p_2i_2d_2$	1.36	10.50	14.66	28.14	29.06
$p_2i_3d_2$	1.30	8.46	12.53	22.94	25.03
SEm (±)	0.06	0.20	0.39	0.39	0.42
CD (0.05)	0.176	0.594	1.144	1.141	1.245

4.3.3 Root Shoot Ratio

Influence of colonization with *P. indica*, irrigation interval, depth of irrigation and its interactions on root shoot ratio at 15, 30, 45, 60 DAT and harvest are presented in Table 10a, 10b and 10c.

P. indica colonized plants produced significantly superior root shoot ratios of 0.186, 0.209, 0.177, 0.2 and 0.201 at all growth stages. Effect of irrigation interval and depth of irrigation was significant on root shoot ratio at all growth stages of observation, except at 15 DAT. Among irrigation intervals, rice plants irrigated at 30 mm CPE exhibited significantly higher root shoot ratio at all growth stages, except at 15 DAT followed by i_2. Depth of irrigation at 3 cm (d_2) produced significantly higher root shoot ratios of 0.228, 0.193, 0.218 and 0.221 at 30, 45, 60 DAT and harvest respectively.

Among the first order interactions, effect of P x I, P x D and I x D were significant on root shoot ratio at all stages, except at 15 DAT. *P. indica* colonized plants with an irrigation at 30 mm CPE showed a higher root shoot ratio at all stages of observation, except at 15 DAT. *P. indica* colonized plants irrigated to a depth of 3 cm brought about maximum root shoot ratio at all stages, except at 15 DAT. The minimum root shoot ratio was recorded with non-colonized plants irrigated to a depth of 1.5 cm.

Significantly superior root shoot ratio viz., 0.239, 0.213, 0.234, 0.236 at 30, 45, 60 DAT and harvest respectively were recorded with i_1d_2 (irrigated at 30 mm CPE to a depth of 3 cm), followed by i_2d_2 (irrigated at 35 mm CPE to a depth of 3 cm).

Among the second order interactions, P x I x D had significant influence on root shoot ratio of rice at all stages of observation, except at 15 DAT. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm evinced significantly the highest root shoot ratio (0.254) at harvest whereas, non-colonized plants had 0.219 at harvest at the same irrigation schedule.

Table 10a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on root shoot ratio

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1 (*P. indica* colonized rice)	0.186	0.209	0.177	0.200	0.201
p_2 (non-colonized rice)	0.168	0.183	0.170	0.171	0.174
SEm (±)	0.006	0.001	0.001	0.001	0.001
CD (0.05)	0.017	0.002	0.002	0.002	0.003
Irrigation interval (I)					
i_1 (30 mm CPE)	0.174	0.216	0.195	0.201	0.205
i_2 (35 mm CPE)	0.168	0.199	0.172	0.186	0.188
i_3 (40 mm CPE)	0.190	0.172	0.154	0.168	0.171
SEm (±)	0.007	0.001	0.001	0.001	0.001
CD (0.05)	NS	0.003	0.003	0.003	0.003
Depth of irrigation (D)					
d_1 (1.5 cm)	0.170	0.164	0.155	0.152	0.155
d_2 (3 cm)	0.185	0.228	0.193	0.218	0.221
SEm (±)	0.006	0.001	0.001	0.001	0.001
CD (0.05)	NS	0.002	0.002	0.002	0.003

Table 10c. Effects of P×I×D interaction on root shoot ratio

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	0.188	0.193	0.182	0.183	0.184
$p_1i_2d_1$	0.167	0.175	0.155	0.164	0.165
$p_1i_3d_1$	0.165	0.154	0.133	0.135	0.137
$p_1i_1d_2$	0.180	0.242	0.222	0.253	0.254
$p_1i_2d_2$	0.180	0.254	0.195	0.239	0.240
$p_1i_3d_2$	0.237	0.235	0.176	0.224	0.226
$p_2i_1d_1$	0.170	0.194	0.171	0.153	0.163
$p_2i_2d_1$	0.153	0.153	0.152	0.143	0.145
$p_2i_3d_1$	0.177	0.115	0.134	0.132	0.135
$p_2i_1d_2$	0.157	0.235	0.203	0.214	0.219
$p_2i_2d_2$	0.173	0.214	0.184	0.198	0.200
$p_2i_3d_2$	0.180	0.185	0.174	0.183	0.185
SEm (±)	0.014	0.002	0.002	0.002	0.002
CD (0.05)	NS	0.006	0.006	0.006	0.006

4.3.4 Root Dry Weight

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and its interaction are furnished in Table 11a, 11b and 11c.

The main effects of *P. indica* colonization and irrigation interval significantly influenced the root dry weight at all stages of observation. Plants irrigated at 30 mm CPE produced significantly superior root dry weight (4.51, 7.94, 11.12 and 11.69 g at 30, 45, 60 DAT and harvest respectively), followed by i_2 (35 mm CPE) and i_3 (40 mm CPE). Depth of irrigation also significantly influenced the root dry weight of rice, except at 15 DAT. Irrigating to deeper depth at 3 cm recorded significantly higher root dry weight at all stages except 15 DAT.

Among the first order interactions, the effect of P x I was significant on root dry weight at all stages of observation. *P. indica* colonized plants irrigated at 30 mm CPE exhibited maximum root dry weight (0.89, 5.39, 9.60, 12.22 and 12.77g) at all stages of observation. This was followed by non-colonized plants irrigated at 30 mm CPE. Effect of P x D was significant on root dry weight of rice at all stages of observation, except at 15 DAT. The highest root dry weight of 6.34, 10.37, 13.08 and 13.77 g was recorded in p_1d_2 at 30, 45, 60 DAT and harvest and was significantly higher.

Interaction I x D could significantly influence the root dry weight of rice, except at 15 DAT. Significantly superior root dry weight (7.20, 12.03, 16.84 and 17.59 g) at 30, 45, 60 DAT and harvest respectively was reported in i_1d_2, followed by i_2d_2 (5.36, 8.40, 11.68 and 12.36 g).

Among second order interactions, *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm recorded significantly superior root dry weight (8.38, 13.77, 18.16 and 19.06 g) at 30, 45, 60 DAT and harvest respectively. There was 28.93 and 40.17 percent increase in root dry weight in *P. indica* colonized plants compared to non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm at 30 and 45 DAT respectively. The lowest root dry weight of 0.75, 1.38, 1.97 and 2.29 g was recorded in $p_2i_3d_1$ at 30, 45, 60 DAT and harvest respectively and was significantly inferior.

Table 11a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on root dry weight, g

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1 (*P. indica* colonized rice)	0.82	3.92	6.75	8.78	9.33
p_2 (non-colonized rice)	0.66	2.89	4.77	7.42	7.94
SEm (±)	0.01	0.01	0.05	0.06	0.07
CD (0.05)	0.039	0.056	0.161	0.185	0.204
Irrigation interval (I)					
i_1 (30 mm CPE)	0.78	4.51	7.94	11.12	11.69
i_2 (35 mm CPE)	0.75	3.20	5.06	7.59	8.10
i_3 (40 mm CPE)	0.69	2.51	4.28	5.59	6.13
SEm (±)	0.02	0.02	0.07	0.08	0.08
CD (0.05)	0.048	0.069	0.197	0.227	0.250
Depth of irrigation (D)					
d_1 (1.5 cm)	0.73	1.23	2.39	3.72	4.12
d_2 (3 cm)	0.75	5.58	9.13	12.48	13.15
SEm (±)	0.01	0.02	0.05	0.06	0.07
CD (0.05)	NS	0.056	0.161	0.185	0.204

Table 11b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on root dry weight, g

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	0.89	5.39	9.60	12.22	12.77
p_1i_2	0.78	3.53	5.66	8.18	8.65
p_1i_3	0.80	2.84	4.99	5.94	6.58
p_2i_1	0.66	3.62	6.28	10.02	10.60
p_2i_2	0.73	2.87	4.47	7.00	7.55
p_2i_3	0.59	2.19	3.56	5.25	5.68
SEm (±)	0.02	0.03	0.09	0.11	0.12
CD (0.05)	0.068	0.097	0.279	0.321	0.353
P×D interaction					
p_1d_1	0.81	1.51	3.13	4.48	4.90
p_1d_2	0.83	6.34	10.37	13.08	13.77
p_2d_1	0.65	0.96	1.65	2.96	3.34
p_2d_2	0.68	4.82	7.89	11.89	12.54
SEm (±)	0.02	0.03	0.08	0.09	0.10
CD (0.05)	NS	0.079	0.228	0.262	0.289
I×D interaction					
i_1d_1	0.77	1.81	3.84	5.40	5.78
i_2d_1	0.73	1.03	1.73	3.50	3.84
i_3d_1	0.69	0.86	1.59	2.25	2.75
i_1d_2	0.79	7.20	12.03	16.84	17.59
i_2d_2	0.77	5.36	8.40	11.68	12.36
i_3d_2	0.70	4.17	6.96	8.93	9.51
SEm (±)	0.02	0.03	0.09	0.11	0.12
CD (0.05)	NS	0.097	0.279	0.321	0.353

Table 11c. Effects of P×I×D interaction on root dry weight, g

Treatment combinations	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	0.85	2.41	5.43	6.28	6.47
$p_1i_2d_1$	0.80	1.14	2.15	4.61	5.02
$p_1i_3d_1$	0.79	0.97	1.80	2.54	3.21
$p_1i_1d_2$	0.81	8.38	13.77	18.16	19.06
$p_1i_2d_2$	0.76	5.92	9.17	11.75	12.28
$p_1i_3d_2$	0.80	4.72	8.18	9.34	9.95
$p_2i_1d_1$	0.68	1.22	2.25	4.52	5.09
$p_2i_2d_1$	0.67	0.93	1.31	2.39	2.65
$p_2i_3d_1$	0.59	0.75	1.38	1.97	2.29
$p_2i_1d_2$	0.65	6.03	10.30	15.53	16.12
$p_2i_2d_2$	0.79	4.81	7.63	11.61	12.44
$p_2i_3d_2$	0.6	3.63	5.74	8.53	9.07
SEm (±)	0.03	0.05	0.13	0.15	0.17
CD (0.05)	0.096	0.137	0.395	0.454	0.500

4.3.5 Average Root Length

Table 12a, 12b and 12c represent the influence of *P. indica*, irrigation interval and depth on average root length of rice plants.

Colonization with *P. indica* and depth of irrigation had significant influence on average root length at all stages of observation. Colonized plants produced significantly superior average root length (10.74, 15.72, 19.81, 25.62 and 28.58 cm at 15, 30, 45, 60 DAT and harvest respectively). Plants irrigated at 35 mm CPE produced superior average root length (15.9, 19.65, 24.82 and 28 cm at 30, 45, 60 DAT and harvest respectively), followed by i_1 (30 mm CPE). Regarding depth of irrigation, superior average root length (10.94, 18.61, 23.07, 30.25 and 33.58 at 15, 30, 45, 60 DAT and harvest respectively) was recorded in depth d_2.

Among the first order interactions, the effect of P x I significantly influenced the average root length of rice at all stages of observation, except at 15 DAT. *P. indica* colonized plants irrigated at 35 mm CPE recorded significantly superior average root length (17.23, 21.30, 26.73 and 29.51 cm). P x D interaction significantly influenced the average root length of rice at 30, 45 DAT and harvest. *P. indica* colonization and plants irrigated to a depth of 3 cm resulted in significantly superior average root length of 19.87, 24.68 and 34.97 cm at 30, 45 DAT and harvest respectively.

Among I x D interactions, i_2d_2 had significantly superior average root length (21.56, 26.15, 32.39 and 34.95 cm at 30, 45, 60 DAT and harvest respectively). But at 15 DAT, irrigation at 40 mm CPE and to a depth of 3 cm (i_3d_2) brought about a higher average root length (11.43), which was on par with i_2d_2 (11.23).

Three factor interactions, P x I x D remained significant at all stages of observation, except at 15 DAT. The highest average root length of 23.36, 28.4, 34.87 and 36.20 cm was recorded at 30, 45, 60 DAT and harvest respectively for *P. indica* colonized plants irrigated at 35 mm CPE to a depth of 3 cm ($p_1i_2d_2$). The lowest average root length (9.03, 10.43, 14.78 and 18.16) was recorded in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm ($p_2i_3d_1$) at 30, 45, 60 DAT and harvest respectively.

Table 12a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on average root length, cm

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
Colonizing with *P. indica* (P)					
p_1 (*P. indica* colonized rice)	10.74	15.72	19.81	25.62	28.58
p_2 (non-colonized rice)	9.80	13.71	17.01	22.68	26.08
SEm (±)	0.13	0.14	0.15	0.16	0.22
CD (0.05)	0.384	0.404	0.428	0.467	0.637
Irrigation interval (I)					
i_1 (30 mm CPE)	10.28	14.60	18.59	24.40	27.81
i_2 (35 mm CPE)	10.30	15.90	19.65	24.82	28.00
i_3 (40 mm CPE)	10.23	13.65	17.00	23.23	26.19
SEm (±)	0.16	0.17	0.18	0.19	0.27
CD (0.05)	NS	0.494	0.524	0.572	0.780
Depth of irrigation (D)					
d_1 (1.5 cm)	9.60	10.82	13.76	18.05	21.09
d_2 (3 cm)	10.94	18.61	23.07	30.25	33.58
SEm (±)	0.13	0.14	0.15	0.16	0.22
CD (0.05)	0.384	0.404	0.428	0.467	0.637

Table 12b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on average root length, cm

Interactions	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
P×I interaction					
p_1i_1	10.76	15.58	20.01	25.25	28.56
p_1i_2	10.66	17.23	21.30	26.73	29.51
p_1i_3	10.80	14.36	18.13	24.89	27.68
p_2i_1	9.80	13.63	17.16	23.55	27.06
p_2i_2	9.95	14.56	18.01	22.92	26.50
p_2i_3	9.66	12.93	15.86	21.57	24.70
SEm (±)	0.23	0.24	0.25	0.28	0.38
CD (0.05)	NS	0.699	0.741	0.809	1.103
P×D interaction					
p_1d_1	9.94	11.57	14.94	19.47	22.20
p_1d_2	11.54	19.87	24.68	31.78	34.97
p_2d_1	9.26	10.06	12.57	16.64	19.98
p_2d_2	10.34	17.35	21.45	28.72	32.18
SEm (±)	0.18	0.19	0.21	0.22	0.31
CD (0.05)	NS	0.571	0.605	NS	0.901
I×D interaction					
i_1d_1	10.40	12.71	16.45	20.55	22.66
i_2d_1	9.38	10.23	13.16	17.26	21.06
i_3d_1	9.03	9.51	11.66	16.35	19.55
i_1d_2	10.16	16.50	20.73	28.25	32.96
i_2d_2	11.23	21.56	26.15	32.39	34.95
i_3d_2	11.43	17.78	22.33	30.11	32.83
SEm (±)	0.23	0.24	0.25	0.28	0.38
CD (0.05)	0.664	0.699	0.741	0.809	1.103

Table 12c. Effects of P×I×D interaction on average root length, cm

Treatments	15 DAT	30 DAT	45 DAT	60 DAT	At harvest
$p_1i_1d_1$	10.76	13.63	17.73	21.9	22.83
$p_1i_2d_1$	9.76	11.10	14.20	18.58	22.83
$p_1i_3d_1$	9.30	10.00	12.90	17.92	20.93
$p_1i_1d_2$	10.76	17.53	22.30	28.6	34.30
$p_1i_2d_2$	11.56	23.36	28.40	34.87	36.20
$p_1i_3d_2$	12.30	18.73	23.36	31.86	34.43
$p_2i_1d_1$	10.03	11.80	15.16	19.2	22.50
$p_2i_2d_1$	9.00	9.36	12.13	15.93	19.30
$p_2i_3d_1$	8.76	9.03	10.43	14.78	18.16
$p_2i_1d_2$	9.56	15.46	19.16	27.9	31.63
$p_2i_2d_2$	10.90	19.76	23.90	29.91	33.70
$p_2i_3d_2$	10.56	16.83	21.30	28.36	31.23
SEm (±)	0.32	0.34	0.36	0.39	0.53
CD (0.05)	NS	0.988	1.048	1.145	1.560

4.4 PHYSIOLOGICAL PARAMETERS

4.4.1 Proline

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and its interaction on proline are furnished in Table 13a, 13b and 13c.

The main effects of all the factors were significant at PI and flowering stages. Maximum proline at PI and flowering (83.11 and 71.83 µmole g^{-1} respectively) were recorded in *P. indica* colonized plants. Proline content declined in the order of decreasing CPE, 40 mm >35 mm > 30 mm CPE. Irrigation at 40 mm CPE produced significantly higher proline (86.66 and 75.91 µmole g^{-1} at PI and flowering), followed by i_2 (35 mm CPE) and i_1 (30 mm CPE). Irrigation to lower depth of 1.5 cm showed significantly higher proline content (94.72 and 83.38 µmole g^{-1} at PI and flowering respectively), over plants irrigated to a depth of 3 cm.

Among the first order interactions, P x I interaction evinced significant variation in proline at PI and flowering stages. Irrigation of *P. indica* colonized rice plants at 40 mm CPE exhibited significantly superior proline content (92.50 and 82.66 µmole g^{-1}) at PI and flowering. Lowest proline of 59.00 and 53.33 µmole g^{-1} were recorded with p_2i_1 (non-colonized rice plants irrigated at 30 mm CPE) at PI and flowering stage. P x D interaction showed significant influence on proline content at PI and flowering stages of rice. *P. indica* colonized rice plants irrigated to a lower depth of 1.5 cm recorded significantly superior proline of 102.22 and 92.11 µmole g^{-1} at PI and flowering respectively, followed by non-colonized rice plants to a depth of 1.5 cm (87.22 and 74.66 µmole g^{-1}).

The effect of I x D also registered significant variation on proline at PI and flowering. Interaction i_3d_1 produced superior proline of 106.50 and 96.66 µmole g^{-1} followed by i_2d_1 (96.66 and 84.16 µmole g^{-1}) and i_1d_1 (81.00 and 69.33 µmole g^{-1}) at PI and flowering stage respectively. The lowest proline of 48.66 and 44.50 µmole g^{-1} were recorded in plants irrigated at 30 mm CPE to a depth of 3 cm at PI and flowering respectively.

Among the second order interactions, *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm produced significantly superior proline of 115.33 and 106.00 µmole g^{-1}, followed by $p_1i_2d_1$ (105.66 and 95.66 µmole g^{-1}) at PI and flowering. The lowest proline content was reported with non-colonized plants irrigated at 30 mm CPE to a depth of 3 cm (41.66 and 42.66 µmole g^{-1}) at PI and flowering respectively.

Table 13a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on proline and relative leaf water content.

Treatments	Proline (µmole g^{-1})		Relative Leaf Water Content(%)	
	PI	Flowering	PI	Flowering
Colonizing with *P. indica* (P)				
p_1 (*P. indica* colonized rice)	83.11	71.83	77.50	74.00
p_2 (non-colonized rice)	70.94	60.44	73.61	70.33
SEm (±)	0.46	0.40	0.13	0.15
CD (0.05)	1.343	1.185	0.384	0.441
Irrigation interval (I)				
i_1 (30 mm CPE)	64.83	56.91	79.65	76.46
i_2 (35 mm CPE)	79.58	65.58	75.35	71.67
i_3 (40 mm CPE)	86.66	75.91	71.66	68.36
SEm (±)	0.56	0.49	0.16	0.18
CD (0.05)	1.644	1.451	0.470	0.541
Depth of irrigation (D)				
d_1 (1.5 cm)	94.72	83.38	70.76	66.35
d_2 (3 cm)	59.33	48.88	80.35	77.97
SEm (±)	0.46	0.40	0.13	0.15
CD (0.05)	1.343	1.185	0.384	0.441

Table 13b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on proline and relative leaf water content.

