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Evaluation of Biomass Productivity and Estimated Carbon Sequestration Potential of Eucalyptus Clones Under High Water Table Conditions of South Western Punjab

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ABSTRACT

The present study was conducted during 2022–2024 at the Krishi Vigyan Kendra of Punjab Agricultural University, Ludhiana, located at Goniana, District Sri Muktsar Sahib, Punjab, to evaluate the growth performance, biomass productivity, and carbon mitigation potential of six Eucalyptus clones (C-2045, C-2135, C-413, C-3020, C-316, and C-288) growing in a 9-year-old plantation under high water table conditions. The experiment was laid out in a factorial completely randomized block design with three replications. Significant variation was observed among the clones for growth, stem form, biomass accumulation, and carbon sequestration attributes. Clone C-2045 exhibited the best overall performance, recording superior growth, stem quality, biomass production, carbon stock, and CO_2 assimilation potential. Clone C-3020 ranked second and also demonstrated good adaptability to high water table conditions, whereas C-288 showed the poorest performance. Based on integrated growth and biomass indices, the overall clonal ranking was C-2045 > C-3020 > C-413 > C-2135 > C-316 > C-288. The results indicate that clones C-2045 and C-3020 are well suited for high water table regions of South-Western Punjab and offer considerable potential for enhancing timber production and carbon sequestration under climate-resilient forestry systems. A limitation of the study is that the evaluation was conducted at a single site, and carbon stock estimates were derived from biomass estimation equations rather than direct carbon measurements. These findings provide valuable guidance for clone selection in high water table environments and support sustainable plantation management in similar agro ecological regions.

INTRODUCTION

India's forest and tree cover constitutes approximately 25.17% of its total geographical area, with forest cover accounting for 21.76% and tree cover for 3.41% (FSI, 2023). Since 2021, this green cover has increased by 1,445.81 km², reflecting a gradual but encouraging trend in ecological restoration and climate change mitigation. However, Punjab, occupying 1.53% of the national land area (50,362 km²), continues to lag behind with a forest cover of only 4.86%, highlighting the urgent need for scalable and site-specific afforestation strategies. Among the fast-growing species suitable for such interventions, Eucalyptus, a genus under the Myrtaceae family has emerged as a valuable candidate due to its rapid growth, high biomass productivity, and ability to adapt to diverse and degraded soil conditions. Native to Australia and comprising over 700 species (Brooker, 2000; *Rassaeifar et al.,* 2013), Eucalyptus has been planted on more than 22 million hectares globally (Solís, 2025), making it one of the most widely cultivated hardwood genera. In India, *Eucalyptus tereticornis* is the predominant species used in agroforestry, commercial block plantations, and social forestry programs (Vijayaraghavan & Sivakumar 2017), especially due to its adaptability to semi-arid, sub-humid, and waterlogged zones.

The evolution of clonal forestry utilizing vegetatively propagated, genetically superior planting material has significantly enhanced plantation productivity by improving growth, stem form, and resistance to environmental stress (Lal, 2001; Mushtaq *et al.,* 2017). Such clonal plantations often yield 20–25 times more wood than natural forests, with shorter rotations and higher uniformity (Arya *et al.,* 2009), making them particularly beneficial for marginal and problematic soils, including saline and waterlogged lands. Beyond their timber and industrial value, eucalyptus plantations are now recognized for their role in climate change mitigation, particularly through carbon sequestration. Genetically improved clones with high biomass yield can sequester substantial amounts of atmospheric CO_2, thereby supporting India's Nationally Determined Contributions (NDCs) under the Paris Agreement (MoEFCC, 2021). However, clonal performance varies under different site conditions, and localized screening is essential to identify genotypes best suited for specific environmental constraints such as high water tables and salinity (Dagar *et al.,* 2016).