Interactions	Proline (µmole g^{-1})		Relative Leaf Water Content (%)	
	PI	Flowering	PI	Flowering
P x I interaction				
p_1i_1	70.66	60.50	82.01	78.65
p_1i_2	86.16	72.33	77.00	73.25
p_1i_3	92.50	82.66	73.48	70.10
p_2i_1	59.00	53.33	77.28	74.27
p_2i_2	73.00	58.83	73.70	70.08
p_2i_3	80.83	69.16	69.85	66.63
SEm (±)	0.79	0.70	0.23	0.26
CD (0.05)	2.325	2.052	0.667	0.765
P x D interaction				
p_1d_1	102.22	92.11	72.64	68.70
p_1d_2	64.00	51.55	82.35	79.30
p_2d_1	87.22	74.66	68.87	64.01
p_2d_2	54.66	46.22	78.34	76.65
SEm (±)	0.65	0.57	0.18	0.21
CD (0.05)	1.899	1.676	0.545	0.624
I × D interaction				
i_1d_1	81.00	69.33	74.93	69.93
i_2d_1	96.66	84.16	71.38	66.52
i_3d_1	106.50	96.66	65.96	62.61
i_1d_2	48.66	44.50	84.36	82.99
i_2d_2	62.50	47.00	79.31	76.82
i_3d_2	66.83	55.16	77.36	74.11
SEm (±)	0.79	0.70	0.23	0.26
CD (0.05)	2.325	2.052	0.667	0.765

Table 13c. Effects of P×I×D interaction on proline and relative leaf water content.

Treatment combinations.	Proline (µmole g^{-1})		Relative Leaf Water Content (%)	
	PI	Flowering	PI	Flowering
$p_1i_1d_1$	85.66	74.66	76.10	72.16
$p_1i_2d_1$	105.66	95.66	73.13	68.85
$p_1i_3d_1$	115.33	106.00	68.70	65.10
$p_1i_1d_2$	55.66	46.33	87.93	85.13
$p_1i_2d_2$	66.66	49.00	80.86	77.66
$p_1i_3d_2$	69.66	59.33	78.26	75.10
$p_2i_1d_1$	76.33	64.00	73.76	67.70
$p_2i_2d_1$	87.66	72.66	69.63	64.20
$p_2i_3d_1$	97.66	87.33	63.23	60.13
$p_2i_1d_2$	41.66	42.66	80.80	80.85
$p_2i_2d_2$	58.33	45.00	77.76	75.97
$p_2i_3d_2$	64.00	51.00	76.46	73.13
SEm (±)	1.12	0.99	0.32	0.37
CD (0.05)	3.289	2.903	0.943	1.081

4.4.2 Relative Leaf Water Content

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and its interaction on relative leaf water content (RLWC) are furnished in Table 13a, 13b and 13c.

P. indica colonization had significant effect on RLWC of rice plants at panicle initiation (PI) and flowering stages. Maximum RLWC of 77.50 and 74.00 per cent respectively were measured at PI and flowering stages in *P. indica* colonized plants against RLWC of 73.61 and 70.33 per cent in non-colonized plants. Irrigation interval was significantly superior for plants irrigated at 30 mm CPE (79.65 and 76.46 % at PI and flowering), followed by i_2 (35 mm CPE) and i_3 (40 mm CPE). Depth of irrigation also significantly influenced the RLWC of rice. Significantly superior RLWC viz., 80.35 and 77.97 per cent at PI and flowering respectively were recorded with depth of irrigation 3 cm (d_2).

Among the first order interactions, P x I interaction had significant variation in RLWC at PI stage and flowering. Irrigation of *P. indica* colonized rice plants at irrigation interval i_1 (30 mm CPE) observed significantly superior RLWC of 82.01 and 78.65 per cent at PI stage and flowering. The lowest RLWC of 69.85 and 66.63 per cent were recorded with non-colonized rice plants irrigated at 40 mm CPE (p_2i_3) at PI stage and flowering. P x D interaction showed significant influence on RLWC at PI and flowering. Irrigation of *P. indica* colonized rice plants to a depth of 3 cm (d_2) observed significantly superior RLWC of 82.35 and 79.30 per cent, followed by non-colonized rice plants to a depth of 3 cm (78.34 and 76.65 %) at PI stage and flowering respectively.

The effect of I x D interaction was significant on RLWC at PI and flowering stages. Significantly superior RLWC of 84.36 and 82.99 per cent at PI and flowering stage respectively were recorded in i_1d_2 followed by i_2d_2 (79.31 and 76.82 %) and i_3d_2 (77.36 and 74.11 %). The lowest RLWC of 65.96 and 62.61 per cent at PI and flowering respectively were recorded with i_3d_1(irrigated at 40 mm CPE to a depth of 1.5 cm).

Among the second order interactions, *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) observed significantly superior RLWC of 87.93 and 85.13 per cent at PI and flowering followed by $p_1i_2d_2$ (80.86 % at PI stage), which was on par with $p_2i_1d_2$ (80.8 % at PI stage). Non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm observed the lowest RLWC (63.23 and 60.13 %) at PI and flowering.

4.4.3 Cell Membrane Stability

Influence of colonization with *P. indica*, irrigation interval and depth of irrigation and its interaction on cell membrane stability (CMS) of rice at PI and flowering are presented in Table 14a, 14b and 14c.

Perusal of the data revealed the significant influence of colonizing *P. indica* on CMS at PI and flowering. CMS was significantly superior at PI and flowering for colonized plants (75.82 and 67.32 %) at PI and flowering. The variation in CMS due to irrigation interval was significant at PI and flowering. Irrigation interval (30 mm CPE) produced significantly higher CMS (78.18 and 69.93 %) at PI and flowering compared to 35 mm and 40 mm CPE. The effect of depth of irrigation on CMS was significant at PI and flowering. Plants irrigated to a depth of 3 cm (d_2) recorded significantly superior CMS (85.88 and 76.88 %) at PI and flowering compared to those irrigated at 1.5 cm depth (d_1).

Among the two factor interactions, P x I interaction showed significant influence on CMS at PI and flowering. Colonized plants irrigated at 30 mm CPE resulted in significantly superior CMS (81.58 and 73.08 %) at PI and flowering. Effect of P x D interaction showed significant influence on CMS at PI and flowering. At PI and flowering, p_1d_2 (colonized plants irrigated at a depth of 3 cm) evinced maximum CMS of 88.93 and 80.93 per cent and was significantly superior. The least CMS was recorded by p_2d_1 the values being, 53.31 and 47.97 per cent at PI and flowering respectively.

The effect of I x D interaction on CMS was significant at PI and flowering. Plants irrigated at 30 mm CPE to a depth of 3 cm recorded significantly superior CMS of 91.55 and 81.88 per cent at PI and flowering respectively, followed by i_2d_2 (85.40 and 76.56 %) at PI and flowering respectively.

Effect of P x I x D was significant at PI and flowering. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm recorded the maximum CMS of 95.00 and 85.00 per cent at PI and flowering respectively and was significantly superior. At the same irrigation interval and depth, non-colonized plants produced CMS of 88.10 and 78.76 per cent at PI and flowering respectively, which was 7.83 and 7.92 per cent lower than CMS registered in colonized plants at PI and flowering respectively. The lowest CMS of 43.90 at both PI and flowering was recorded with $p_2i_3d_1$ (non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm). At the same interval and depth, colonized plants recorded 22.75 and 7.57 per cent increment in CMS at PI and flowering, compared to non-colonized plants.

4.4.4 Chlorophyll Stability Index

Influence of colonization with *P. indica*, irrigation interval, depth of irrigation and its interaction on chlorophyll stability index (CSI) of rice at PI and flowering are presented in Table 14a, 14b and 14c.

The data revealed the significant influence of main effects namely colonizing with *P. indica*, irrigation interval and depth of irrigation on CSI at PI and flowering. CSI was significantly superior at PI and flowering for colonized plants (79.20 and 70.01 %). Irrigation at 30 mm CPE produced significantly higher CSI (80.82 and 74.15 %) at PI and flowering, compared to i_2 and i_3. Plants irrigated to a depth of 3 cm (d_2) exhibited significantly superior CSI of 82.90 and 78.39 per cent at PI and flowering.

Among the two factor interactions, P x I interaction showed significant influence on CSI at PI and flowering stages. Colonized plants irrigated at 30 mm CPE brought about significantly superior CSI (86.00 and 77.25 %) at PI and flowering stages respectively. The effects of P x D and I x D interaction were significant on CSI at PI and flowering. Colonized plants irrigated to a depth of 3 cm showed significantly superior CSI (86.98 and 82.26 %) at both the stages. The least CSI was recorded in non-colonized plants irrigated to a depth of 1.5 cm (60.76 and 51.44 %) at PI and flowering respectively. Plants irrigated at 30 mm CPE to a depth of 3 cm had significantly superior CSI of (89.98 and 85.70 %), followed by i_2d_2 (81.73 and 76.61 %) at PI and flowering respectively.

The effect of P x I x D was significant at PI and flowering. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm had the significantly higher CSI of 95.80 and 88.63 per cent at PI and flowering respectively. At the same irrigation interval and depth, non-colonized plants produced CSI which was 13.83 and 7.09 per cent lower than colonized plants at PI and flowering respectively. A lower CSI of 54.13 and 43.90 per cent at PI and flowering respectively was recorded with $p_2i_3d_1$ (non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm). At the same interval and depth, colonized plants recorded CSI of 66.20 and 49.90 per cent at PI and flowering, which was 22.29 and 13.66 per cent higher than non-colonized plants under severe stress situation.

Table 14a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on cell membrane stability and chlorophyll stability index.

Treatments	Cell Membrane Stability (%)		Chlorophyll Stability Index (%)	
	PI	Flowering	PI	Flowering
Colonizing with *P. indica* (P)				
p_1 (*P. indica* colonized rice)	75.82	67.32	79.20	70.01
p_2 (non-colonized rice)	68.07	60.41	69.78	62.98
SEm (±)	0.44	0.26	0.19	0.18
CD (0.05)	1.296	0.755	0.549	0.535
Irrigation interval (I)				
i_1 (30 mm CPE)	78.18	69.93	80.82	74.15
i_2 (35 mm CPE)	72.13	62.71	74.08	65.45
i_3 (40 mm CPE)	65.54	58.95	68.57	59.88
SEm (±)	0.54	0.31	0.23	0.22
CD (0.05)	1.588	0.924	0.672	0.655
Depth of irrigation (D)				
d_1 (1.5 cm)	58.01	50.85	66.08	54.60
d_2 (3 cm)	85.88	76.88	82.90	78.39
SEm (±)	0.44	0.26	0.19	0.18
CD (0.05)	1.296	0.755	0.549	0.535

Table 14b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on cell membrane stability and chlorophyll stability index.

Interactions	Cell Membrane Stability (%)		Chlorophyll Stability Index (%)	
	PI	Flowering	PI	Flowering
P x I interaction				
p_1i_1	81.58	73.08	86.00	77.25
p_1i_2	75.88	66.88	78.38	69.36
p_1i_3	70.01	62.01	73.21	63.41
p_2i_1	74.78	66.78	75.65	71.05
p_2i_2	68.38	58.55	69.78	61.55
p_2i_3	61.06	55.90	63.93	56.35
SEm (±)	0.76	0.45	0.32	0.32
CD (0.05)	2.245	1.307	0.951	0.926
P x D interaction				
p_1d_1	62.72	53.72	71.41	57.75
p_1d_2	88.93	80.93	86.98	82.26
p_2d_1	53.31	47.97	60.76	51.44
p_2d_2	82.84	72.84	78.81	74.52
SEm (±)	0.62	0.36	0.26	0.26
CD (0.05)	1.833	1.067	0.776	0.756
I x D interaction				
i_1d_1	64.81	57.98	71.66	62.60
i_2d_1	58.86	48.86	66.43	54.30
i_3d_1	50.36	45.70	60.16	46.90
i_1d_2	91.55	81.88	89.98	85.70
i_2d_2	85.40	76.56	81.73	76.61
i_3d_2	80.71	72.21	76.98	72.86
SEm (±)	0.76	0.45	0.32	0.32
CD (0.05)	2.245	1.307	0.951	0.926

Table 14c. Effects of P×I×D interaction on cell membrane stability and chlorophyll stability index

Treatment combinations	Cell Membrane Stability (%)		Chlorophyll Stability Index (%)	
	PI	Flowering	PI	Flowering
$p_1i_1d_1$	68.16	61.16	76.20	65.86
$p_1i_2d_1$	63.16	52.50	71.83	57.50
$p_1i_3d_1$	56.83	47.50	66.20	49.90
$p_1i_1d_2$	95.00	85.00	95.80	88.63
$p_1i_2d_2$	88.60	81.26	84.93	81.23
$p_1i_3d_2$	83.20	76.53	80.23	76.93
$p_2i_1d_1$	61.46	54.80	67.13	59.33
$p_2i_2d_1$	54.56	45.23	61.03	51.10
$p_2i_3d_1$	43.90	43.90	54.13	43.90
$p_2i_1d_2$	88.10	78.76	84.16	82.76
$p_2i_2d_2$	82.20	71.86	78.53	72.00
$p_2i_3d_2$	78.23	67.90	73.73	68.80
SEm (±)	1.08	0.63	0.46	0.44
CD (0.05)	3.175	1.848	1.344	1.309

4.5 WATER USE EFFICIENCY

Table 15a, 15b and 15c represent the influence of *P. indica*, irrigation interval and depth of irrigation on water use efficiency (WUE) of rice plants.

The result revealed that colonization with *P. indica*, irrigation interval and depth of irrigation had significant influence on WUE of rice. Colonized plants exhibited significantly superior WUE (2.97 kg ha^{-1} mm^{-1}) compared to non-colonized plants. Among irrigation intervals, plants irrigated at 30 mm CPE had superior WUE (3.05 kg ha^{-1} mm^{-1}) followed by i_2 (35 mm CPE). Regarding depth of irrigation, irrigation at 3 cm depth resulted in maximum WUE (3.04 kg ha^{-1} mm^{-1}).

Among the first order interactions, the effect of P x I, P x D and I x D were significant. Among P x I interaction, *P. indica* colonized plants irrigated at 30 mm CPE observed superior WUE of 3.28 kg ha^{-1} mm^{-1}. *P. indica* colonized plants irrigated to a depth of 3 cm resulted in significantly superior WUE (3.19 kg ha^{-1} mm^{-1}), followed by p_2d_2. Among I x D interactions, i_1d_2 recorded significantly superior WUE (3.21 kg ha^{-1} mm^{-1}).

Among the three factor interactions, P x I x D remained significant with the highest WUE of 3.47 kg ha^{-1} mm^{-1} for $p_1i_1d_2$ (*P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm). The lowest WUE (1.86 kg ha^{-1} mm^{-1}) was recorded in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm ($p_2i_3d_1$). *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm resulted in 15.56 per cent enhancement in WUE over non-colonized plants at the same irrigation frequency.

Table 15a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on water use efficiency.

Treatments	Water use efficiency (kg ha^{-1} mm^{-1})
Colonizing with *P. indica* (P)	
p_1 (*P. indica* colonized rice)	3.00
p_2 (non-colonized rice)	2.55
SEm (±)	0.02
CD (0.05)	0.059
Irrigation interval (I)	
i_1 (30 mm CPE)	3.00
i_2 (35 mm CPE)	2.73
i_3 (40 mm CPE)	2.59
SEm (±)	0.02
CD (0.05)	0.072
Depth of irrigation (D)	
d_1 (1.5 cm)	2.49
d_2 (3 cm)	3.05
SEm (±)	0.02
CD (0.05)	0.059

Table 15b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on water use efficiency.

P x I interaction	Water use efficiency (kg ha^{-1} mm^{-1})
p_1i_1	3.28
p_1i_2	2.91
p_1i_3	2.81
p_2i_1	2.71
p_2i_2	2.55
p_2i_3	2.37
SEm (±)	0.03
CD (0.05)	0.102
P x D interaction	
p_1d_1	2.80
p_1d_2	3.19
p_2d_1	2.17
p_2d_2	2.92
SEm (±)	0.03
CD (0.05)	0.083
I x D interaction	
i_1d_1	2.78
i_2d_1	2.48
i_3d_1	2.21
i_1d_2	3.21
i_2d_2	2.98
i_3d_2	2.97
SEm (±)	0.03
CD (0.05)	0.102

Table 15c. Effect of P x I x D interaction on water use efficiency

Treatment combinations	Water use efficiency (kg ha^{-1} mm^{-1})
$p_1i_1d_1$	3.09
$p_1i_2d_1$	2.77
$p_1i_3d_1$	2.55
$p_1i_1d_2$	3.47
$p_1i_2d_2$	3.05
$p_1i_3d_2$	3.07
$p_2i_1d_1$	2.47
$p_2i_2d_1$	2.20
$p_2i_3d_1$	1.86
$p_2i_1d_2$	2.96
$p_2i_2d_2$	2.91
$p_2i_3d_2$	2.88
SEm (±)	0.05
CD (0.05)	0.144

4.6 SOIL ANALYSIS

4.6.1 Soil Organic Carbon

Tables 16 a, 16b and 16 c represent the influence of *P. indica*, irrigation interval and depth of irrigation on soil organic carbon after experiment.

The data revealed that P. *indica* colonization and irrigation interval had no significant influence on soil organic carbon. However, depth of irrigation exerted significant variation in soil organic carbon after harvest with d_2 being superior.

Among two factor interactions, P x I and I x D did not influence the soil organic carbon. *P. indica* and depth of irrigation (P x D) could significantly influence the soil organic carbon. *P. indica* colonized plants irrigated to a depth of 3 cm observed a higher soil organic carbon (0.638 %), which was on par with p_2d_2 (0.632) and p_1d_1 (0.626).

The result revealed that three factor interactions (P x I x D) showed no significant influence on soil organic carbon.

4.6.2 Available Nitrogen

Tables 16 a, 16b and 16 c represent the influence of *P. indica*, irrigation interval and depth of irrigation on available nitrogen after experiment.

The data on available nitrogen revealed that *P. indica*, irrigation interval and depth of irrigation could significantly influence the available nitrogen after experiment. Plots grown with *P. indica* colonized plants observed a low available nitrogen (121.61 kg ha^{-1}) compared to plots grown with non-colonized plants (137.24 kg ha^{-1}). Irrigation at 40 mm CPE resulted in significantly higher available nitrogen (134.82 kg ha^{-1}), followed by 35 mm CPE (130.02 kg ha^{-1}). Irrigation to a depth 1.5 cm brought about superior available nitrogen (139.52 kg ha^{-1}).

Among the first order interactions, P x I had significant influence on available nitrogen status. Significantly superior available nitrogen (141.05 kg ha^{-1}) was observed in p_2i_3, followed by p_2i_2 (137.56). The lowest status of available nitrogen (114.22 kg ha^{-1}) was recorded in p_1i_1. P x D interaction could also significantly influence the available nitrogen in soil after experiment. Non-colonized plants irrigated to a depth of 1.5 cm resulted in higher available nitrogen status (144.42), followed by p_1d_1 (134.62). Available nitrogen status was significantly higher in plots irrigated at 40 mm CPE to a depth of 1.5 cm (144.57), followed by i_2d_1 (139.70).

Among the second order interactions, P x I x D could significantly influence the available nitrogen. Plots with non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm showed a higher amount of available nitrogen (150.64), followed by $p_2i_2d_1$ (143.83). *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm brought about the lowest amount of available nitrogen (98.65).

4.6.3 Available Phosphorus

Tables 16a, 16b and 16c represent the influence of *P. indica*, irrigation interval and depth of irrigation on soil available phosphorus after experiment.

The data obtained from the analysis revealed that *P. indica*, irrigation interval and depth could significantly influence the soil available phosphorus. Colonization with *P. indica* resulted in significantly higher available soil phosphorus (172.53 kg ha^{-1}) compared to non-colonized plants. Irrigation at 40 mm CPE evinced the highest available phosphorus (171.84 kg ha^{-1}), followed by 35 mm CPE (169.64). Regarding depth of irrigation, lower depth of 1.5 cm resulted in significantly superior available phosphorus (173.54 kg ha^{-1}), followed by depth of 3 cm (165.15).

Among the first order interactions, P x I and P x D interaction exerted significant variation in available phosphorus status. *P. indica* colonized plants irrigated at 40 mm CPE led to the highest available phosphorus (174.78 kg ha^{-1}), followed by p_1i_2 (172.93). The highest available phosphorus (177.54 kg ha^{-1}) was observed in p_1d_1 (*P. indica* colonized irrigate to a depth 1.5 cm), followed by p_2d_1 (169.51 kg ha^{-1}). The lowest available phosphorus status was recorded in p_2d_2 (162.81 kg ha^{-1}). I x D interaction could also significantly influence the soil available phosphorus. High available phosphorus status (176.53 kg ha^{-1}) was recorded in irrigation at 40 mm CPE to a depth of 1.5 cm, while the lowest amount of available phosphorus (162.33 kg ha^{-1}) was recorded in irrigation at 30 mm CPE to a depth of 3 cm.

Among the second order interactions, P x I x D could significantly influence the available soil phosphorus. Plots with *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm resulted in significantly superior available phosphorus (179.93 kg ha^{-1}). The lowest available soil phosphorus (159.92 kg ha^{-1}) was reported in non-colonized plants irrigated at 30 mm CPE to a depth of 3 cm. There was 3 per cent increase in available soil phosphorus in plots grown with colonized plants irrigated at 30 mm CPE to a depth of 3 cm over the plots with non-colonized plants irrigated at same interval and depth.

4.6.4 Available Potassium

Tables 16a, 16b and 16c represent the influence of *P. indica*, irrigation interval and depth of irrigation on soil available potassium after experiment.

The main effect of factors, *P. indica* colonization, irrigation interval and depth of irrigation showed significant variation in available potassium in soil. Plots of non-colonized plants exhibited a significantly higher available potassium (290.96 kg ha^{-1}) over plots with colonized plants (261.39 kg ha^{-1}). Plants irrigated at 40 mm CPE had the highest available potassium (291.02 kg ha^{-1}). Available K status was significantly superior in plots irrigated to a depth of 1.5 cm (303.20 kg ha^{-1}).

Among the first order interactions, I x D did not influence the available potassium. The effect of P x I and P x D showed significant influence on available potassium. Non-colonized plants irrigated at 40 mm CPE brought about the highest available potassium (303.43 kg ha^{-1}). In the case of P x D, non-colonized plants irrigated to a depth of 1.5 cm resulted in significantly superior soil available potassium status (314.20 kg ha^{-1}). The lowest soil available potassium (230.57 kg ha^{-1}) was recorded in P. *indica* colonized plants irrigated to a depth of 3 cm.

Among the three factor interactions, effect of P x I x D showed significant influence on available potassium. Non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm showed the highest available potassium (329.55 kg ha^{-1}). The lowest available potassium (209.48 kg ha^{-1}) was recorded in $p_1i_1d_2$.

Table 16a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on organic carbon, available N, available P and available K

Treatments	Organic carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
Colonizing with *P. indica* (P)				
p_1 (*P. indica* colonized rice)	0.632	121.61	172.53	261.39
p_2 (non-colonized rice)	0.627	137.24	166.16	290.96
SEm (±)	0.002	0.25	0.14	1.37
CD (0.05)	NS	0.723	0.393	4.016
Irrigation interval (I)				
i_1 (30 mm CPE)	0.633	123.43	166.56	258.64
i_2 (35 mm CPE)	0.628	130.02	169.64	278.86
i_3 (40 mm CPE)	0.628	134.82	171.84	291.02
SEm (±)	0.002	0.30	0.17	1.68
CD (0.05)	NS	0.886	0.481	4.919
Depth of irrigation (D)				
d_1 (1.5 cm)	0.623	139.52	173.54	303.20
d_2 (3 cm)	0.635	119.32	165.15	249.19
SEm (±)	0.002	0.25	0.14	1.37
CD (0.05)	0.0050	0.723	0.393	4.016

Table 16b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on organic carbon, available N, P and K

Interactions	Organic Carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
P×I interaction				
p_1i_1	0.637	114.22	169.87	242.24
p_1i_2	0.630	122.47	172.93	263.31
p_1i_3	0.628	128.13	174.78	278.61
p_2i_1	0.628	132.65	163.24	275.04
p_2i_2	0.625	137.56	166.35	294.41
p_2i_3	0.627	141.05	168.89	303.43
SEm (±)	0.003	0.43	0.24	2.37
CD (0.05)	NS	1.253	0.681	0.695
P×D interaction				
p_1d_1	0.626	134.62	177.54	292.20
p_1d_2	0.638	108.59	167.48	230.57
p_2d_1	0.621	144.42	169.51	314.20
p_2d_2	0.632	130.05	162.81	267.72
SEm (±)	0.003	0.35	0.18	1.94
CD (0.05)	0.0070	1.023	0.556	5.680
I×D interaction				
i_1d_1	0.627	134.29	170.79	285.23
i_2d_1	0.622	139.70	173.30	305.32
i_3d_1	0.622	144.57	176.53	319.06
i_1d_2	0.638	112.58	162.33	232.05
i_2d_2	0.633	120.33	165.98	252.41
i_3d_2	0.633	125.06	167.14	262.98
SEm (±)	0.003	0.43	0.24	2.37
CD (0.05)	NS	1.253	0.681	NS

Table 16c. Effects of P×I×D interaction on organic carbon, available N, P and K

Treatments	Organic carbon (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
$p_1i_1d_1$	0.630	129.78	175.01	274.99
$p_1i_2d_1$	0.623	135.58	177.77	293.04
$p_1i_3d_1$	0.623	138.50	179.93	308.57
$p_1i_1d_2$	0.643	98.65	164.73	209.48
$p_1i_2d_2$	0.637	109.37	168.09	233.58
$p_1i_3d_2$	0.633	117.76	169.63	248.65
$p_2i_1d_1$	0.623	138.80	166.57	295.47
$p_2i_2d_1$	0.620	143.83	168.83	317.59
$p_2i_3d_1$	0.620	150.64	173.14	329.55
$p_2i_1d_2$	0.633	126.50	159.92	254.62
$p_2i_2d_2$	0.630	131.29	163.87	271.24
$p_2i_3d_2$	0.633	132.37	164.65	277.31
SEm (±)	0.004	0.60	0.32	3.35
CD (0.05)	NS	1.772	0.963	9.840

4.7 PLANT ANALYSIS

4.7.1 Nitrogen Uptake

Tables 17a, 17b and 17c represent the influence of *P. indica*, irrigation interval and depth of irrigation on nitrogen uptake.

P. indica, irrigation interval and depth of irrigation could significantly influence the nitrogen uptake. *P. indica* colonized plants evinced significantly higher nitrogen uptake (53.91 kg ha^{-1}). Among the irrigation intervals, the highest nitrogen uptake was computed in plants irrigated at 30 mm CPE (55.05 kg ha^{-1}). Between depth of irrigation, a higher nitrogen uptake was observed in plants irrigated at 3 cm depth (57.08 kg ha^{-1}).

Among the first order interactions, P x I, P x D and I x D exerted significant variation in nitrogen uptake. Combination of *P. indica* colonized plants irrigated at 30 mm CPE had significantly superior nitrogen uptake (58.06 kg ha^{-1}). The lowest nitrogen uptake (46.42 kg ha^{-1}) was noticed in non-colonized plants irrigated at 40 mm CPE. Significantly superior nitrogen uptake (59.97 kg ha^{-1}) was recorded in *P. indica* colonized plants irrigated to a depth of 3 cm, followed by p_2d_2 (non-colonized plants irrigated to a depth of 3 cm). In the case of I x D, plants irrigated at 30 mm CPE to a depth of 3 cm had the highest nitrogen uptake (60.50 kg ha^{-1}).

Among the second order interactions, P x I x D could significantly influence the nitrogen uptake. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm observed significantly superior nitrogen uptake (64.72 kg ha^{-1}). The lowest nitrogen uptake was noticed in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm (40.68 kg ha^{-1}). There was 14.99 per cent increase in nitrogen uptake in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants at same irrigation interval and depth.

Table 17a. Effect of colonizing with *P. indica*, irrigation interval and depth of irrigation on N, P and K uptake

Treatments	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Colonizing with *P. indica* (P)			
p_1 (*P. indica* colonized rice)	53.91	10.56	115.99
p_2 (non-colonized rice)	49.22	8.84	94.93
SEm (±)	0.13	0.08	0.41
CD (0.05)	0.382	0.233	1.195
Irrigation interval (I)			
i_1 (30 mm CPE)	55.05	10.98	121.01
i_2 (35 mm CPE)	51.22	9.45	102.62
i_3 (40 mm CPE)	48.43	8.67	92.75
SEm (±)	0.16	0.10	0.50
CD (0.05)	0.468	0.286	1.463
Depth of irrigation (D)			
d_1 (1.5 cm)	46.05	8.24	82.32
d_2 (3 cm)	57.08	11.16	128.60
SEm (±)	0.13	0.08	0.41
CD (0.05)	0.382	0.233	1.195

Table 17b. Interaction effects of colonizing with *P. indica*, irrigation interval and depth of irrigation on N, P and K uptake

Interactions	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
P×I interaction			
p_1i_1	58.06	12.13	134.71
p_1i_2	53.23	10.22	110.31
p_1i_3	50.44	9.33	102.95
p_2i_1	52.03	9.84	107.30
p_2i_2	49.22	8.67	94.94
p_2i_3	46.42	8.01	82.55
SEm (±)	0.23	0.14	0.70
CD (0.05)	0.662	0.404	2.070
P×D interaction			
p_1d_1	47.85	8.76	91.04
p_1d_2	59.97	12.36	140.95
p_2d_1	44.26	7.72	73.61
p_2d_2	54.19	9.96	116.25
SEm (±)	0.18	0.11	0.58
CD (0.05)	0.540	0.330	1.690
I×D interaction			
i_1d_1	49.59	9.07	93.95
i_2d_1	45.79	8.06	81.50
i_3d_1	42.78	7.59	71.53
i_1d_2	60.50	12.89	148.07
i_2d_2	56.66	10.84	123.75
i_3d_2	54.08	9.75	113.98
SEm (±)	0.23	0.14	0.70
CD (0.05)	0.662	0.404	2.070

Table 17c. Effects of P×I×D interaction on N, P and K uptake

Treatment combinations	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
$p_1i_1d_1$	51.40	9.66	103.24
$p_1i_2d_1$	47.26	8.54	87.99
$p_1i_3d_1$	44.88	8.09	81.89
$p_1i_1d_2$	64.72	14.60	166.19
$p_1i_2d_2$	59.20	11.91	132.64
$p_1i_3d_2$	56.01	10.57	124.02
$p_2i_1d_1$	47.79	8.49	84.65
$p_2i_2d_1$	44.31	7.57	75.01
$p_2i_3d_1$	40.68	7.09	61.17
$p_2i_1d_2$	56.28	11.19	129.95
$p_2i_2d_2$	54.12	9.77	114.87
$p_2i_3d_2$	52.16	8.92	103.94
SEm (±)	0.32	0.19	0.10
CD (0.05)	0.936	0.571	2.927

4.7.2 Phosphorus Uptake

Tables 17a, 17b and 17c represent the influence of *P. indica*, irrigation interval and depth of irrigation on phosphorus uptake.

The data revealed the significant influence of main effects on phosphorus uptake. Phosphorous uptake was significantly higher in *P. indica* colonized plants. Irrigation at 30 mm CPE had the highest phosphorus uptake (10.98 kg ha^{-1}), followed by 35 mm CPE (9.45 kg ha^{-1}) and 40 mm CPE (8.67 kg ha^{-1}). Irrigation given at 3 cm showed significantly the highest phosphorus uptake (11.16 kg ha^{-1}).

The effect of P x I, P x D and I x D were significant. In the case of P x I interaction, p_1i_1 evinced significantly superior P uptake (12.13 kg ha^{-1}). The lowest phosphorus uptake (8.01 kg ha^{-1}) was noticed in non-colonized plants irrigated at 40 mm CPE. In P x D interaction, significantly superior phosphorus uptake was recorded in *P. indica* colonized plants irrigated to a depth of 3 cm (12.36 kg ha^{-1}).

Among the first order interactions, I x D could also significantly influence the phosphorus uptake. High phosphorus uptake was noticed in irrigation at 30 mm CPE to a depth of 3 cm (12.89 kg ha^{-1}). The lowest P uptake was noticed in irrigation at 40 mm CPE to a depth of 1.5 cm (7.59 kg ha^{-1}).

Among the second order interactions, P x I x D significantly influenced P uptake. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm exhibited significantly superior P uptake (14.60 kg ha^{-1}). The lowest phosphorus uptake was noticed in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm (7.09 kg ha^{-1}). There was 30.47 per cent increase in P uptake in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants at same irrigation interval and depth.

4.7.3 Potassium Uptake

Tables 17a, 17b and 17c represent the influence of *P. indica*, irrigation interval and depth of irrigation on potassium uptake.

P. indica, irrigation interval and depth of irrigation exerted significant variation on potassium uptake. *P. indica* colonized plants exported significantly higher K (115.99

kg ha^{-1}), compared to non-colonized plants (94.93 kg ha^{-1}). Among the irrigation intervals, irrigation at 30 mm CPE had the highest K uptake (121.01 kg ha^{-1}). Between the depths of irrigation, a depth of 3 cm resulted in high potassium uptake (128.60 kg ha^{-1}).

The effects of P x I, P x D and I x D had significant influence on potassium uptake. *P. indica* colonized plants irrigated at 30 mm CPE showed significantly higher potassium uptake (134.71 kg ha^{-1}). A lower potassium uptake was noticed in non-colonized plants irrigated at 40 mm CPE (82.55 kg ha^{-1}). Significantly superior potassium uptake was recorded in *P. indica* colonized plants irrigated to a depth of 3 cm (140.95 kg ha^{-1}). Among I x D, high potassium uptake was noticed with irrigation at 30 mm CPE to a depth of 3 cm (148.07 kg ha^{-1}). The lowest potassium uptake was registered in plants irrigated at 40 mm CPE to a depth of 1.5 cm (71.53 kg ha^{-1}).

Among the second order interactions, P x I x D exerted significant influence on potassium uptake. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm exhibited significantly higher potassium uptake (166.19 kg ha^{-1}). The lowest potassium uptake registered in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm (61.17 kg ha^{-1}). There was 27.88 per cent increase in potassium uptake in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants at same irrigation interval and depth.

4.8 ECONOMICS

4.8.1 Gross Income

Results on the effect of colonizing with *P. indica*, irrigation interval, depth of irrigation and their interaction on gross income are presented in a Table 18.

P. indica colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) recorded the highest gross income of ₹ 88951 ha^{-1}, followed by non-colonized plants irrigated at 30 mm CPE to a depth of 3 cm (₹ 76013 ha^{-1}). The lowest gross income (₹ 39431 ha^{-1}) was obtained from non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm.

Table 18. Effects of P×I×D interaction on gross income, net income and B: C ratio

Treatments	Gross income (₹ ha^{-1})	Net income (₹ ha^{-1})	B: C ratio
$p_1i_1d_1$	67984	9384	1.16
$p_1i_2d_1$	58758	3358	1.06
$p_1 i_3d_1$	53061	61	1.00
$p_1 i_1d_2$	88951	30351	1.51
$p_1 i_2d_2$	72836	17436	1.31
$p_1 i_3d_2$	70075	17075	1.32
$p_2 i_1d_1$	55220	-2379	0.95
$p_2 i_2d_1$	46950	-7449	0.86
$p_2 i_3d_1$	39431	-12568	0.75
$p_2 i_1d_2$	76013	18413	1.31
$p_2 i_2d_2$	69724	15324	1.28
$p_2 i_3d_2$	66309	14309	1.27

4.8.2 Net Income

Table 18 represented the influence of *P. indica*, irrigation interval and depth of irrigation on net income.

P. indica colonized plants irrigated at 30 mm CPE to a depth of 3 cm resulted in the highest net income (₹ 30351 ha^{-1}), followed by $p_2i_1d_2$ (₹ 18413 ha^{-1}). Colonized plants irrigated to severe stress (irrigated at 40 mm CPE to a depth of 1.5 cm) realized a higher net income of ₹ 61 ha^{-1}, while non-colonized plants irrigated to same irrigation frequency recorded a loss of ₹ 12568 ha^{-1}.

4.8.3 B: C ratio

Influence of colonization with *P. indica*, irrigation interval, depth of irrigation and its interaction on B: C ratio are presented in Table 18.

The data revealed that the highest B: C ratio (1.51) was recorded in colonized plants irrigated at 30 mm CPE to a depth of 3 cm followed by colonized plants irrigated at 40 mm CPE to a depth of 3 cm (1.32). The lowest B: C ratio of 0.75 was recorded in non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm.

DISCUSSION

5. DISCUSSION

Water stress is a critical constraint in rice production, especially during summer season. Root endophytes stands as one of the promising fields for enhancing drought stress tolerance in rice. This calls for field evaluation of root endophyte in rice to produce high yields in water-limited conditions. The present study was conducted to evaluate the performance of *Piriformospora indica* colonized rice to mitigate water stress. The different levels of water stress imposed in the study were, ideal or non-stress or normal [30 mm CPE (cumulative pan evaporation) to a depth 3 cm], mild stress (35 mm CPE to a depth 3 cm), moderate stress (40 mm CPE to a depth 3 cm and 30 mm CPE to a depth 1.5 cm) and severe stress (35 mm and 40 mm CPE to a depth 1.5 cm).

The results of the experiment has been discussed in this chapter.

5.1 GROWTH AND GROWTH ATTRIBUTES

Growth and growth attributes of rice plants were found to be significantly influenced by *P. indica* colonization under field conditions. Plant height, tiller number m^{-2}, leaf area index and dry matter production enhanced with *P. indica* colonization even under water stress situation.

In general, plant height showed a descending trend with enhancing drought stress. Of the different levels of moisture stress, *P. indica* colonized plants irrigated at 35 mm CPE to a depth of 3 cm resulted in taller plants (105.76 cm). However, *P. indica* colonized plants both under ideal non stressed condition (irrigation interval at 30 mm CPE to a depth 3 cm) and severe stress condition (irrigation interval at 40 mm CPE to a depth 1.5 cm) resulted in taller plants than non-colonized/ control plants at the same degree of stress (Fig. 4). This indicated that the detrimental effect of moisture stress on plant height was counteracted by *P. indica* colonization. Rice plant requires higher amount of water (1200 mm) for its potential growth and development. Being an endophyte, presence of *P. indica* could have benefitted the plant through enhanced availability and maintenance of water within the system and in turn nutrients for the efficient growth of plants. Oelmuller *et al.* (2009) stated that *P. indica* colonization improved water uptake that resulted in enhanced volume and turgor of plant cell, leading to cell elongation and plant height. Production of phytohormones like auxins by *P. indica* had also been reported which could lead to acidification and softening of cell wall responsible for cell elongation. These findings were in agreement with the reports of Hussain *et al.* (2018) in rice. It was observed that colonization of *P. indica* promoted the production of ethylene, which is responsible for plant growth promotion (Barazani *et al.*, 2005). The lowest plant height (71.63 cm) was registered in control plants under severe water stress (irrigated at 40 mm CPE to a depth 1.5 cm). This could be the result of lack of water at the critical stages. Water stress alone resulted in reduced plant height due to blocking of translocation of assimilates, water and nutrients through xylem and phloem vessels (Nagarajan and Nagarajan, 2010).