This is especially relevant in regions like South-Western Punjab, where waterlogging and soil salinity pose major challenges to conventional agriculture. An estimated 5.5 million hectares in India are affected by waterlogging, with 84,000 hectares located in Muktsar Sahib District alone (Krishan & Chopra, 2015). Shallow water tables, poor drainage, and saline soils severely limit the success of traditional forestry species. Eucalyptus is capable of accessing deep groundwater and absorbing surface moisture, making it an effective tool for bio-drainage and land reclamation (Hazrat *et al.,* 2014; Hogar *et al.,* 2019). Certain clones have demonstrated resilience to both salinity and waterlogging (Marcar & Benyon, 2003; Singh *et al.,* 2023), further reinforcing their suitability for stressed ecologies. Despite the widespread adoption of *Eucalyptus* in plantation forestry and the availability of studies on growth performance, productivity, and stress tolerance of selected clones, information on their comparative biomass production and carbon sequestration potential under high water table conditions of South-Western Punjab remains limited. Most previous investigations have focused on either growth performance under normal site conditions or tolerance to salinity and waterlogging separately, with limited emphasis on integrated assessment of growth, biomass accumulation, carbon stock, and CO_2 mitigation potential under shallow water table environments. This represents an important knowledge gap, particularly for regions where rising water tables and soil degradation constrain the success of conventional forestry species. The novelty of the present study lies in the comprehensive evaluation of six commercially important Eucalyptus clones for growth performance, stem form, biomass productivity, carbon stock, and carbon mitigation potential under field conditions characterized by a persistently high water table. It was hypothesized that significant variation exists among Eucalyptus clones in their adaptability and productivity under high water table conditions, and that certain clones would exhibit superior growth and carbon sequestration potential, making them suitable candidates for sustainable plantation development and climate-resilient forestry in South-Western Punjab.

Table 1: Soil properties of the experimental site at the initiation and the end of the experiment and after harvesting

Soil properties	Initiation	At the end
pH	8.10	7.23
EC (dS/m)	0.13	0.80
OC (%)	0.34	0.66
Available N (kg ha^{-1})	93.3	222.8
Available P (kg ha^{-1})	9.20	12.0
Available K (kg ha^{-1})	59.19	97.3

MATERIAL AND METHODS

Location and climate of experimental site

The study was conducted at the Krishi Vigyan Kendra (KVK), Punjab Agricultural University, Ludhiana, located at Goniana, Sri Muktsar Sahib district, Punjab (30°44′41″ N, 74°50′04″ E; 194 m amsl). The site is characterized by low-lying loamy sand soils and a shallow groundwater table, with water levels occurring within 1.5 m of the surface in 12% of the district area and within 5 m in about 75% of the area (Krishna and Copra 2015). The region experiences hot summers, cool winters, and frequent drought-like conditions, which often affect the productivity of annual crops. Soil properties and meteorological data of the study site are presented in Table 1 and Fig. 1, respectively.

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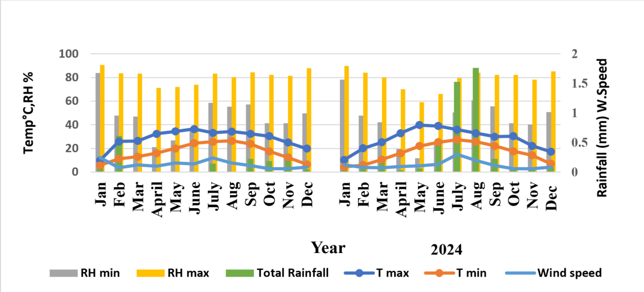

Figure 1: Meteorological data of experimental area

Experimental design

The experiment was conducted during 2022–24 with the objective of assessing the productivity potential of *Eucalyptus* clones under high water table conditions. The plantation of six different *Eucalyptus* clones, raised under field conditions in October 2013 at a spacing of 3 m × 1.5 m in a North-East direction, was evaluated for various growth and biomass traits. The six clones (C-2045, C-2135, C-413, C-3020, C-316, and C-288) were sourced from Pragati biotechnology Ltd. planted following a randomized block design with three replications and a plot size of 15 trees.

Measurement of growth parameters

Tree growth observations *viz.* total height, girth at breast height (GBH), number of branches, straightness score, and crown length were recorded 8 years after planting. Tree height was measured from ground level to the apical point using Ravi's Multimeter, while GBH was measured at 1.37 m above ground using a measuring tape and subsequently converted to diameter at breast height (DBH) using the standard formula. Above-ground biomass components, including leaf and log biomass, were estimated through destructive sampling. However, due to logistical constraints in oven-drying large samples, timber volume, below-ground biomass, and additional parameters were computed using established allometric equations.

Timber volume was estimated from these parameters every year by the following regression equations:

Timber volume for eucalyptus (m^3 $tree^{-1}$) =−0.00321 + 0.32098 × (D2H), (Dhanda and Singh, 1990) (1)

Where **D** is DBH (m) and **H** is tree height (m).