Production of tillers was significantly affected with the colonization and water stress condition. *P. indica* colonized plants registered superior tiller production with an enhancement by 11.65, 6.09 and 6.4 per cent over non colonized control plants under non-stress conditions (irrigated at 30 mm CPE to a depth of 3 cm, IW/CPE is 1.0) at 30, 45 and 60 DAT. At the same level of soil moisture, *P. indica* colonized plants could produce a greater number of tillers per m^2 which could be attributed to the endophyte mediated enhanced absorption of nutrients and moisture. Availability of sufficient water and air in the crop root zone implies adequate acquisition of water and nutrients (Duvvada *et al.*, 2020). In addition to the ideal conditions for tiller production, *P. indica* colonization enhanced nutrient absorption in a better way than control plants and resulted in superior tiller production (Fig. 5). Higher root volume recorded in *P. indica* colonized plants indicated the superiority of tiller production in colonized plants for more absorption of water and nutrients from soil. Colonized plants increased tiller production by 33.03, 32.39 and 46.15 per cent over control plants at severe stressed conditions (irrigated at 40 mm CPE to a depth of 1.5 cm, IW/CPE is 0.37) at 30, 45 and 60 DAT. Lack of sufficient water to crop creates moisture deficit and cell flaccidity which eventually reduces the cell mitosis. Water stress specifically at tillering stage might have resulted in lower accumulation of assimilates, photosynthates, water and nutrient uptake and hence effected the tiller production. The findings were on agreement with the result of Hossain *et al.* (2020).

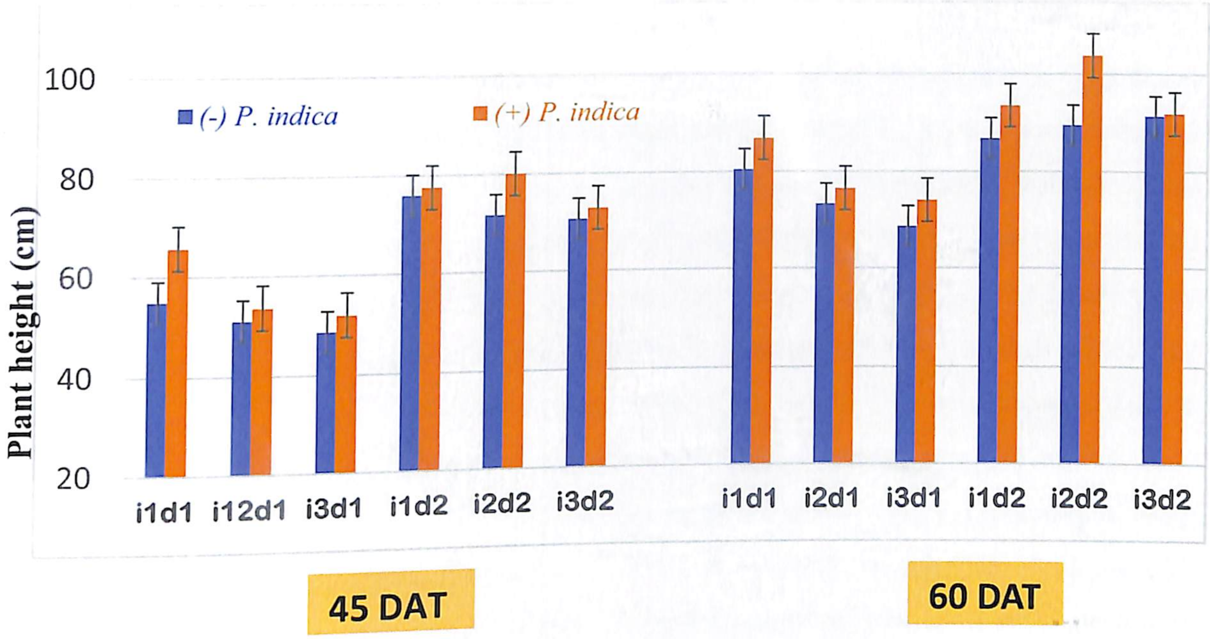

Fig. 4 Effect of *P. indica* colonization on plant height at different irrigation interval and depth at 45 and 60 DAT

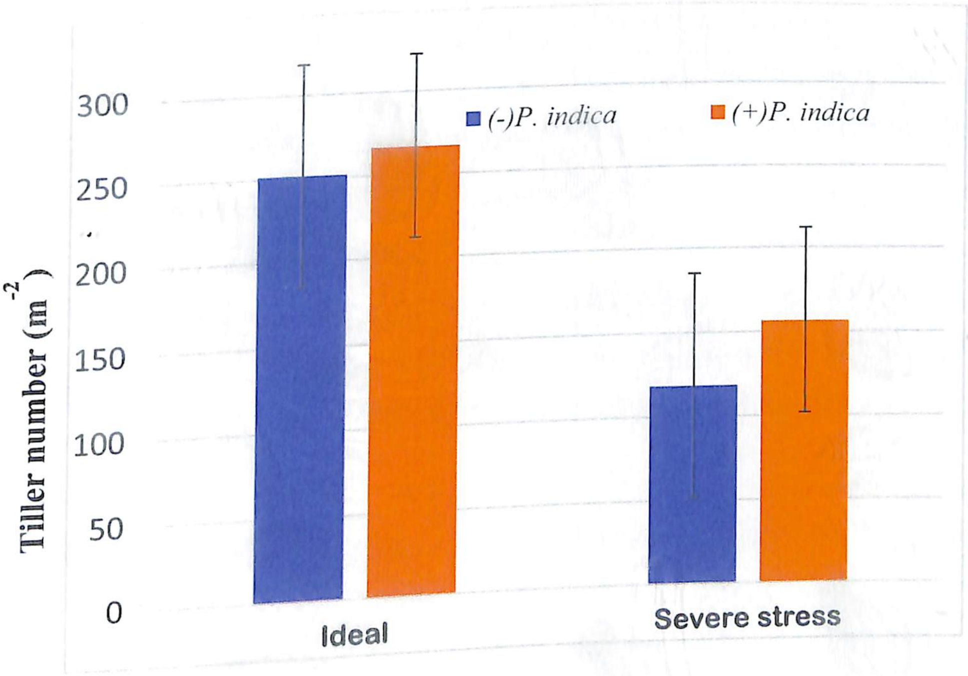

Fig. 5 Effect of *P. indica* colonization on tiller number m^{-2} at different irrigation interval and depth at 60 DAT

P. indica colonization significantly influenced the leaf area index (LAI) at stress and non-stress situation. Colonized plants recorded superior LAI with plants irrigated at 30 mm CPE to a depth of 3cm recording the highest leaf area index upto 60 DAT. Under non-stress situation, maintenance of higher water status under colonization might have improved LAI. With increasing in drought stress, LAI was found to be decreased at all the stages of observation. These results were in agreement with Praba *et al.* (2009). *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm enhanced leaf area index over non-colonized/ control plants irrigated at the same frequency at 30, 45 and 60 DAT. At the same irrigation interval and depth, non-colonized plants ($p_2i_1d_2$) produced LAI of 4.1 at 60 DAT, which was 10.73 per cent lower than colonized plants However, *P. indica* colonized plants which experienced severe stress (irrigated at 40 mm CPE to a depth of 1.5 cm) showed an increment of 21.34, 10.13 and 9.05 per cent in LAI over non-colonized plants at 30, 45 and 60 DAT. Researchers observed that inadequate leaf water potential reduced the leaf expansion ratio to half the level. According to Cutler *et al.* (1980) growth of leaf is totally dependent on the leaf water potential, which will be limited under a situation of water stress. In the current study, colonized plants maintained superior relative leaf water content even under water stress which helped to maintain water potential in leaves. This coupled with higher chlorophyll stability might have resulted in higher LAI. Fungal colonization also enhanced nitrogen uptake which could lead to chlorophyll production thereby higher leaf area index. These results are in conformity with the findings of Hosseini *et al.* (2017) where *P. indica* colonization resulted in higher LAI under stressed situation which was attributed to higher water status in leaf that led to high LAI for drought tolerance in stress situation. At harvest, LAI was found to decline in all treatments might be due to leaf mortality, senescence and translocation of assimilates to grain.

Dry matter production (DMP) of a plant explains the growth and development of plant in response to the net photosynthetic efficiency. Colonization of fungal endophyte enhanced the dry matter production by 30.87 per cent over control plants under stressed situation. There was 15.12 per cent enhancement in DMP in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm over non-colonized plants at the same irrigation frequency. Biomass production positively correlate with the production of assimilates. High water and nutrient uptake mediated by *P. indica* might have enhanced the photosynthetic efficiency and production of assimilates that resulted in a greater number of tillers and panicles leading to higher DMP. Jolly *et al.* (2019) pointed out that dry matter production enhanced with high consumptive use of water, which was possible with greater number of irrigations during crop period. Several studies authenticated the role of *P. indica* in enhancing biomass accumulation as reported by Kumar *et al.* (2009) in maize and Gosal *et al.* (2013) in sugarcane.

5.2 YIELD AND YIELD ATTRIBUTES

Drought is the situation of prolonged lack of water that affects plant growth and survival, ultimately reducing crop yield. In the current study, *P. indica* colonization recorded higher yield attributes *viz.*, productive tillers, filled grains per panicle and lower sterility percentage. Colonized plants irrigated at 30 mm CPE to a depth of 3 cm reported superior yield attributes than control plants irrigated at the same frequency. Plants under severe moisture stress (irrigation at 40 mm CPE to a depth of 1.5 cm) on colonization recorded 73.88 and 18.80 per cent improvement in number of productive tillers and filled grains per panicle over non-inoculated plants experiencing the same stress. Sterility percentage was decreased by 22.74 per cent in colonized stressed plants over control stressed plants (irrigation interval at 40 mm CPE to a depth of 1.5 cm) (Fig.6). Plants under severe stress with wider irrigation interval and lower depth recorded the least yield attributes. Yield attributes declined with the rise in irrigation interval (Parihar, 2004). Panicle initiation (PI) is a critical stage of water requirement deciding the number of productive tillers per unit area. In the present study, maintaining a higher relative leaf water content at PI stage by colonized plants might have resulted in higher productive tillers. Colonization had a positive impact on chlorophyll stability index that might have enhanced the rate of photosynthesis which resulted in higher accumulation of assimilates and its translocation leading to production of higher number of panicles both under non-stressed and stressed conditions. Colonized plants, with improved root parameters like root volume and rooting depth could have enhanced water and nutrient uptake avoiding pollen abortion expressed as lower sterility

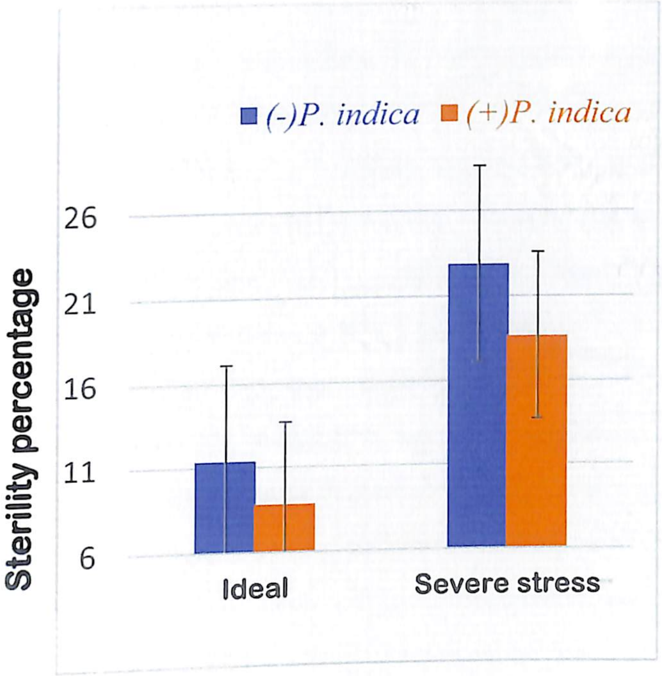

Fig. 6 Effect of *P. indica* colonization on sterility percentage at different irrigation interval and depth at harvest

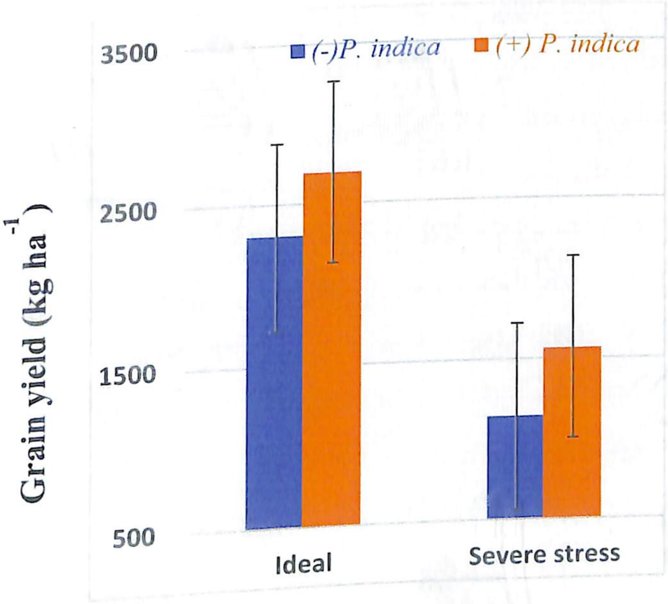

Fig.7 Effect of *P. indica* colonization on grain yield at different irrigation interval and depth at harvest

percentage. Generally, water stress induced lower nutrient and water uptake, inhibits the activity of photosynthesis to minimum, less accumulation and translocation of photosynthates prior to and during flowering period which finally led to pollen abortion and high sterility percentage (Praba *et al.,* 2009). Grain filling is an effect of nutrient translocation and accumulation which are minimum from dry soil (Liu *et al.,* 2005). *P. indica* biotization improved the water and nutrient uptake even from stressed soil by higher absorbing surface area and rooting depth and length (Ahmadvand and Hajinia, 2018). Water stress at vegetative stage can cause an inhibition at reproductive stage as reproductive organs are covered by vegetative tissues (Barnabas *et al.,* 2008). Jolly *et al.* (2019) noticed that smaller number of irrigations during the growing period can lead to lower consumptive use of water leading to lower acquisition of water and nutrients which can result in minimum production of productive tillers and poor grain filling. Ahmadvand and Hajinia (2018) also made observations on this line.

Yield is an integration of productive tillers and filled grains per panicle. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm recorded superior grain yield over non-colonized/ control plants irrigated at the same frequency. Under severe stress condition (40 mm CPE, 1.5 cm depth), colonization reported yield improvement of 37.03 per cent over uncolonized plants (Fig. 7). Straw yield was also found to be enhanced by 12.71 per cent in *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3cm over non-colonized plants at same irrigation frequency. Waller *et al.* (2005) also reported that fungus colonization improved overall yield and yield component in barley. Water stress condition induce lower water status in plant cells, cell membrane stability (CMS) and chlorophyll stability which were not tolerant to drought leading to damage to the cell membrane, chlorophyll apparatus and low photosynthates to plant for yield (Praba *et al.,* 2009). Colonization improved shoot and root morphological features *viz.,* LAI, rooting depth and volume which finally resulted in higher uptake of water and nutrients especially phosphorus which is needed for high seed production (Das, 2015). Taghinasab *et al.* (2018) observed higher yield with enhanced phosphorus uptake in *P. indica* colonized wheat plants. *P. indica* colonization improved physiological factors *viz.,* proline, relative leaf water content (RLWC), CMS and chlorophyll stability enhancing tolerance to drought situation without breakdown of cell membrane and chlorophyll apparatus and helped to maintain the process of photosynthesis for accumulation and translocation of assimilates to grain. All these favourable conditions provided by *P. indica* helped to produce more number of productive tillers and filled grains per panicle and contributed to higher yield. Higher nutrient uptake and water use efficiency (WUE) registered in colonized plants indicated the supremacy of *P. indica* to mitigate drought stress without any economic yield loss. This was confirmed with the investigations of Waller *et al.* (2005), Fard *et al.* (2017) and Ahmadvand and Hajinia (2018).

5.3 ROOT OBSERVATIONS

Roots are the foremost plant organ devoted to the uptake of water, and are the primary site where a lack of water is perceived. Results of root parameters indicated that *P. indica* colonization enhanced rooting depth, root volume, average root length, root dry weight and root shoot ratio in both ideal and stress conditions.

P. indica colonized plants irrigated at 35 mm and 40 mm CPE to a depth of 3 cm recorded higher rooting depth. Colonized rice plants irrigated at 35 mm CPE to a depth of 3 cm recorded significantly superior rooting depth which was 19.01 per cent higher than non-colonized plants at the same irrigation schedule at 30 DAT. Colonized rice plants showed 15.53, 26.13 and 21.93 per cent longer rooting depth over non-colonized rice plants at 40 mm CPE to a depth of 1.5 cm at 30, 60 DAT and harvest respectively. An enhancement in rooting depth by 10.51 per cent was observed in colonized plants over non-colonized plants under mild stress. However, under severe stress the enhancement in rooting depth was to the tune of 24.43 per cent in colonized plants (Fig. 9). The study indicated the more beneficial effect of *P. indica* under severe stress than mild stress condition. Hosseini *et al.* (2017) reported that *P. indica* enhanced the production of plant growth regulators like auxins and ABA in roots leading to improved rooting depth and length. Non-colonized plants under mild stress also recorded higher rooting depth which would be for exploration of moisture from deeper layers. Zhang *et al.* (2020) made a similar observation where plants under medium stress recorded higher rooting depth compared to normal and severe stress condition of cell membrane and chlorophyll apparatus and helped to maintain the process of photosynthesis for accumulation and translocation of assimilates to grain. All these favourable conditions provided by *P. indica* helped to produce more number of productive tillers and filled grains per panicle and contributed to higher yield. Higher nutrient uptake and water use efficiency (WUE) registered in colonized plants indicated the supremacy of *P. indica* to mitigate drought stress without any economic yield loss. This was confirmed with the investigations of Waller *et al.* (2005), Fard *et al.* (2017) and Ahmadvand and Hajinia (2018).

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Plate 6. Effect of *P. indica* on rooting depth at different levels of water stress

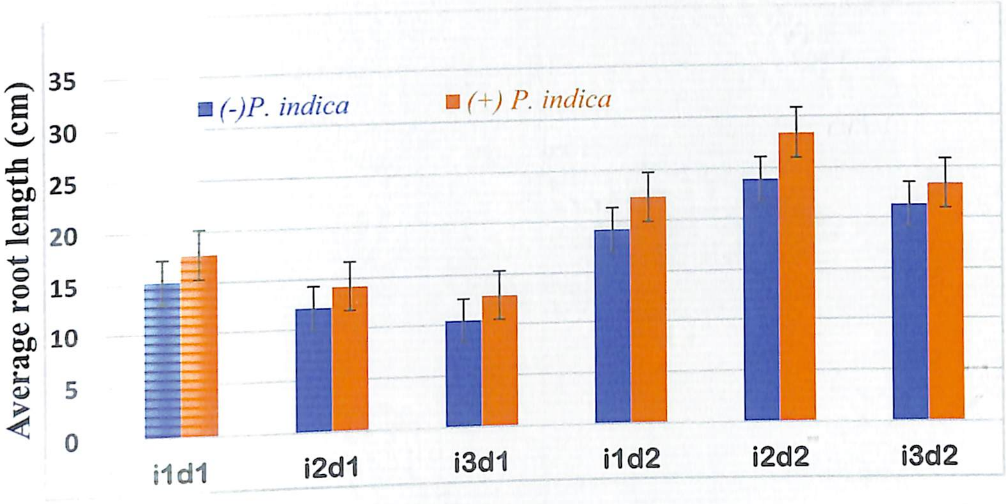

Fig. 8 Effect of *P. indica* colonization on average root length at different irrigation interval and depth at 45 DAT

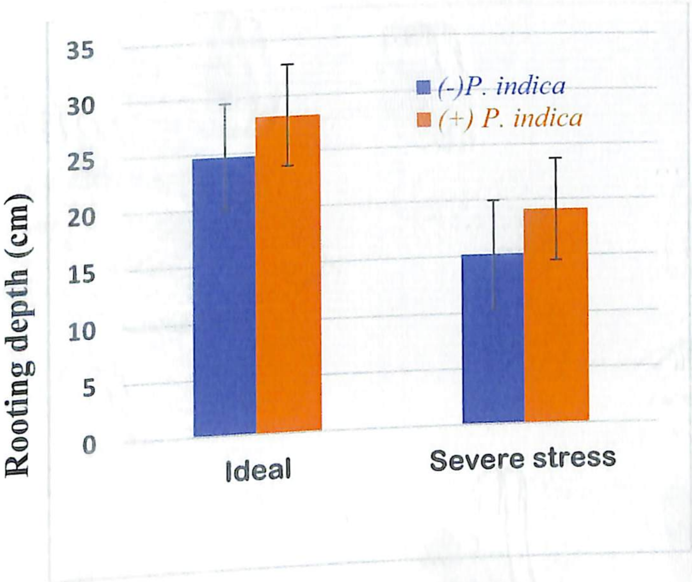

Fig. 9 Effect of *P. indica* colonization on rooting depth at different irrigation interval and depth at 60 DAT

Plate 5. Effect of *P. indica* on root volume at varied levels of water stress

which was attributed to production of ABA and penetration of roots to deeper layers in search of water. Both colonized and control plants under severe stress recorded the lowest rooting depth in contrast to ideal conditions. It might be due to lower root response and higher sensitivity of rice compared to other cereal crops (Kondo *et al.*, 2000) and another possible reason was dried soil have high mechanical resistance for root penetration into the deeper layers to extract water and nutrients (Jolly *et al.*, 2019).

Generally, tolerance of crop to water stress relies on the extent of root volume it has developed. Root volume is an important trait deciding the extent of water and nutrient absorption. Water stress reduced root volume, root dry weight and average root length significantly due to lack of water in the rhizosphere zone. Colonization enhanced root volume by 21.21 and 44.12 per cent in ideal and severe stress conditions at 60 DAT respectively. Colonization enhanced production of more lateral roots contributing to 44.12 per cent higher root volume resulting in higher area of absorption under severe stress.

Root dry weight indicated the extent of development of root system. Root dry weight of colonized plants was increased by 16.93 and 28.93 per cent in ideal and severe stress conditions at 60 DAT. The phosphorus uptake in *P. indica* colonized plants was found to be higher even under severe drought stress. It could be deducted that colonization enhanced the uptake of phosphorus from soil to plant which in turn resulted in the development of a profuse root system in terms of higher rooting depth, dry weight and volume. Campos *et al.* (2018) and Tariq *et al.* (2017) opined that high phosphorus availability enhanced root growth and consequently ability of plant for drought tolerance. Higher root growth under severe water stress in colonized plants facilitated improved water and nutrient uptake from deeper layers of soil compared to control plants and acted as an adaptive and tolerance mechanism to alleviate drought stress and better plant performance under stress condition. Similar results were observed by Hosseini *et al.*, 2017, Hosseini *et al.*, 2018 and Swetha and Padmavathi, 2019.

5.4 PHYSIOLOGICAL PARAMETERS

The physiological and biochemical basis of tolerance to moisture stress could be understood in terms of proline content, RLWC, CMS and chlorophyll stability index (CSI). Enhancing drought tolerance by manipulating the biochemical response through *P. indica* colonization was observed with respect to the physiological parameters *viz.*, proline content, RLWC, CMS and CSI. Irrigation at 30 mm CPE and depth of irrigation to 3 cm recorded the highest RLWC, CMS and CSI.

P. indica colonization displayed an osmoprotectant signature with improved proline for enhancing plant tolerance to drought stress. Colonized plants under severe stress recorded the highest proline content over non- colonized experiencing the same level of stress. Proline content was increased by 18.09 and 21.37 per cent at PI and flowering stages in colonized plants at severe stress over non-colonized plants (Fig. 10). An inverse relation between water content and proline accumulation was observed by Dien *et al.* (2019). Proline is an osmoprotectant having major role in the enzyme safeguarding and an important source of cellular carbon and nitrogen. Proline production was favourably enhanced to reduce drought stress by inducing osmotic adjustment of plant cells. Enhancement of proline content in colonized plants might be due to the upregulation of mi RNA with biotization as noticed by Fard *et al.* (2017). It was evident that co-cultivation of *P. indica* enhanced reactive oxygen species (ROS) scavenging/ signaling which reduced ROS thereby reducing the oxidative damage to cells directed to drought tolerance (Nath *et al.*, 2016).

Relative leaf water content is a prime indicator of water status in plants reflecting the adaptability of plants to stress conditions. This parameter is used for the determination of drought tolerance indicating the level of protoplast hydration for extended periods (Sikuku *et al.*, 2012). Colonized plants irrigated at ideal conditions recorded superior RLWC of 87.93 and 85.13 at PI and flowering (Fig. 11). *P. indica* colonized plants under severe stress maintained higher RLWC with an enhancement of 8.6 and 8.26 per cent over stressed control plants at PI and flowering stage. Higher root volume in colonized plants provided greater absorption area for water uptake and

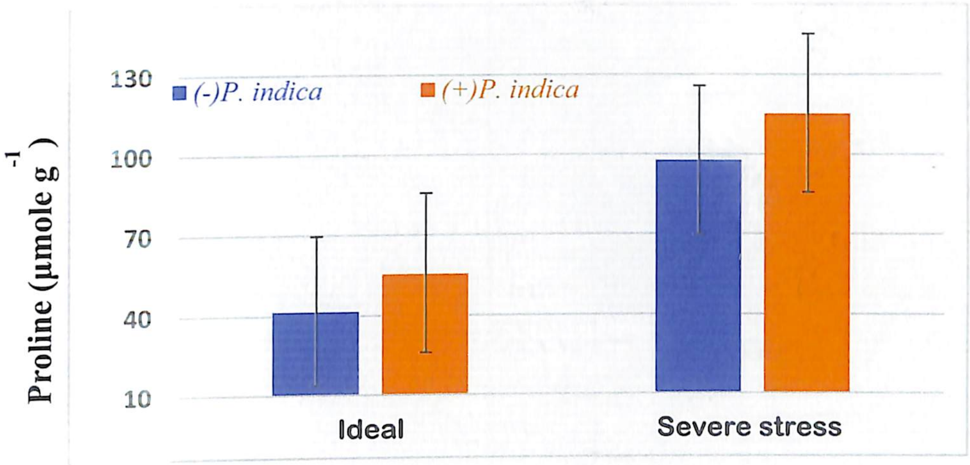

Fig. 10 Effect of *P. indica* colonization on proline content at different irrigation interval and depth at PI stage

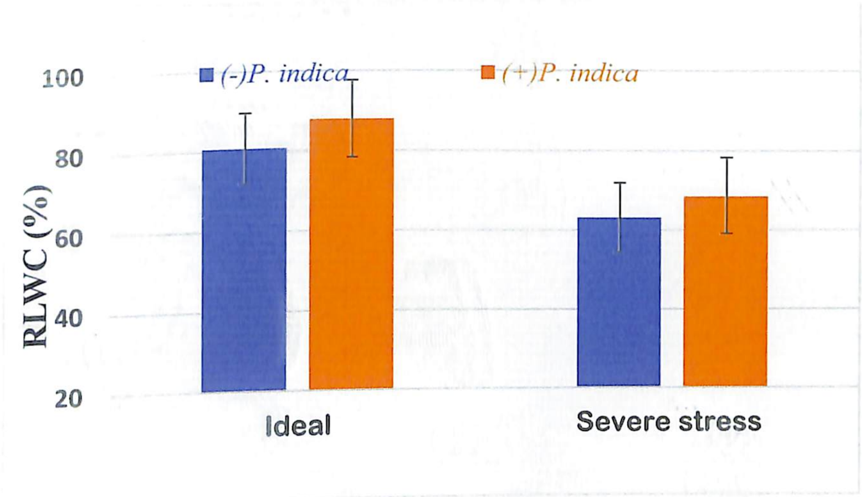

Fig. 11 Effect of *P. indica* colonization on RLWC at different irrigation interval and depth at PI stage

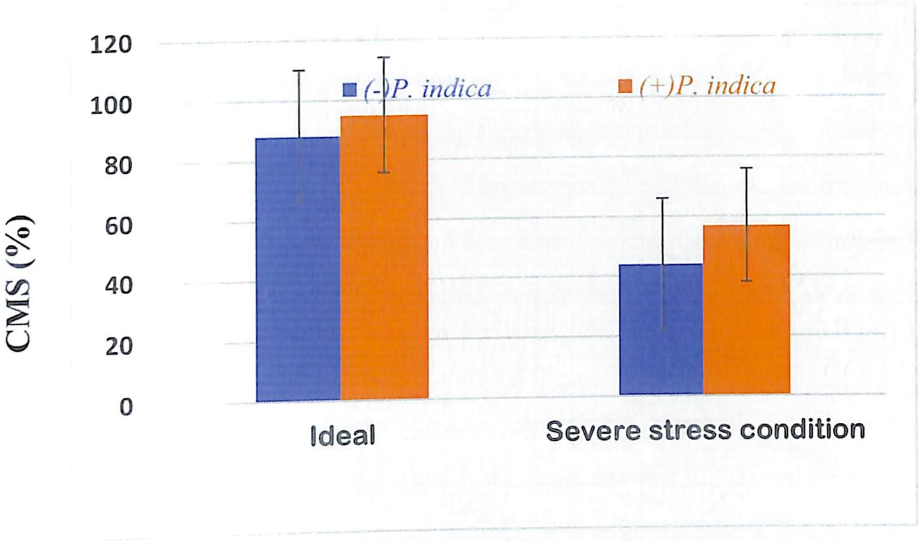

Fig.12 Effect of *P. indica* colonization on cell membrane stability index at different irrigation interval and depth at PI stage

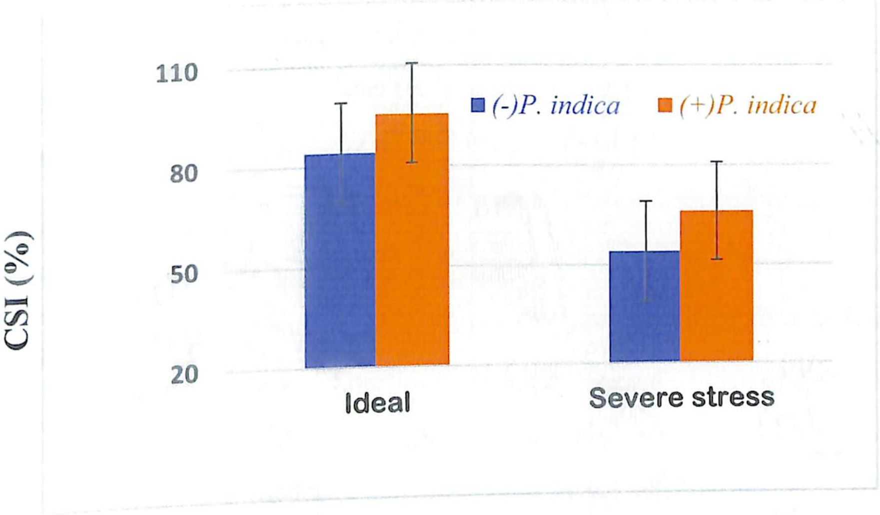

Fig. 13 Effect of *P. indica* colonization on chlorophyll stability index at different irrigation interval and depth at PI stage

maintained plant water status which in turn might have helped to keep higher RLWC even under stress situation alleviating the drought effect on plant. A similar observation was made by Hosseini *et al.* (2017). Non-colonized plants under severe stress recorded the lowest RLWC (63.23 and 60.13 at PI and flowering) due to lower water status in leaves. Jahan *et al.* (2013) attributed lower RLWC to the increase in cell osmotic potential.

Cell membrane stability defines the resistance of cell membrane against damage that restricts electrolyte leakage due to drought stress. Colonized plants irrigated to ideal conditions registered higher CMS (95 and 85) at PI and flowering. It was possible due to presence of fungus which facilitated adequate water uptake and higher acquisition of essential nutrients. Colonized stressed plants (irrigated at 40 mm CPE to a depth of 1.5 cm) recorded superior CMS (56.83 and 47.50) at PI and flowering (Fig. 12). It was 29.45 and 8.2 per cent higher over non-colonized stressed plants. At the same irrigation interval and depth, non-colonized plants produced CMS of 88.10 and 78.76 at PI and flowering respectively which was 7.83 and 7.92 per cent lower than CMS registered in colonized plants at PI and flowering respectively. High CMS recorded in the present study could be correlated with the higher potassium uptake by the plant in the presence of fungus leading to maintenance of cell turgor. Premachandra *et al.* (1991) observed that potassium nutrition improved cell thickness leading to enhanced cell membrane stability during drought stress.

One of the major requisites for drought tolerance is CSI which specifies the stability of chlorophyll apparatus without damage to stress. *P. indica* colonized stressed plants recorded high stability of chlorophyll over non-colonized severe stressed plants and indicated that colonized plants could tolerate drought stress. *P. indica* colonized plants under severe stress recorded 22.29 and 13.66 per cent higher CSI over non-colonized plants at PI and flowering (Fig. 13). It would be due to the fact that *P. indica* produced carotenoids for the protection of chlorophyll apparatus under drought stress which resulted in high chlorophyll stability and ultimately high chlorophyll content under stress enabling drought tolerance (Ahmadvand and Hajinia, 2018). At the same interval and depth, colonized plants recorded CSI of 66.20 and 49.90 at PI and flowering which was 22.29 and 13.66 percent higher than non-colonized plants under severe stress situation. Non-colonized plants recorded lower stability of chlorophyll apparatus which might be due to the production ROS in higher quantity under stress situation as explained by Hosseini *et al.* (2017). Ghabooli *et al.* (2019) noticed that *P. indica* colonization improved protein production necessary for photosynthesis, antioxidant defense system and energy transport which might be a reason for high drought tolerance in colonized plants.

5.5 WATER USE EFFICIENCY

Water use efficiency is an index measuring the capacity of plants to convert water into economic yield. Improving WUE is a prime concern under water scarce situation especially during summer. All the main factors of the experiment showed significant effect on WUE.

Colonized plants under ideal condition recorded the highest WUE (3.47) than non-colonized plants (2.96) irrigated at the same frequency. Even in severe stress condition, colonized plants recorded higher WUE (2.45) than non-colonized plants (1.85) (Fig. 14). Colonization enhanced WUE by 29.62 per cent under severe stress condition over non-colonization. Colonization with *P. indica* resulted in a saving of 30 mm water or 3 irrigations or 3 lakh liters of water per ha in summer rice. Higher WUE recorded by colonized plants could be attributed to the higher water and nutrient uptake made possible through the extensive root surface which ultimately resulted in high economic yield eventually leading to high WUE. This was supported by the investigations of Ahmadvand and Hajinia (2018) and Jolly *et al.* (2019) where fungus colonization enhanced WUE with a positive correlation of water and nutrient absorption.

5.6 SOIL ANALYSIS

P. indica colonization, irrigation interval and depth of irrigation were found to have significant effect on available NPK status of the soil after the experiment. Colonized plants under ideal condition reported the lowest available nutrient status of nitrogen and potassium over non-colonized plants. *P. indica* colonized plants under

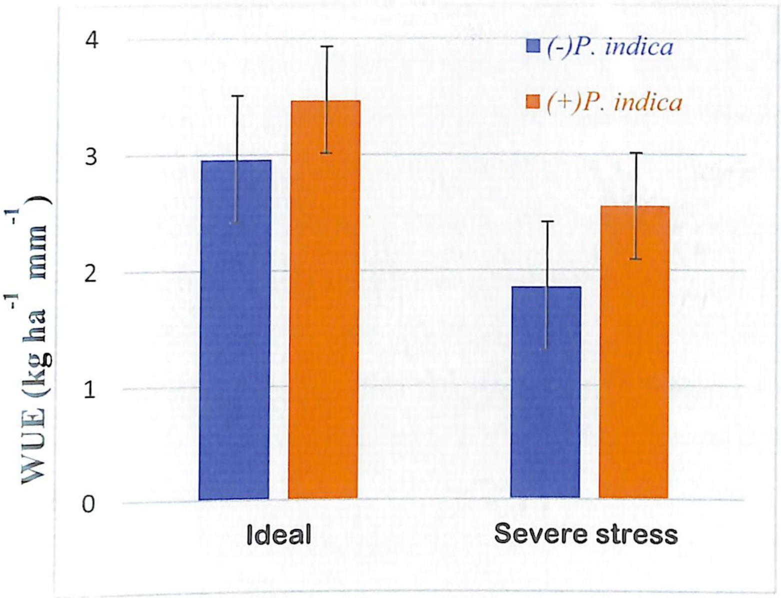

Fig. 14 Effect of *P. indica* colonization on water use efficiency at different irrigation interval and depth of rice

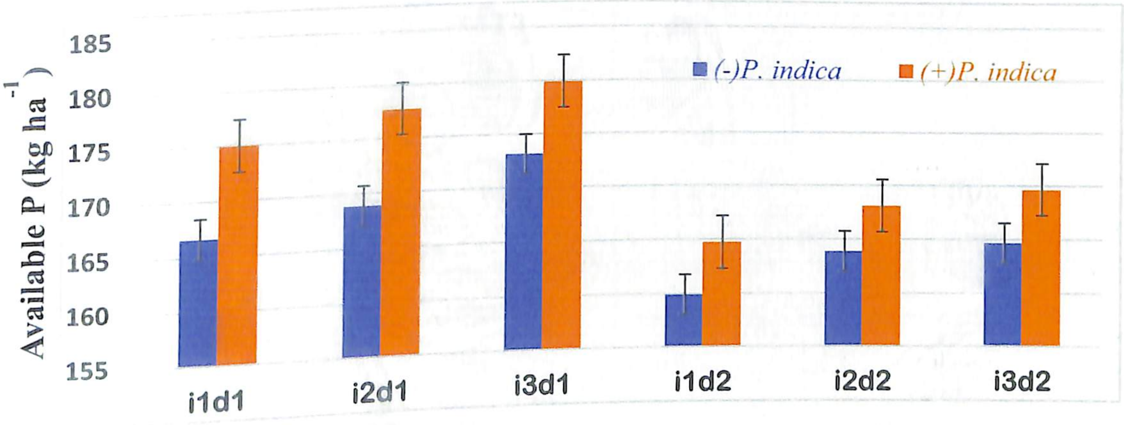

Fig. 15 Effect of *P. indica* colonization on available phosphorus at different irrigation interval and depth of rice

severe stress conditions resulted in low available N and K (138.5 and 308.57 kg ha^{-1}) over non-colonized plants. Higher uptake of nutrients under ideal condition could be due to high dissolution of nutrients in soil water under optimum moisture condition. Colonized plants with higher root surface area would have had the privilege of higher absorption capacity for nutrients leading to lower available nutrient status. Plants under severe stress recorded higher available nitrogen and potassium over plants irrigated to ideal condition which could be due to lower solubility of nutrients under paucity of water. Dissolution of nutrients occurred in the presence of sufficient moisture under ideal condition rather than in stress condition. Higher uptake of nutrients under ideal condition might be the reason for lower available N and K status. Similar observations were made by Aparna (2019) in upland rice.