Assessment of biomass, carbon stock and CO2 assimilation potential

Biomass estimation was carried out using allometric equations developed by Kumar *et al.* (2020) for Eucalyptus plantations in north-western India's semi-arid region. These equations were considered suitable because they were developed from destructive sampling of Eucalyptus trees under agro-climatic conditions comparable to those of south-western Punjab. In the absence of site- and clone-specific allometric models for Eucalyptus under high water table conditions, the use of regionally validated equations provides a robust and widely accepted approach for estimating biomass and carbon stock.

Above Ground Biomass (AGB)**:** AGB was estimated using the following allometric equation developed by the Central Soil Salinity Research Institute

$Y = -12.858 + 3.7309x - 1.4085y$ (2)

Where, Y = biomass (kg), x = girth (cm) and y = height of the tree (m)

Below ground biomass (BGB): The below ground biomass (BGB) was calculated by multiplying AGB by a factor of 0.26 as IPCC default factor for root: shoot ratio.

BGB = AGB × 0.26 (3)

Carbon Stock Estimation**:** Carbon content in AGB and BGB was computed using default carbon conversion factors of 0.45 and 0.48, respectively (Kumar *et al.* 2019)

(4)

Carbon stock AGB = AGB × 0.45

Carbon stock BGB = BGB × 0.48 (5)

Total carbon stock was obtained by summing carbon in AGB and BGB.

CO_2 Assimilation Potential:

Total carbon stock was converted into CO_2equivalents using the molecular weight conversion factor (44/12 = 3.67) as recommended by IPCC(2006).(Newaj *et al.* 2014)

CO_2 = Total Carbon × 44/12 (6)

Soil Analysis

Surface soil samples (0–15 cm depth) were collected before initiating the experiment. Samples were air-dried and sieved through a 2 mm mesh prior to analysis. Soil organic carbon (OC) was estimated by the Walkley and Black method. Available nitrogen (N) was determined using the alkaline $KMnO_4$ method (Subbiah & Asija, 1956), phosphorus (P) by the Olsen method, and potassium (K) using the ammonium acetate extraction method (Jackson, 1973). Nitrogen concentration was further verified through the Kjeldahl method.

Prior to the initiation of the experiment, soil samples were collected and analyzed to determine the baseline physico-chemical properties of the experimental site.: loamy sand texture, pH 7.89 (alkaline), EC 0.29 dS m^{-1} (normal), low organic carbon (0.32%), low available nitrogen (125.2 kg ha^{-1}), medium phosphorus (13.3 kg ha^{-1}), and adequate potassium (176 kg ha^{-1}).

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using the randomized block design (RBD) as per the method outlined by Panse & Sukhatme (1985). Treatment means were compared using the critical difference (CD) test at a 5% significance level. Statistical analysis was performed using OP stat software.

RESULTS AND DISCUSSION

Soil properties before and after the experiment

A noticeable improvement in soil health parameters was observed over the course of the study period. Soil pH decreased from 8.10 at initiation to 7.23 at the end, indicating a shift toward neutral soil reaction. The electrical conductivity increased from 0.13 to 0.80 dS/m, though it remained within the acceptable non-saline limits, indicating no adverse salinization effect during the study period. The organic carbon content showed a marked improvement, rising from 0.34% to 0.66%, reflecting enhanced soil organic matter due to biomass accumulation and litter deposition. Nutrient availability also increased substantially. Available nitrogen content more than doubled, from 93.3 kg ha^{-1} to 222.8 kg ha^{-1}. Available phosphorus increased from 9.20 to 12.0 kg ha^{-1}, and available potassium improved significantly from 59.19 to 97.3 kg ha^{-1}. These changes suggest positive effects of *Eucalyptus* plantation on soil fertility, possibly due to root exudates, nutrient cycling and organic matter additions from litterfall and root turnover.

Survival Performance of Eucalyptus Clones under Stress-Prone Conditions

The survival data of *Eucalyptus* clones after 8 years of establishment, as presented in Fig.2, indicate a generally high adaptability across all clones, despite the challenging site conditions. Survival rates ranged from 85% to 100%, with no statistically significant differences observed among the clones. Clone C-2045 exhibited the highest survival percentage, followed closely by clones C-288 and C-316. In contrast, clones C-2135 and C-413 recorded comparatively lower survival, primarily due to tree mortality occurring during the summer months. Clones C-2045, C-288, and C-316 emerged as the most promising genotypes for the high water table and stress-prone conditions characteristic of South-Western Punjab. The observed variation in survival among clones may be attributed to inherent genetic differences, particularly traits such as deeper root systems, drought tolerance, and early vigor. These findings align with previous studies by Singh *et al.* (2020) and Sandhu *et al.* (2020), reported significant variability in the survival of *Eucalyptus* clones under seasonal waterlogging in the same region. Dhillon *et al.* (2019) highlighted the superior physiological resilience and establishment efficiency of clonal *Eucalyptus* in water-stressed and saline environments. The results emphasize the importance of selecting genetically superior, site-specific clones to enhance survival and productivity in ecologically challenging landscapes.