Colonization had a positive influence on soil available phosphorus status under ideal and stress condition. Soils where *P. indica* colonized plants were grown recorded the highest available phosphorus (164.73 kg ha^{-1}) over soils with non-colonized plants (159.92 kg ha^{-1}) under ideal condition (Fig. 15). Under severe stress condition, high available phosphorus (179.93 kg ha^{-1}) was recorded in soils with colonized plants. It might be possible due to production of acid and alkaline phosphatases by *P. indica* which dissolves the unavailable phosphorus to available form (Das *et al.*, 2014). Nath *et al.* (2016) observed that the production of phosphatases by fungus involved the gene regulation of phosphatase encoding genes *PiPA1* and *PiPA2.*

5.7 PLANT ANALYSIS

All the main factors of the experiment showed significant effect on plant nutrient uptake. Results of the study showed that colonized plants under ideal condition had higher nutrient uptake. The lowest NPK uptake was recorded in non-colonized plants under severe stress. Colonized plants recorded the highest nutrient uptake in both stress and non-stress condition. The lowest uptake of nutrients under water deficit situation could be due to poor dissolution of nutrients and lower root growth for nutrient uptake. The results of the study confirmed that fungal presence improved the nitrogen acquisition by the plants under both severe stress (10.32 %) and non-stress (14.99%) situation (Fig. 16). According to Shermati *et al.* (2008), *P. indica* regulated the enzymes like nitrate reductase responsible for nitrate metabolism which enhanced nitrogen acquisition in the plant.

Phosphorus acquisition by the plant was enhanced with colonization of *P. indica*. The present study revealed that higher phosphorus and potassium uptake could be feasible due to superior root growth under colonization. Release of phosphatases by the fungus was reported earlier by many workers (Singh *et al.*, 2000 ; Das *et al.*, 2014). Soil phosphorus in the fixed form in acidic soils might get solubilized in presence of these released enzymes that could enhance the available phosphorus resulting in higher phosphorus uptake. Yadav *et al.* (2010) validated that colonization regulated the phosphate transfer encoding genes *PiPT* which increased the phosphorus uptake and metabolism leading to higher phosphorus uptake in *P. indica* colonized plants. Nautiyal *et al.* (2010) perceived that colonization upregulated the uptake of nutrients like nitrogen, phosphorus and potassium due to its higher root growth even in stress condition which were in line with our results.

5.8 ECONOMIC ANALYSIS

Economic feasibility of the study has much relevance before actual field implementation. In the present study, colonized plants registered higher gross income, net income and B:C ratio over control plants under the same level of irrigation. Colonized plants under ideal condition recorded the highest gross income of ₹ 88951 ha^{-1}, net income of ₹ 30351 ha^{-1} and B: C ratio of 1.51 over control plants irrigated at the same schedule. Higher net income realized in colonized plants under ideal condition could be due to the favourable effects formed by the fungus that was reflected on growth and yield parameters resulting in higher yield. An additional income of ₹ 11938 ha^{-1} could be generated with *P. indica* colonization under ideal condition. Under ideal conditions, *P. indica* colonization resulted in an enhancement in net income by 64.83 per cent over non-colonized plants. Economic analysis indicated the prospects of utilizing *P. indica* to mitigate water stress in summer rice cultivation.

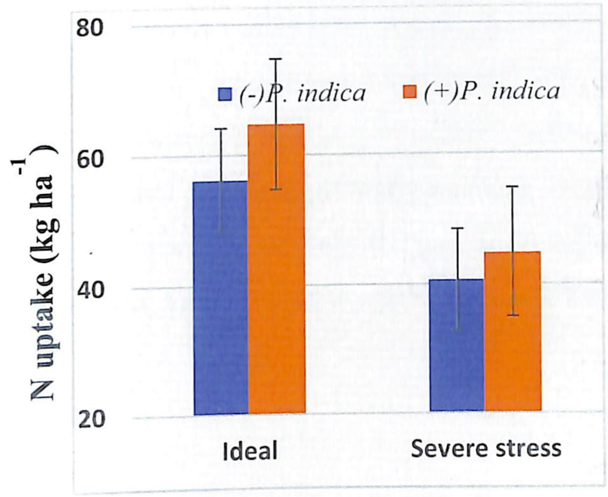

Fig. 16 Effect of *P. indica* colonization on nitrogen uptake at different irrigation interval and depth of rice

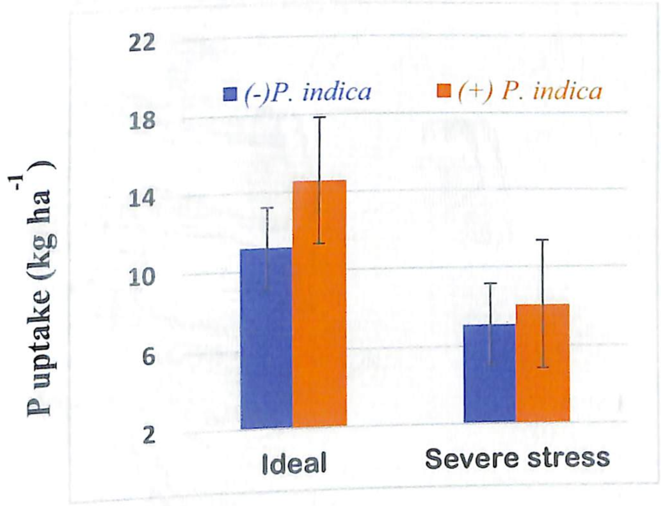

Fig. 17 Effect of *P. indica* colonization on phosphorus uptake at different irrigation interval and depth of rice

Based on the above findings, it could be inferred that rice plants colonized with *P. indica* significantly enhanced growth and yield attributes, root biomass, nutrient uptake and WUE irrespective of interval and depth of irrigation. Rice plants colonized with *P. indica* under severe stress recorded yield and WUE equivalent to noncolonized plants under moderate stress. Colonization with *P. indica* resulted in saving of 30mm water or 3 irrigations or 3 lakh litres of water per ha in summer rice. The study revealed that *P. indica* colonization could help to combat drought stress in summer rice by enhanced root biomass, nutrient uptake and water use efficiency.

SUMMARY

6. SUMMARY

The experiment entitled "Mitigating water stress in summer rice using beneficial root endophytic fungus *Piriformospora indica*" was conducted during summer, 2021 at College of Agriculture, Vellayani.

The experiment was laid out in randomised block design with 2 x 3 x 2 treatment combinations and three replications during summer 2021. The treatments included colonizing with *P. indica* (p_1- *P. indica* colonized rice and p_2- non-colonized rice), three levels of irrigation interval (i_1- 30 mm CPE (cumulative pan evaporation), i_2- 35 mm CPE and i_3- 40mm CPE) and two levels of depth of irrigation (d_1- to a depth of 1.5 cm and d_2- to a depth of 3 cm). The seeds kept for germination in *P. indica* culturing trays for colonisation of the fungus were treated as colonized seedlings and seeds kept in the same media without the fungus were treated as non-colonized seedlings. After 14 days, both the set of seedlings were transplanted to the field as colonized and non-colonized plants under a spacing of 15 cm x 10 cm. Crop was raised as per the KAU package of practices recommendation for short duration rice (KAU, 2016). The data on daily evaporation was used for scheduling the frequency of irrigation and water meter was used to measure the quantity of irrigation water to be diverted to each plot as per treatments.

The results indicated that the *P. indica* colonization, irrigation interval, depth of irrigation and their interaction had significant influence on the growth and growth attributes of rice *viz*., plant height, tiller number m^{-2}, leaf area index and dry matter production harvest.

Significantly taller plants were produced with *P. indica* colonization at 15, 30, 45, 60 DAT and harvest (34.64, 55.56, 67.02, 87.75 and 90.91 cm respectively). Irrigation interval i_1 (30 mm CPE) produced significantly superior plant height of 55.74, 68.57, 86.90 and 90.15 cm at 30, 45, 60 DAT and harvest, respectively followed by the irrigation interval i_2 and i_3. Significantly superior plant height (58.28, 75.85, 93.58 and 96.36 cm) was observed at 3 cm depth (d_2). Irrigation of *P. indica* colonized rice plants at 30 mm CPE resulted in significantly superior plant height of 71.66, 90.16 and 93.08 cm at 45, 60 DAT and harvest respectively. Interaction P x D exerted significant influence on plant height only at 30 DAT. At 60 DAT and harvest, i_2d_2 brought about significantly taller plants of 96.56 and 98.86 cm respectively. *P. indica* colonized plants irrigated at 35 mm CPE to a depth of 3 cm evinced significantly superior plant height of 103.7 and 105.76 cm at 60 DAT and harvest respectively.

Colonized plants produced significantly superior number of tillers m^{-2} (140.38, 208.38, 254.44 and 260.38) at 30, 45, 60 DAT and harvest. Irrigation interval i_1 (30 mm CPE) exhibited significantly higher number of tillers m^{-2} (145.41, 218.41, 261.16 and 267) at 30, 45, 60 DAT and harvest respectively. Plants irrigated to a depth of 3 cm produced significantly greater number of tillers (162.22, 237.88, 277.44 and 282.83) at 30, 45, 60 DAT and harvest. Among P x I interactions, p_1i_1 resulted in significantly superior tiller number (154.16, 226.83, 275 and 281.66) at 30, 45, 60 DAT and harvest respectively. Plants irrigated at 30 mm CPE to a depth of 3 cm (i_1d_2) produced significantly superior number of tillers m^{-2} (181.66, 259.33, 300.66 and 306.16) at 30, 45, 60 DAT and harvest respectively. *P. indica* colonized rice plants irrigated at 30 mm CPE to a depth of 3 cm registered significantly superior number of tillers m^{-2} (191.66, 267, 310 and 316) at 30, 45, 60 DAT and harvest respectively, followed by $p_2i_1d_2$ (171.66, 251.66, 291.33 and 296.33).

Leaf area index (LAI) was significantly superior at all growth stages for colonized plants, the values being 0.9, 1.42, 2.93, 3.82 and 2.19 at different growth stages. Irrigation interval (i_1) produced significantly higher LAI (0.9, 1.39, 2.98 and 3.82) at 15, 30, 45 and 60 DAT. Plants irrigated to a depth of 3 cm (d_2) showed significantly superior LAI. Colonized plants irrigated at 30 mm CPE brought about significantly superior LAI (1.55, 3.15 and 3.99) at 30, 45 and 60 DAT. Colonized plants irrigated to a depth of 3 cm (p_1d_2) exhibited maximum LAI of 0.91, 1.64, 3.27 and 4.37 at 15, 30, 45 and 60 DAT respectively and were significantly superior. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) showed significantly superior LAI of 1.79, 3.54 and 4.54 at 30, 45 and 60 DAT.

P. indica colonization resulted in maximum dry matter production (DMP) of 3630.94 kg ha^{-1} and was significantly superior. Irrigation at 30 mm CPE produced significantly superior DMP of 3789.24 kg ha^{-1}. Irrigation to a depth of 3 cm (d_2) reported significantly higher DMP (3880.19 kg ha^{-1}). The combination of p_1i_1 (colonization with plants irrigated at 30 mm CPE) was significantly superior (4090.89

kg ha^{-1}). Plants irrigated at 30 mm CPE to a depth of 3 cm recorded the highest value (4260.07 kg ha^{-1}). P x I x D also exerted significant variation in DMP with $p_1i_1d_2$ resulting in significantly superior value (4559.26 kg ha^{-1}).

The yield attributes and yield of the crop were significantly affected by *P. indica* colonization, irrigation interval and depth of irrigation. Superior number of productive tillers m^{-2} (222.84), filled grains per panicle (81.11) and the lowest sterility percentage (13.37) were recorded with p_1. Irrigation at 30 mm CPE (i_1) resulted in significantly superior number of productive tillers m^{-2} (210.10), filled grains per panicle (84.58), thousand grain weight (22.94) and the lowest sterility percentage (13.01). Significantly superior number of productive tillers m^{-2} (223.88), filled grains per panicle (89.88) and lower sterility percentage (11.63) were produced at irrigation to a depth of 3 cm. *P. indica* colonized plants irrigated at 30 mm CPE produced significantly superior number of productive tillers (250.20), filled grains per panicle (92.00) and lower sterility percentage (11.71). *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) recorded significantly superior number of productive tillers m^{-2} (256.11) and filled grains per panicle (97.00). Irrigation at 30 mm CPE to a depth of 3 cm (i_1d_2) produced significantly higher number of productive tillers m^{-2} (239.16), filled grains per panicle (100.83) and the lowest sterility percentage (10.09). Treatment combination $p_1i_1d_2$ was found to be significantly superior with 275.00 productive tillers m^{-2}, filled grains per panicle (111.33) and sterility percentage (8.80).

Plants colonized with *P. indica* produced significantly superior grain yield (2056.71 kg ha^{-1}) and straw yield (2393.70 kg ha^{-1}). Grain yield and straw yield were significantly superior for plants irrigated at 30 mm CPE (2165.82 and 2471.47 kg ha^{-1} respectively). Depth of irrigation showed significant effect on grain and straw yield when irrigated to a depth of 3 cm. Maximum grain yield (2366.01 kg ha^{-1}) was recorded in *P. indica* colonized rice irrigated at 30 mm CPE (p_1i_1). *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) produced significantly superior grain yield of 2332.55 kg ha^{-1} and straw yield of 2595.23 kg ha^{-1}. Among the second order interactions, $p_1i_1d_2$ produced significantly superior grain yield (2698.56 kg ha^{-1}) and straw yield (2848.13 kg ha^{-1}).

P. indica colonization, irrigation interval and depth of irrigation had significant effect on root parameters of rice at all stages of observation. *P. indica* colonized plants had significantly superior rooting depth of 8.32, 14.79, 22.11, 25.11 and 26.06 cm at 15, 30, 45, 60 DAT and harvest respectively. Irrigation given at 35 mm CPE produced superior rooting depth of 14.25 and 21.67 cm at 30 and 45 DAT and average root length of 15.9, 19.65, 24.82 and 28 cm at 30, 45, 60 DAT and harvest respectively. Plants irrigated at 3 cm had the highest rooting depth (8.35, 16.35, 25.52, 28.28 and 29.24 cm) at all growth stages. *P. indica* colonized plants irrigated at 30 mm CPE produced the highest rooting depth at 60 DAT and harvest (25.99 and 27.23 cm). *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) produced superior rooting depth of 17.75, 27.03, 29.14 and 29.77 cm at 30, 45, 60 DAT and harvest respectively. Rice plants irrigated at 35 mm CPE to a depth of 3 cm exhibited significantly superior rooting depth *viz.,* 17.85, 27.52, 29.66 and 30.00 cm at 30, 45, 60 DAT and harvest respectively. *P. indica* colonized rice plants irrigated at 35 mm CPE to a depth of 3 cm recorded significantly superior rooting depth *viz.,* 19.4, 29.86 and 30.00 cm and average root length of 23.36, 34.87 and 36.20 cm at 30, 60 DAT and harvest respectively.

Colonized plants irrigated at 30 mm CPE showed significantly superior root volume (13.15, 21.86, 35.42 and 37.16 cm^3) and root dry weight (0.89, 5.39, 9.60, 12.22 and 12.77g) at 30, 45, 60 DAT and harvest. *P. indica* colonized plants irrigated to a depth of 3 cm (p_1d_2) brought about superior root volume (14.23, 23.74, 44.19 and 45.54 cm^3 at 30, 45, 60 DAT and harvest respectively). Significantly superior root dry weight (7.20, 12.03, 16.84 and 17.59 g), root shoot ratio *viz.,* 0.239, 0.213, 0.234, 0.236 at 30, 45, 60 DAT and harvest respectively was reported in i_1d_2. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm recorded significantly superior root volume (18.86, 32.16, 50.57 and 52.56 cm^3) and root dry weight (8.38, 13.77, 18.16 and 19.06 g) at 30, 45, 60 DAT and harvest respectively.

The main effects of all the factors were significant at PI and flowering stages on physiological parameters. Maximum proline (83.11 and 71.83 μ mole g^{-1}), RLWC (77.50 and 74.00 %), CMSI (75.82 and 67.32 %) and CSI (79.20 and 70.01 %) at PI and flowering respectively were recorded in *P. indica* colonized plants. Proline content declined in the order of decreasing CPE, 40 mm >35 mm > 30 mm. Irrigation to lower depth of 1.5 cm had significantly higher proline content (94.72 and 83.38 μ mole g^{-1} at PI and flowering respectively). Significantly superior RLWC (80.35 and 77.97 %), CMSI (85.88 and 76.88 %) and CSI (82.90 and 78.39 %) at PI and flowering respectively were obtained with depth of irrigation 3 cm (d_2). *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm produced significantly superior proline of 115.33 and 106.00 μ mole g^{-1}. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm recorded the maximum RLWC of 87.93 and 85.13 per cent, CMSI of 95.00 and 85.00 per cent and CSI of 95.80 and 88.63 per cent at PI and flowering respectively.

Colonized plants had significantly superior water use efficiency (WUE) of 2.97 kg ha^{-1} mm^{-1}. Plants irrigated at 30 mm CPE exhibited superior WUE (3.05 kg ha^{-1} mm^{-1}). Irrigation at 3 cm depth resulted in maximum WUE (3.04 kg ha^{-1} mm^{-1}). *P. indica* colonized plants irrigated at 30 mm CPE registered superior WUE of 3.28 kg ha^{-1} mm^{-1}. *P. indica* colonized plants irrigated to a depth of 3 cm registered significantly superior WUE (3.19 kg ha^{-1} mm^{-1}). Interaction i_1d_2 exerted significantly superior WUE (3.21 kg ha^{-1} mm^{-1}). P x I x D remained significant with the highest WUE of 3.47 kg ha^{-1} mm^{-1} for $p_1i_1d_2$ (*P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm).

P. indica, irrigation interval and depth of irrigation could significantly influence the available nitrogen, phosphorus and potassium status after experiment. Plots with non-colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm resulted in a higher amount of available nitrogen (150.64 kg ha^{-1}) and available potassium (329.55 kg ha^{-1}). Plots with *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm resulted in significantly superior available phosphorus (179.93 kg ha^{-1}).

P. indica colonized plants showed significantly superior N uptake (53.91kg ha^{-1}), P uptake (10.56 kg ha^{-1}) and K uptake (115.99 kg ha^{-1}). Irrigation at 30 mm CPE reported the highest N uptake (55.05 kg ha^{-1}), P uptake (10.98 kg ha^{-1}) and K uptake (121.01 kg ha^{-1}). Irrigation to a depth of 3 cm showed high N uptake (57.08 kg ha^{-1}), P uptake (11.16 kg ha^{-1}) and K uptake (128.60 kg ha^{-1}). *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm brought about significantly superior N (64.72 kg ha^{-1}), P (14.60 kg ha^{-1}) and K uptake (166.19 kg ha^{-1}).

Colonization with *P. indica*, irrigation interval, depth of irrigation and its interaction significantly influenced the gross income, net income and B: C ratio. *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm ($p_1i_1d_2$) was profitable with highest gross income of ₹ 88951, net income (₹ 30351) and B: C ratio (1.51). Under ideal conditions, *P. indica* colonization resulted in an enhancement in net income by 64.83 per cent over non-colonized plants.

Rice plants colonized with *P. indica* significantly enhanced growth and yield attributes, root biomass , nutrient uptake and WUE, irrespective of interval and depth of irrigation. Rice plants colonized with *P. indica* under severe stress recorded yield and WUE equivalent to noncolonized plants under moderate stress. Colonization with *P. indica* resulted in saving of 30 mm water or 3 irrigations or 3 lakh liters of water per ha in summer rice. *P. indica* colonization could help to combat drought stress in summer rice by enhanced root biomass, nutrient uptake and water use efficiency.

FUTURE LINE OF WORK

- Performance of *P. indica* colonized rice under rainfed condition
- Performance of *P. indica* colonized rice under low light condition
- Evaluating phosphorus use efficiency in *P. indica* colonized rice under zero phosphorus levels

REFERENCES

REFERENCES

Abdelaziz, E.M., Dongjin, K., Ali, S., Fedoroff, V.N., and Al-Babili, S. 2017. The endophytic fungus *Piriformospora indica* enhances *Arabidopsis thaliana* growth and modulates Na+/K+ homeostasis under salt stress conditions. *Plant Sci.* : 1-25.

Abdelaziz, E.M., Abdelsattar, M., Emad A., Abdeldaym, A.E., Atia, M.A.M., Mahmoud, M.W.A., Saad, M.M., and Hirt, H. 2019. *Piriformospora indica* alters Na+/K+ homeostasis, antioxidant enzymes and LeNHX1 expression of greenhouse tomato grown under salt stress. *Sci. Horti.* 256 : 108532.

Abu, S.T. and Malgwi, W.B. 2011. Effect of deficit irrigation regime and interval on chemical properties and paddy rice yield in sudan savanna of Nigeria. *J. Agron.* 10(2): 48-55.

Achatz, B., Kogel, K., Franken, P., and Waller, F. 2015. *Piriformospora indica* mycorrhization increases grain yield by accelerating early development of barley plants. *Plant Signal. Behav.* 5(12): 1685-1687.

Ahmadvand, G. and Hajinia, S. 2018. Effect of endophytic fungus *Piriformospora indica* on yield and some physiological traits of millet (*Panicum miliaceum*) under water stress. *Crop Pasture Sci.: A-L. DOI:* https://doi.org/10.1071/CP17364. [March 8 2021]

Akram, H.M., Ali, A., Sattar, A., Rehman, H.S.U., and Bibi, A. 2013. Impact of water deficit stress on various physiological and agronomic traits of three basmati rice (*Oryza sativa L.*) cultivars. *The J. Animal Plant Sci.* 23 (5): 1415-1423.

Alikhani, M., Khatabi, B., Sepehri, M., Nekouei, K.M., Mardi, M., and Salekdeh, H.G. 2013. A proteomics approach to study the molecular basis of enhanced salt tolerance in barley (*Hordeum vulgare* L.) conferred by the root mutualistic fungus *Piriformospora indica*. *Mol. Biosyst.* : 1-13.

Amini, R., Zafarani-Moattar, P., Shakiba, M.R., and Sarikhani, M.R. 2020. Essential oil yield and composition of moldavian balm (*Dracocephalum moldavica* L.) as affected by inoculation treatments under drought stress condition. *J. Essen. Oil Bearing Plants* 23(4): 728-742. DOI:10.1080/0972060X.2020.1815593. [Jun 6, 2021]

Andrade-Linares, R. D., Iler, M.A., Fakhro, A., Schwarz, D., and Franken, P. 2013. Impact of *Piriformospora indica* on tomato. *Soil Bio.* (33): 107-117.

Anith, K.N., Faseela, K.M., Archana, A.P., and Prathapan, K.D. 2011. Compatibility of *Piriformospora indica* and *Trichoderma harzianum* as dual inoculants in black pepper (*Piper nigrum* L.). *Symbiosis* 55: 11-17.

Anith, K.N., Aswini, S., Varkey, S., Radhakrishnan, N.V., and Nair, D.S. 2018. Root colonization by the endophytic fungus *Piriformospora indica* improves growth, yield and piperine content in black pepper (*Piper nigurm* L.). *Biocatalysis Agric. Biotech.* https://doi.org/10.1016/j.bcab.2018.03.012. [Mar 8, 2021]

Aparna, R.A. 2018. Irrigation scheduling and live mulching in upland rice (*Oryza sativa* L.). *MSc thesis, Kerala Agricultural University, Thrissur, India.*

Bagde, U.S., Prasad, R., and Varma, A. 2010. Interaction of *Piriformospora indica* with medicinal plants and of economic importance. *Afr. J. Biotechnol.* 9: 9214–9226.

Bagde, U.S., Prasad, R., and Varma, A. 2011. Influence of culture filtrate of *Piriformospora indica* on growth and yield of seed oil in *Helianthus annus*. *Symbiosis* 53 :83–88.

Bagheri, A.A., Saadatmand, S., Niknam, V., Nejadsatari, T., and Babaeizad, V. 2013. Effect of endophytic fungus, *Piriformospora indica*, on growth and activity of antioxidant enzymes of rice (*Oryza sativa* L.) under salinity stress. *Int. j. Adv. Bio. Biomed. Res.* 11(1): 1337-1350.

Bajaj, R., Agarwal, A., Rajpal, K., Asthana, S., Prasad, R., Kharkwal, C.A., Kumar, R., Sherameti., oelmuller, R., and Varma, A. 2014. Co-cultivation of curcuma longa with *Piriformospora indica* enhances the yield and active ingredients. *American J. Current Microbio.* 2(1): 6-17.

Baltruschat, H., Fodor, J., Harrach, D.B., Niemczyk, E., Barna, B., Gullner, G., Janeczko, A., Kogel, K., Schafer, P., Schwarczinger, I., Zuccaro, A., and Skoczowski, A. 2008. Salt tolerance of barley induced by the root endophyte *Piriformospora indica* is associated with a strong increase in antioxidants. *New Phytologist* 180: 501- 510.

Barazani, O., Benderoth, M., Groten, K., Kuhlemeier, C., and Baldwin, T.I. 2005. *Piriformospora indica* and *Sebacina vermifera* increase growth performance at the expense of herbivore resistance in nicotiana attenuate. *Oecologia* 146: 234–243. DOI 10.1007/s00442-005-0193-2.[Mar. 18, 2021]

Barnabas, B., Jager, K., and Feher, A. 2008.The effect of drought and heat stress on reproductive processes in cereals. *Plant Cell Env.* 31: 11–38.

Bates, L. S., Waldren, R. P., and Teagre, T. D. 1973. Rapid determination of free proline in water stress studies. *Plant Soil.* 39: 205-08.

Bertolazi, A.A., de Souza, S.B., Ruas, K.F., Campostrini, E., de Rezende, C.E., Cruz, C., Melo, J., Colodete, C.M., Varma, A., and Ramos, A.C. 2019. Inoculation with *Piriformospora indica* is more efficient in wild-type rice than in transgenic rice over-expressing the vacuolar H+-P phase. *Front. Microbiol.* 10:1087.

Blum, A. and Ebercon, A. 1981. Cell membrane stability as a measure of drought and heat tolerance in wheat. *Crop Sci.*21(1): 43-47.

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analysis of soil. *Agron. J.* 54: 464-465.

Bray, R.H. and Kurtz, L.T. 1945. Determination of total, organic and available forms of phosphorus in soils. *Soil sci.* 59 :39-45.

Das, J., Ramesh, K.V., Maithri, U., Mutangana, D., and Suresh, C.K. 2014. Response of aerobic rice to *Piriformospora indica. Indian J. Experi. Bio.* 52: 237-251.

Dasgupta, P., Das, S.B., and Sen, K.S. 2015. Soil water potential and recoverable water stress in drought tolerant and susceptible rice varieties. *Agrl. Water Manag.* 152: 110-118.

Dien, C.D., Mochizuki, T., and Yamakawa, T. 2019. Effect of various drought stresses and subsequent recovery on proline, total soluble sugar and starch metabolisms in rice (*Oryza sativa* L.) varieties. *Plant Prod. Sci.*: 1-15.

Dolatabadi, K.H., Goltapeh, M.E., Jaimand, K., Rohani, N., and Varma, A. 2011. Effects of *Piriformospora indica* and *Sebacina vermifera* on growth and yield of essential oil in fennel (*Foeniculum vulgare*) under greenhouse conditions. *J. Basic Microbio.* 51: 33-39.

Donald, C. M. and Hamblin, J. 1976. Biological yield and harvest index of cereals as agronomic and plant breeding criteria. *Adv. Agron.* 28: 361-405.

Druege, W., Baltruschat, H., and Franken, P. 2007. *Piriformospora indica* promotes adventitious root formation in cuttings. *Sci. Horti.* 112: 422–426.

Duvvada, S.K., Mishra, G.C., Maitra, S., and Adhikary, R. 2020. Effect of irrigation regimes and staggered transplanting on growth and yield of summer rice (*Oryza sativa* L.) in south odisha. *Int. J. Agric. Env. Biotech,* 13(2): 205-211.DOI: 10.30954/0974-1712.02.2020.14. [Feb 21, 2021]

Fard, E.M., Ghabooli, M., Mehri, N., and Bakhshi, B. 2017. Regulation of mir159 and mir396 mediated by *Piriformospora indica* confer drought tolerance in rice. *J. Plant Mol. Breed.* 5(1): 10 – 18. DOI: 10.22058/JPMB.2017.60864.1129.[Mar 13, 2021]

Ghabooli, M., Rostami, M., and Kaboosi, E. 2019. Combination effect of *Piriformospora indica,* chilling and gibberellic acid on seed germination traits of *Kelussia odoratissima* Mozaff. *J. Med. plants by-products* 1: 33-40.

Gill, S.S., Gill, R., Trivedi, D.K., Anjum, N.A., Sharma, K.K., Ansari, M.W., Ansari, A.A., Johri, A.K., Prasad, R., Pereira, E., Varma, A., and Tuteja, N. 2016. *Piriformospora indica*: potential and significance in plant stress tolerance. *Front. Microbiol.* 7:332.

[GOI] Government of India. 2020. *Third Advance Estimates of Principal Crops for 2020-21.* Ministry of Agriculture and Farmers Welfare. Delhi.

Gosal, S.K., Kalia, A., and Varma, A. 2013. *Piriformospora indica*: Perspectives and retrospectives. In: *Piriformospora indica*: Sebacinales and their biotechnological applications. *Soil Biol.* 33:53-77.

Gosal, S.K., Karlupia, A., Gosal, S.S., Chhibba, M., and Varma, A. 2010. Biotization with *Piriformospora indica* and *pseudomonas fluorescens* improves survival rate, nutrient acquisition, field performance and saponin content of micropropagated *Chlorophytum sp. Indian J. Biotech.* 9: 289-297.

Hazman, M. and Brown, K.M. 2018. Progressive drought alters architectural and anatomical traits of rice roots. *Rice* 62(11): 1-16.

Hilbert, M., Voll, L.M., Ding, Y., Hofmann, J., Sharma, M., and Zuccaro, A. 2012. Indole derivative production by the root endophyte *Piriformospora indica* is not required for growth promotion but for biotrophic colonization of barley roots. *New Phytologist* 196: 520–534.

Hiscox, J.D. and Israelstam, G.F.1979. Different methods of chlorophyll extraction. *Can. J. Bot.* 57: 1332.

Hosseini, F., Mosaddeghi, M.R., Dexter, A.R., and Sepehri, M. 2018. Effect of endophytic fungus *Piriformospora indica* and PEG-induced water stress on maximum root growth pressure and elongation rate of maize. Plant soil: 1-14. DOI: https://doi.org/10.1007/s11104-018-03909-7. [Mar 21, 2021]

Hossain, M.Z., Sikder, S., Husna, A., Sultana, S., Akhter, S., Alim, A., and Joardar, J.C. 2020. Influence of water stress on morphology, physiology and yield contributing characterstics of rice. *SAARC J. Agric.* 18(1): 61-71.

Hosseini, F., Mosaddeghi, M.R., and Dexter, A.R. 2017. Effect of the fungus *Piriformospora indica* on physiological characteristics and root morphology of wheat under combined drought and mechanical stresses. *Plant Physio. Biochem.: 1-55.* doi: 10.1016/j.plaphy.2017.06.005.[Mar 19, 2021]

Husaini, M.A., Abdin, Z.M., Khan, S., Xu, W.Y., Aquil, S., and Ansi, M. 2012. Modifying strawberry for better adaptability to adverse impact of climate change. *Current Sci.* 102(12): 1660-1673.

Hussain, T., Anothai, J., Nualsri, C., and Soonsuwon, W. 2018. Application of CSM–CERES–Rice in scheduling irrigation and simulating effect of drought stress on upland rice yield *Indian J. Agric. Res.* 52 (2): 140-145.

Jabasingh, C. and Babu, S.S. 2013. Proline content of *Oryza sativa* L. under water stress. *J. Acad. Industrial Res.* 2(7): 442-445.

Jackson, M.L. 1973. *Soil Chemical Analysis*. (Indian Reprint, 1976). Prentice Hall of India, New Delhi, 498p.

Jahan, M.S., Khanif, Y.M., and Sinniah, U.R. 2013. Effects of low water input on rice yield: Fe and Mn bioavailability in soil. *Pertanika J. Trop. Agric.* 36: 27-34.

Jiang, W., Pan, R., Wu, C., Xu, L., Abdelaziz, E.M., Oelmüller, R., and Zhang, W. 2020. *Piriformospora indica* enhances freezing tolerance and post-thaw recovery in *Arabidopsis* by stimulating the expression of *CBF* genes. *Plant Signaling and Behavior,* 15(4): 1745472.

water stress. *Soil Sci. Plant Nutrition* 46 (3) : 721-732. DOI: 10.1080/00380768.2000.10409137. [Mar 21, 2021]

Kukal, S.S., Hira, G.S., and Sidhu, A.S. 2005. Soil matric potential-based irrigation scheduling to rice (*Oryza sativa*). *Irrig. Sci.* 23: 153–159. DOI 10.1007/s00271-005-0103-8.[Feb 8, 2021]

Kumar, K.A., Reddy, M.D., Reddy, N.V., and Rao, S. 2006. Effect of irrigation scheduling on performance of summer rice (*Oryza sativa* L.). *Oryza* 43(2): 97-100.

Kumar, M., Yadav, V., Tuteja, N., and Johri, K.A. 2009. Antioxidant enzyme activities in maize plants colonized with *Piriformospora indica. Microbio.* 155: 780- 790.

Lakshmipriya, P., Nath, S.V., Veena, S.S., Anith, K.N., Sreekumar, J., and Jeeva, M.L. 2016. *Piriformospora indica,* a cultivable endophyte for growth promotion and disease management in taro (*Colocasia esculenta* (L.). *J. Root Crops* 42(2): 107-114.

Li, Q., Kuo, Y., Lin, K., Huang, W., Deng, C., Yeh, K., and Chen, S. 2020. *Piriformospora indica* colonization increases the growth, development, and herbivory resistance of sweet potato (*Ipomoea batatas* L.). *Plant Cell Rep.* : 1-12.

Lin, H., Xiong, J., Zhou, H., Chen, C., Lin, F., Xu, X., Oelmuller, R., Xu, W., and Yeh, K. 2019. Growth promotion and disease resistance induced in anthurium colonized by the beneficial root endophyte *Piriformospora indica. BMC Plant Bio.* : 19-40.

Liu, F., Jensen, C.R., and Andersen, M.N. 2015. A review of drought adaptation in crop plants: changes in vegetative and reproductive physiology induced by ABA- based chemical signals. *Australian J. Agric. Res.* 56: 1245-1252.

Maheswari, J., Bose, J., Sangeetha, S.P., Saniutha, S., and Priya, R.S. 2008. Irrigation regimes and N levels influence chlorophyll, leaf area index, proline and soluble protein content of aerobic rice (*Oryza sativa* L.). *Int. J. Agri. Res.* 3(4): 307-316.

Majeed, A., Salim, M., Bano, A., Asim, M., and Hadees, M. 2011. Physiology and productivity of rice crop influenced by drought stress induced at different developmental stages. *African J. Biotechnol.* 10 (26): 5121-5136. DOI: 10.5897/AJB09.1261.[Mar 3, 2021]

Mishra, R.D. and Ahmed, M. 1989. *Manual on Irrigation Agronomy*. Oxford and IBH Publishing Co. Pvt. Ltd, New Delhi, 410p.

Mishra, S.S., Behera, P.K., Kumar, V., Lenka, S.K., and Panda, S. 2018. Physiological characterization and allelic diversity of selected drought tolerant traditional rice (*Oryza sativa* L.) landraces of Koraput, India. *Physiol. Mol. Biol. Plants*:1-12. Doi: https://doi.org/10.1007/s12298-018-0606-4. [Mar 3, 2021]

Moonmoon, S., Fakir, M.S.A., and Islam, M.T. 2017. Effect of drought stress on grain dry weight, photosynthesis and chlorophyll. *Sch. J. Agric. Vet. Sci.* 4(1): 13-17.

Mostajeran, A. and Eichi, V.R. 2009. Effects of drought stress on growth and yield of rice (*oryza sativa* l.) cultivars and accumulation of proline and soluble sugars in sheath and blades of their different ages leaves. American-Eurasian. *J. Agric. Environ. Sci.* 5(2): 264-272.

Murphy, R.B., Doohan, M.F., and Hodkinson, R.T. 2014. Yield increase induced by the fungal root endophyte *Piriformospora indica* in barley grown at low temperature is nutrient limited. *Symbiosis*: 1-11.

Muthurajan, R., Shobbar, Z., Jagadish, S.V.K., Bruskiewich, R., Ismail, A., Leung, H., and Bennett, J. 2011. Physiological and proteomic responses of rice peduncles to drought stress. *Mol. Biotechnol.* 48:173–182.

Nagarajan, S. and Nagarajan, S. 2010. Bohnert and Govindjee (eds.), *Abiotic Stress Adaptation in Plants: Phys. Mol. Genomic Foundation,* 1–11pp.

Nasrin, S., Saha, S., Begum, H.H., and Samad, R. 2020. Impacts of drought stress on growth, protein, proline, pigment content and antioxidant enzyme activities in rice (*Oryza sativa* l. var. irri dhan-24). *J. Biol. Sci.* 29 (1): 117-123.

Nath, M., Bhatt, D., Prasad, R., Gill, S.S., Anjum, N.A., and Tuteja, T. 2016. Reactive oxygen species generation-scavenging and signaling during plant-arbuscular mycorrhizal and *Piriformospora indica* interaction under stress condition. *Front. Plant Sci.* 7:1574. doi: 10.3389/fpls.2016.01574.[Mar 3, 2021]

Nautiyal, C.S., Chauhan, P.S., Gupta, S.M.D., Seem. K., Varma, A., and Staddon, W.J. 2010. Tripartite interactions among *Paenibacillus lentimorbus* NRRL B-30488, *Piriformospora indica* DSM 11827, and *Cicer arietinum* L. *World J. Microbiol. Biotechnol.* 26:1393–1399.