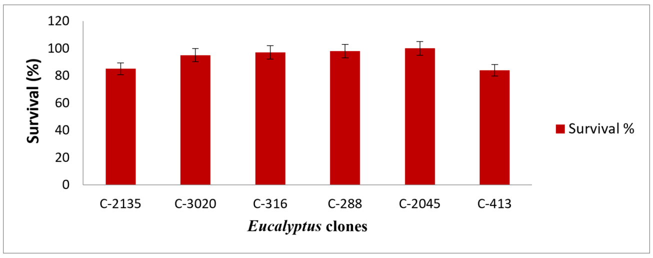

Figure 2: Mean survival percentage of Eucalyptus clones planted under water logging conditions (age 8 years)

Growth attributes

The present investigation under high water table and seasonally waterlogged conditions with close spacing, revealed substantial variation in growth performance among the six evaluated clones (Table 2). The diameter at breast height (DBH) ranged from 12.57 to 17.14 cm, tree height from 18.59 to 25.48 m, and wood volume varied between 187.91 and 474.50 m^3 ha^{-1}. Clone 2045 emerged as the most promising genotype, recording the highest DBH, height, and wood volume. This superior performance was statistically at par with Clone 3020, recorded 15.78 cm DBH, 22.46 m height, and 352.72 m^3 ha^{-1} volume, highlighting its high yield potential under the prevailing site conditions.

The observed variation in clonal growth performance is likely attributable to differences in physiological responses to excess soil moisture, hypoxic stress, and inter-tree competition under close spacing. Waterlogged soils are characterized by reduced oxygen availability, which can induce specific morphological and anatomical adaptations in plants (Dat *et al.* 2004). However, prolonged root zone flooding adversely affects stomatal conductance, photosynthetic efficiency, and root hydraulic conductivity, ultimately impairing

Table 2: Mean growth trait of *Eucalyptus* clones

Treatments	Diameter at breast height (cm)	Tree height (m)	Volume (m^3/ha)
C-2135	13.44	18.59	209.12
C-3020	15.78	22.46	352.72
C-316	12.60	19.84	195.79
C-288	12.57	19.16	187.91
C-2045	17.14	25.48	474.50
C-413	14.89	20.70	288.30
CD (p= 0.05)	1.96	3.90	33.50

plant growth (Parent *et al.* 2008; Valadares *et al.* 2014). The ability of Clones 2045 and 3020 to sustain superior growth under such stress conditions suggests the presence of adaptive traits, such as enhanced root aeration, greater phenotypic plasticity, or internal oxygen transport mechanisms. In addition to waterlogging stress, in high-density plantations, trees compete vigorously for sunlight, especially during early developmental stages. This promotes increased vertical growth, as trees prioritize height to access light, often at the expense of lateral crown development and radial stem expansion (Binkley *et al.* 2013). As a result, tree height tends to increase, while DBH expansion becomes restricted due to limited resource availability and canopy spread. Overlapping root systems in closely spaced stands intensify competition for nutrients, water, and oxygen particularly in waterlogged soils further constraining radial growth and DBH (Hakamada *et al.* 2020). Gindaba *et al* (2005) also reported significant differences in tree height and diameter at various soil moisture levels.