Noorjahan, K., Naik, R.M., Ramaiah, M., and Gopal, K. 2018. Influence of nutrients and *Piriformospora indica* on growth and biochemical attributes of african marigold cv. Pusa basanthi Gainda. *J. Pharmac. Phytochem.* 7(4): 55-60.

Oelmuller, R., Sherameti, I., Tripathi, S., and Varma, A. 2009. *Piriformospora indica*, a cultivable root endophyte with multiple biotechnological applications. *Symbiosis* 49 :1–17.

Pandey, N., Verma, A.K., and Tripathi, R.S. 2010. Response of hybrid rice to scheduling of nitrogen and irrigation during dry season. *Oryza* 47 (1): 34-37.

Panse, V. G. and Sukhatme, P. V. 1985. *Statistical Method for Agricultural Workers* (4th Ed.). Indian Council of Agricultural Research, New Delhi, 347p.

Parihar, S.S. 2004. Influence of nitrogen and irrigation schedule on yield, water use and economics of rice in summer season. *Ann. Plant Soil Res.* 6: 29-31.

Singh, S., Prasad, S., Yadav, V., Kumar, A., Jaiswal, B., Kumar, A., Khan, N.A., and Dwivedi, D.K. 2018. Effect of drought stress on yield and yield components of rice (*Oryza sativa* L.) genotypes. *Int. J. Curr. Microbiol. App. Sci.* 7: 2752-2759.

Slatyer, R.O. and Barrs, H.D. 1965. *Methodology of plant Eco physiology.* United Nations Educational Scientific and Cultural Organization, Rome. 468p.

Snedecor, G.W. and Cochran, W.G. 1967. *Statistical Method* (16th Ed.). Oxford and IBH publishing Co., Calcutta, 351p.

Sonit, A., Rathore, A.L., Hemlata., Deepti, J.H.A., Rathour, S.K., and Nandeha, K.L. 2015. Effect of pressurized irrigation systems on productivity, water and energy use efficiency of summer rice. *The Ecoscan* 9(1&2): 249-254.

Sovannarun, V., Nualsri, C., Nakkanong, K., and Duangpan, S. 2019. Morphological and physiological responses of local rice varieties to drought stress. Songklanakarin. *J. Plant Sci.* 6(4): 47-54.

Su, Z., Ting, W., Neeraj, S., Youyuan, C., Xiaoxi, L., Chao, S., Yufeng, Y., Qi-kang, G., and Bing-gan, L. 2017. *Piriformospora indica* promotes growth, seed yield and quality of *Brassica napus L. Microbiological Research.* http://dx.doi.org/doi:10.1016/j.micres.2017.02.006. [Mar 13, 2021]

Subbiah, D.V. and Asija, G.L. 1956. Rapid procedure for estimation of available nitrogen in soil. *Curr. Sci.* 25: 259-260.

Swetha, S. and Padmavathi, T. 2019. Mitigation of drought stress by *Piriformospora indica* in *Solanum melongena* L. cultivars. *Proc. Natl. Acad. Sci., India, Sect. B. Biol. Sci.* : 1-12. DOI: https://doi.org/10.1007/s40011-019-01128-3. [Mar 2, 2021]

Taghinasab, M., Imani, J., Steffens, D., Glaeser, S.P., and Kogel, K. 2018. The root endophytes *Trametes versicolor* and *Piriformospora indica* increase grain yield and P content in wheat. *Plant soil*: 1-10. https://doi.org/10.1007/s11104-018-3624-7. [Feb 24, 2021]

Tanha, S.R., Ghasemnezhad, A., and Babaeizad, V. 2014. A study on the effect of endophyte fungus, *Piriformospora indica*, on the yield and phytochemical changes of globe artichoke (*Cynara scolymus* L.) leaves under water stress. *Int. j. Adv. Biol. Biomed. Res.* 2(6): 1907-1921.

Tariq, A., Pan, K., Olatunji, O.A., Graciano, C., Li, Z., Sun, F., Sun, X., Song, D., Chen, W., Zhang, A., Wu, X., Zhang, L., Mingrui, D., Xiong, Q., and Liu, C. 2017. Phosphorous application improves drought tolerance of *Phoebe zhennan*. *Front. Plant Sci.* 8:1561. doi: 10.3389/fpls.2017.01561 [Mar 14, 2021]

Tsai, H., Shao, K., Chan, M., Cheng, C., Yeh, K., Oelmuller, R., and Wang, S. 2020. *Piriformospora indica* symbiosis improves water stress tolerance of rice through regulating stomata behavior and ROS scavenging systems. *Plant Signal. Behav.* e1722447: 1-10. DOI: 10.1080/15592324.2020.1722447 [Feb 11, 2021]

Verma, S., Varma, A., Rexer, K.H., Hassel, A., Kost, G., Sarbhoy, A., Bisen, P.S., Butehorn, B., and Franken, P. 1998. *Piriformospora indica* gen. nov. sp. nov., a new root colonizing fungus. *Mycologia* 90: 896-903.

Walkley, A. and Black, C.A. 1934. An examination of the digestion method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 40: 233-23.

Waller, F., Achatz, B., Baltruschat, H., Fodor, J., Becker,K., Fischer, M., Heier, T., Ckelhoven, R., Neumann, C., Wettstein, D., Franken, P., and Kogel, K. 2005. The endophytic fungus *Piriformospora indica* reprograms barley to salt-stress tolerance, disease resistance, and higher yield. *Agri. Sci.* 102(38): 13386–13391.

Xu, L., Wang, A., Wang, J., Wei, Q., and Zhang, W. 2017. *Piriformospora indica* confers drought tolerance on *Zea mays* L. through enhancement of antioxidant activity and expression of drought-related genes. *The Crop J.* 5 : 251 – 258.

Yadav, V., Kumar, M., Deep, K.D., Kumar, H., Sharma, R., Tripathi, T., Tuteja, N., Saxena, K.A., and Johri, A.K. 2010. A phosphate transporter from the root endophytic fungus *Piriformospora indica* plays a role in phosphate transport to the host plant. *The J. Bio. Chem.* 285(34): 26532–26544. DOI 10.1074/jbc.M110.111021. [Mar 2, 2021]

Yaghoubian, Y., Goltapeh, E.M., Pirdashti, H., Esfandiari, E., Feiziasl, V., Dolatabadi, H.K., Varma, A., and Hassim, M.H. 2014. Effect of *Glomus mosseae* and *Piriformospora indica* on growth and antioxidant defense responses of wheat plants under drought stress. *Agric. Res.* 3(3):239–245.

Yoshida, S., Doughlas, A., Fornojamesh, W., Cock., and Geomez, K. A. 1976. *Laboratory Manual for Physiological Studies in Rice.* IRRI, Los Banos, Philippines, 75p.

Yun, P., Xu, Le., Wang, S., Shabala, L., Shabala, S., and Zhang, W. 2018. *Piriformospora indica* improves salinity stress tolerance in *Zea mays* L. plants by regulating Na+ and K+ loading in root and allocating K+ in shoot. *Plant Growth Reg.* : 1-9.

Zain, N.A.M., Ismail, M.R., Mahmood, M., Puteh, A., and Ibrahim, M.H. 2014. Alleviation of water stress effects on mr220 rice by application of periodical water stress and potassium fertilization. *Molecules 19*: 1795-1819. doi:10.3390/molecules19021795. [Mar 2, 2021]

Zamani, J., Hajabbasi, A.M., Alaie, E., Sepehri, M., Leuchtmann, A., and Schulin, R. 2015. The effect of *Piriformospora indica* on the root development of maize (*Zea mays* L.) and remediation of petroleum contaminated soil. *Int. J. Phytoremediation*: 1-39. DOI: 10.1080/15226514.2015.1085831. [Feb 21, 2021]

Zhang, Y., Du, H., Gui, Y., Xu, F., Liu, J., Zhang, J., and Xu, W. 2020. Moderate water stress in rice induces rhizosheath formation associated with abscisic acid and auxin responses. *J. Exper. Botany* 71 (9): 2740–2751.

MITIGATING WATER STRESS IN SUMMER RICE USING BENEFICIAL ROOT ENDOPHYTIC FUNGUS *Piriformospora indica*

By

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ABSTRACT

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ABSTRACT

The study entitled 'Mitigating water stress in summer rice using beneficial root endophytic fungus *Piriformospora indica*' was undertaken at College of Agriculture, Vellayani during 2019 - 2021. The objective of the study was to assess the performance of *P. indica* colonized rice under different levels of moisture stress during summer.

The field experiment was laid out in randomized block design with 2 x 3 x 2 treatments, replicated thrice in the low land paddy fields during February to May 2021, using variety *Prathyasa*. The treatments included colonizing with *P. indica* [p_1- *P. indica* colonized rice and p_2- non-colonized rice(control)], three irrigation intervals[i_1- 30 mm CPE (cumulative pan evaporation), i_2- 35 mm CPE and i_3- 40mm CPE] and two irrigation depths(d_1- to a depth of 1.5 cm and d_2- to a depth of 3 cm). *P. indica* colonized/ non-colonized rice seedlings raised in trays were transplanted at 14 days after sowing at 15 cm x 10 cm and uniformly irrigated till 10 days after transplanting (DAT). The crop was raised as per the KAU package of practices recommendation for short duration rice (KAU, 2016).

The results of the study revealed that colonization and irrigation to 3 cm depth improved the growth and growth attributes *viz.*, plant height, tiller number m^{-2}, leaf area index and dry matter production of summer rice. Colonization with *P.indica* significantly influenced the number of tillers m^{-2} with 10.64, 16 and 15.69 per cent increase in tiller production at 30, 45 and 60 DAT respectively, compared to non-colonized plants. Colonized plants irrigated at 30 mm CPE to a depth of 3 cm evinced the maximum leaf area index (4.54) at 60 DAT and dry matter production (4559.26 kg ha^{-1}) at harvest.

Yield attributes and yield of rice were significantly affected by *P. indica* colonization, irrigation interval and depth of irrigation. Superior number of productive tillers m^{-2}(222.84), filled grains per panicle (81.11) and the lowest sterility percentage (13.37) were recorded with colonization. Colonized plants irrigated at 30 mm CPE to a depth of 3 cm produced significantly superior productive tillers m^{-2} (275.00), filled grains per panicle (111.33) and the lowest sterility percentage (8.80). Among second

order interactions, $p_1i_1d_2$ produced significantly superior grain yield (2698.56 kg ha^{-1}) and straw yield (2848.13kg ha^{-1}).

P. indica colonization, irrigation interval and depth of irrigation had significant effect on root parameters of rice at all stages of observation. *P. indica* colonized plants showed significantly superior rooting depth at all stages. Colonized rice plants irrigated at 35 mm CPE to a depth of 3 cm revealed superior rooting depth *viz.*, 19.4, 29.86 and 30.00 cm and average root length of 23.36, 34.87 and 36.20 cm at 30, 60 DAT and harvest respectively. Significantly superior root volume and root dry weight at 30, 45, 60 DAT and harvest respectively were recorded in colonized plants irrigated at 30 mm CPE to a depth of 3 cm.

Among the physiological parameters studied, proline content declined in the order of decreasing CPE, 40 mm >35 mm > 30 mm. *P. indica* colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm produced significantly greater proline (115.33 and 106.00 µmole g^{-1}at panicle initiation and flowering respectively). Colonized rice plants at 30 mm CPE to a depth of 3 cm observed the maximum relative leaf water content, cell membrane stability and chlorophyll stability index at panicle initiation and flowering respectively. P x I x D remained significant with the highest water use efficiency (WUE) of 3.47 kg ha^{-1}mm^{-1} for *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm.

P. indica, irrigation interval and depth of irrigation could significantly influence the available nitrogen, phosphorus and potassium status of soil after experiment. Colonized plants irrigated at 40 mm CPE to a depth of 1.5 cm resulted in significantly superior available phosphorus (179.93 kg ha^{-1}). Considering the economics, *P. indica* colonized plants irrigated at 30 mm CPE to a depth of 3 cm brought about the highest gross income (₹ 88951 ha^{-1}), net income (₹ 30351 ha^{-1}) and B: C ratio (1.51).

Based on the above findings, it could be inferred that rice plants colonized with *P. indica* significantly enhanced the growth and yield attributes, root biomass, nutrient uptake and WUE, irrespective of interval and depth of irrigation.Yield and WUE of *P. indica* colonized plants subjected to severe stress, were observed to be equivalent to those of non-colonized plants under moderate stress. Colonization resulted in saving of 30 mm water or 3 irrigations and could help rice to combat drought stress by enhanced root biomass, nutrient uptake and water use efficiency during summer.

സംഗ്രഹം

‘വേരിനുള്ളിൽ വളരുന്ന പിരിഫോമോസ്പോറ ഇൻഡിക്ക എന്ന കുമിൾ ഉപയോഗിച്ച് നെല്ലിലെ ജലലഭ്യതക്കുറവ് മൂലമുണ്ടാകുന്ന വിളനഷ്ടം പരിഹരിക്കൽ’ എന്ന വിഷയത്തിൽ വെള്ളായണി കാർഷിക കോളേജിൽ 2019 -2021 കാലയളവിൽ ഒരു പഠനം നടത്തുകയുണ്ടായി. മണ്ണിലെ വിവിധതരം ജലലഭ്യതക്കനുസ്തൃമായി പി. ഇൻഡിക്ക വേരിൽ വളർത്തിയ നെൽച്ചെടികളും പി. ഇൻഡിക്ക ഇല്ലാത്ത നെൽച്ചെടികളും എങ്ങനെ വരൾച്ചയെ പ്രതിരോധിക്കുന്നുവെന്ന് നിരീക്ഷിക്കുകയായിരുന്നു പ്രധാന ലക്ഷ്യം.

റാൻഡമൈസ്ഡ് ബ്ലോക്ക് ഡിസൈനിൽ പന്ത്രണ്ട് ട്രീറ്റമെന്റ് ഉൾപ്പെടുത്തി പ്രത്യാശ എന്ന നെല്ലിനം ഉപയോഗിച്ച് 2021 ഫെബ്രുവരി മുതൽ മെയ് വരെയാണ് പരീക്ഷണം നടത്തിയത്. ഒിവിധ പരീക്ഷണ ഘടകങ്ങളിലുണ്ടായ പി. ഇൻഡിക്കയുടെ സാന്നിദ്ധ്യം വേരുകളിൽ / അസാന്നിദ്ധ്യം, ജലസേചനം നൽകുന്ന ഇടവേളകൾ (30 മി.മി, 35 മി.മി, 40 മി.മി, എന്നീ അധികരിച്ച ബഷ്പീകരണത്തിന്റെ തോത് പ്രകാരം) ജലസേചനം നൽകുന്ന ആഴം (1.5 സെമി, 3സെമി) എന്നിവയുടെ ഒറ്റക്കും കൂട്ടായും ഉള്ള രീതികളായിരുന്നു ജലലഭ്യതക്കുറവിന്റെ അളവ് നിശ്ചച്ചത്. പി. ഇൻഡിക്ക ഉള്ള മാദ്ധ്യമത്തിൽ വളർത്തിയ നെല്ല്, ഇല്ലാത്ത മാദ്ധ്യമത്തിൽ വളർത്തിയ നെല്ല് മുളപ്പിച്ച് 14 ാം ദിവസം പറിച്ചുനട്ട് ഒരേപ്രകാരം 10ദിവസത്തേക്ക് ജലസേചനം നൽകി. തുടർന്നുള്ള കേരള കാർഷിക സർവ്വകലാശാല ശുപാർശപ്രകാരമായിരുന്നു.

പി. ഇൻഡിക്ക വേരുകളിൽ വളർന്ന നെല്ലിൽ വിളവ്, വളർച്ചാഘടകങ്ങൾ, വേരുപടലത്തിന്റെ ഭാരം, പോഷകമൂലകങ്ങളുടെ ആഗീകരണം, ജലയുപയോഗകാര്യക്ഷമത എന്നിവ മികച്ചതായിരുന്നു. അതികഠിനമായ ജലലഭ്യതക്കറവിലും പി. ഇൻഡിക്കയുടെ സാന്നിദ്ധ്യത്തിൽ വളർന്ന നെൽച്ചെടികൾ ഇടത്തരം ജലലഭ്യതയിൽ വർന്ന നെൽചെടിയോട് തുല്യമായ വിളവും ജല ഉപയോഗ കാര്യക്ഷമതയും രേഖപ്പെ

ടുത്തി. പി. ഇൻഡിക്ക വേരിൽ വളർന്ന നെല്ല് കൃഷിചെയ്യുന്നത് 30 സെ.മി ജലസേചനം മൂന്ന് തവണ ജലസേചനം ചെയ്യുന്നതോ ഒഴിവാക്കാൻ സഹായിക്കുന്നതായി കണ്ടെത്തി. പി. ഇൻഡിക്ക യുടെ ഉപയോഗത്തിലൂടെ ഹെക്ടറിന് മൂന്ന് ലക്ഷം ലിറ്റർ ജലം ലാഭിക്കാൻ സാധിക്കുന്നതായി പഠനം രേഖപ്പെടുത്തി.

പിരിഫോമോസ്പോറ ഇൻഡിക്ക എന്ന കുമിൾ വേരിൽ വളർത്തിയുപയോഗിക്കുന്നത് ഏറ്റവും അനുയോജ്യമായ സാഹചര്യത്തിൽ വളരുന്ന നെല്ലിന്റെ ഉൽപാദനം - ശതമാനം വർദ്ധിക്കുന്നതായി കണ്ടെത്തി.വേനൽക്കാല നെൽകൃഷിയിൽ ജലലഭ്യതക്കുറവ് മൂലമുണ്ടാകുന്ന വളർച്ചയെ നേരിടാൻ പി. ഇൻഡിക്ക എന്ന കുമിൾ ഉപയോഗം സഹായിക്കുമെന്ന് തെളിയിക്കപ്പെട്ടു.

APPENDIX

APPENDIX I

Weather parameters during the period of field experiment (March 2021- June 2021)

Standard week	Mean temperature		Mean RH		Rainfall	Evaporation
	Max	Min	Max	Min		
10 (05Mar - 11Mar)	34.0	20.4	90	66	0.0	5.6
11 (12Mar- 18Mar)	34.3	23	88	65	0.0	4.8
12 (19Mar – 25Mar)	34.1	25.4	88.9	68.3	0.0	4.2
13 (26Mar- 01April)	34.1	25.8	89	79	0.0	4.1
14 (2April- 08April)	34.3	26.4	88.3	76.1	0.0	4.9
15 (9April- 15April)	33.4	25.6	90.1	79	8.6	3.5
16 (16April- 22April)	33.4	25.4	87.3	79.3	2.5	4.0
17 (23April- 29 April)	34.2	26.1	88	77.3	0.5	4.4
18 (30 April- 06May)	33.6	26	89.4	76.7	4.1	4.2
19 (07May-13May)	33.5	25.5	93	79.5	7.3	3.3
20 (14 May- 20 May)	31.1	24.1	96	87.4	23.8	2.3
21 (21 May-27May)	30.5	24.1	94.5	88.1	59.1	1.3
22 (28May- 03Jun)	32.2	25.1	90.5	78.8	22.6	3.2

APPENDIX II

AVERAGE INPUT COST AND MARKET PRICE OF PRODUCE

Items	Cost
Labour charge	
Men / Women	800/ day
Inputs	
Paddy seeds	40 ₹ kg^{-1}
Urea	8 ₹ kg^{-1}
Rajphos	20 ₹ kg^{-1}
MOP	22 ₹ kg^{-1}
Market price of produce	
Paddy	27.5 kg^{-1}
Straw	5 kg^{-1}