Stem quality traits

Stem quality traits play a crucial role in the timber industry, as straight stems reduce processing costs and maximize the proportion of usable wood (Zobel and Talbert, 1984). Among the quality parameters, number of branches and clear bole length exhibited significant variation among clones, whereas crown length and straightness showed non-significant differences. The number of branches varied significantly, ranging from 9.90 (Clone 288) to 36.14 (Clone 413). The notably high branching in Clone 413 may reflect a physiological response to stress, possibly due to suboptimal root conditions caused by prolonged saturation of the root zone. Waterlogging and high water tables often induce hypoxic stress, which negatively affects root function, disrupts hormonal balance (e.g., ethylene accumulation), and alters shoot architecture, often leading to increased branching and reduced apical dominance in sensitive genotypes (Dat *et al.* 2004; Parent *et al.* 2008). Clear bole length also showed significant variation, ranging from 15.80 m to 22.36 m. Clone 2045 recorded the longest clear bole (22.36 m), followed closely by Clone 413 (19.89 m). These results suggest that certain clones possess inherent traits favoring apical dominance and reduced lower branching under competitive or stressful environments. Close spacing typically intensifies vertical competition for light, which induces trees to invest more in vertical growth at the expense of lateral branches, thereby increasing clear bole length and improving stem form (De Bastos *et al.* 2024).

Crown length, although statistically non-significant, ranged from 3.04 m (Clone 2045) to 4.18 m (Clone 3020). The relatively uniform crown lengths among clones could be attributed to environmental constraints common across the site, such as poor soil aeration and intense canopy competition due to close spacing, which likely limited lateral expansion in all genotypes. The stem straightness score varied from 2.84 (Clone 2135) to 3.83 (Clone 2045), with the latter indicating superior stem form and alignment. Although variation in straightness was not statistically significant, the better performance of Clone 2045 suggests genetic superiority in maintaining vertical stem orientation, even under adverse conditions. Mechanical instability caused by poor root anchorage in saturated soils may lead to deviations in stem straightness (Colmer & Voesenek, 2009), though this effect appeared minimal in the present study. These findings are in agreement with earlier reports.(Dhillon *et al.* 2019) also noted differential clonal responses under similar conditions, which were attributed to genotypic variation. Likewise, Rout (2022) reported comparable trends while examining crown traits in *Eucalyptus* clones. Overall, Clone 2045 demonstrated superior quality traits, likely due to a combination of genetic resilience and adaptive responses to environmental stressors such as waterlogging and close spacing.

Fresh Biomass

The log weight of the six clones revealed statistically significant differences, ranging from 153.40 to 305.33 kg (Table 4). The maximum log weight (305.33 kg $tree^{-1}$) and leaf weight (31.47 kg $tree^{-1}$) were recorded in clone 2045, which was statistically comparable to clone

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Table 3: Mean stem quality parameters of *Eucalyptus* clones

Treatments	Number of Branch	Straightness score (1-5)	Clear bole (m)	Crown length (m)
C-2135	18.83	2.84	15.80	3.51
C-3020	14.57	3.05	18.55	4.18
C-316	10.83	3.07	16.75	3.30
C-288	9.90	3.08	16.46	3.09
C-2045	12.95	3.83	22.36	3.04
C-413	36.14	3.07	19.89	3.27
CD (p=0.05)	7.98	NS	4.03	NS

Table 4: Mean values for fresh biomass parameters of *Eucalyptus* clones

Treatments	Log weight (kg/ tree)	Leaf weight (kg tree-1)
C-2135	248.30	27.83
C-3020	263.50	29.00
C-316	210.23	25.53
C-288	153.40	19.20
C-2045	305.33	31.47
C-413	245.30	24.17
CD (5%)	21.52	4.01

3020. In contrast, clone 288 recorded the minimum log weight (153.40 kg tree^{-1}) and leaf weight (19.20 kg tree^{-1}). Several studies have revealed that variations in growth and yield among *Eucalyptus* clones can be attributed to both environmental and genetic factors (Sharma, 2022; Ara, 2009; Saravanan, 2019). Similarly, Nagarjuna (2023) observed that clone BCM-2169 recorded a maximum log weight of 125.8 kg tree^{-1} and a total above-ground biomass of 148.7 kg tree^{-1}. The significantly higher log and leaf weights in clone 2045 may be attributed to its unique genetic constitution. Likewise, Vellini *et al* (2008) observed significant differences in the dry matter of leaves, stems, and roots, as well as in the root-to-shoot ratio, among genotypes and water regimes.

C-Storage

Significant variation was observed among the six *Eucalyptus* clones in terms of dry biomass production, carbon stock, and CO_2 assimilation (Table 5). The total dry biomass ranged from 134.6 to 191.6 Mg ha^{-1}, with Clone 2045 recording the highest total biomass (191.6 Mg ha^{-1}), followed by Clone 3020 (176.9 Mg ha^{-1}). Similarly, Clone 2045 also registered the maximum carbon stock (87.4 Mg C ha^{-1}) and the highest total CO_2 assimilation (291.3 Mg ha^{-1}). On the contrary, Clone 316 and Clone 288 had comparatively lower biomass (134.6 and 135.3 Mg ha^{-1}, respectively), carbon stock, and CO_2 assimilation, indicating moderate productivity.

AGB contributed the majority of the total dry biomass across all clones, with AGB ranging from 106.8 to 152.1 Mg ha^{-1}, while BGB ranged from 27.8 to 39.5 Mg ha^{-1}. The AGB: BGB remained relatively consistent, suggesting uniform root-to-shoot allocation patterns across clones. The trends in carbon stock closely followed those in biomass, given that carbon content is proportionally derived from biomass estimates. This superior performance of Clone 2045 may be associated with differences in resource utilization and biomass allocation under high water table conditions. Previous studies have shown that biomass productivity and carbon sequestration in *eucalyptus* plantations are strongly influenced by genetic makeup, growth rate, and site conditions (Singh *et al.* 2023). The enhanced growth and carbon sequestration observed in certain clones under high water table conditions may also be influenced by better nutrient dynamics, as demonstrated by Singh *et al.* (2025), reported that application of organic nutrient sources, including sewage sludge, significantly improved growth and carbon storage in *Eucalyptus tereticornis* plantations under stressed environments. The significant differences observed among clones indicate strong genotypic control over carbon assimilation efficiency and dry matter partitioning. CO_2 assimilation, estimated based on carbon content showed a wide range from 204.7 to 291.3 Mg CO_2 ha^{-1}, with the highest values again observed in Clone 2045. These results underscore the potential of clonal selection not only for productivity but also for ecosystem services like carbon capture, essential in the context of India's Nationally Determined Contributions under the Paris Agreement (MoEFCC, 2021).

CONCLUSION

It is concluded that significant variation was observed among the six *Eucalyptus* clones evaluated under high water table conditions. Clone 2045 recorded the highest survival, growth, biomass production, timber yield, and estimated carbon sequestration, while Clone 3020 also demonstrated consistently superior performance across most traits. In contrast, Clones 316 and 288 exhibited comparatively lower growth and productivity. Clone 413 showed poor self-pruning behaviour,

Table 5: Estimation of dry biomass and C- assimilation in *Eucalyptus* clones through allometric equations

Treatments	Dry Biomass (Mg ha^{-1})			C-stock (Mg C ha^{-1})			CO_2 assimilation (Mg ha^{-1})		
	AGB	BGB	Total	AGB	BGB	Total	AGB	BGB	Total
C-2135	118.4±2.5	30.8±0.6	149.2±3.1	53.3±1.1	14.8±0.3	68.1±1.4	177.6±3.7	49.3±1.0	226.9±4.7
C-3020	140.4±1.6	36.5±0.4	176.9±2.0	63.2±0.7	17.5±0.2	80.7±0.9	210.6±2.4	58.4±0.6	269.0±3.1
C-316	106.8±0.4	27.8±0.1	134.6±0.6	48.1±0.2	13.3±0.1	61.4±0.3	160.2±0.7	44.4±0.2	204.7±0.8
C-288	107.4±3.4	27.9±0.9	135.3±4.3	48.3±1.5	13.4±0.4	61.7±1.9	161.1±5.1	44.7±1.4	205.8±6.4
C-2045	152.1±3.9	39.5±1.0	191.6±4.9	68.4±1.8	19.0±0.5	87.4±2.2	228.1±5.8	63.3±1.6	291.3±7.4
C-413	132.4±0.3	34.4±0.1	166.9±1.4	59.6±0.1	16.5±0.1	76.1±0.2	198.6±0.5	55.1±0.1	253.7±0.6
SE± m	2.5	0.7	3.2	1.1	0.3	1.4	3.8	1.1	4.8
CD (p=0.05)	8.0	2.1	10.1	3.6	1.0	4.6	12.0	3.3	15.3

which may adversely affect stem quality. Based on overall performance, Clones 2045 and 3020 appear to be the most suitable genotypes for cultivation under high water table and seasonally waterlogged conditions in south-western Punjab.

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any research involving people as objects of research.

CONFLICT OF INTEREST

No conflict of interest exists among the authors of the research paper.

AUTHOR CONTRIBUTIONS

All authors have made substantial contributions: the conception and design of the study (AS, GPS), acquisition of data or analysis (IS, HK) and interpretation of data (IS, HK, BS, AS), drafting the article (IS, HK, AS, BS)

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