



RESEARCH ARTICLE

Interactive effects of plantlet height and hydroponic medium characteristics on growth of acclimatised pineapple (*Ananas comosus* (L.) Merr.) plantlets

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Abstract

The successful establishment of hydroponically acclimatised plantlets produced from pineapple axillary buds requires optimal substrate with water-related properties which regulate moisture availability, aeration, shoot growth and canopy formation. A hydroponic study was conducted to examine the synergistic effect of different levels of plantlet height and inert hydroponic substrates on physical and water-related characteristics of substrate and subsequent plant shoot growth responses and canopy formation. High water-holding capacity (100 %), high porosity (94.93 %), low bulk density (0.120 g/cm³) and substantial expansion volume (99.79 %) was shown by cocopeat, whereas pebbles exhibited a high bulk density (5.373 g/cm³) alongside an enhanced coarse particle distribution (3.556 mm) and pebbles exhibited the highest air capacity (30.30 %). Increased height, leaf production, leaf area and shoot biomass were consistently greater produced by taller pineapple plantlets. Among the hydroponic medium tested, superior growth occurred in cocopeat, which favoured biomass accumulation, whereas pebble medium supported the shoot elongation response due to aeration. Sufficient initial plantlet vigour and properties of substrates such as balanced water retention and aeration indicated significant difference in interaction effects. Principal component analysis (PCA) yielded ten independent components which accounted for 99.8 % of the total variance. Among the first three principal components, PC1 had the highest variability (85.7 %). The correlation analysis revealed a strong and statistically significant positive relationship among most traits whereas leaf area on 60th day exhibited significant negative correlations with almost all traits. Overall, the findings reveal that taller plantlets grown in cocopeat as hydroponic medium are optimum for production of good quality pineapple plantlets.

Keywords: acclimatisation; biomass accumulation; hydroponic medium; leaf area; morphological growth; plant vigour; substrate properties

Introduction

In pineapple (*Ananas comosus* (L.) Merr.), rapid multiplication of planting material is achieved by stem sectioning yet during early establishment plantlets often exhibit poor adaptation due to reduced root functionality and sensitivity to environmental fluctuations (1). Precise control of moisture supply, nutrient availability and root oxygenation has emerged as a promising approach for improving acclimatisation efficiency. However, in hydroponic systems water retention, aeration, nutrient buffering and root anchorage provided by the substrate play a crucial role in determining the successful establishment of plantlets (2).

Physical structure of the growing medium is the key determinant of crop performance in hydroponics. The balance between root hydration and oxygen availability is determined by the water relation characteristics of hydroponic medium like bulk density, particle density, porosity, air-filled pore space and water holding capacity (3, 4). Root initiation and nutrient absorption are promoted by moderate water retention and high porosity of substrate; however, diffusion of oxygen and root activity may be reduced by excessive moisture retention (3). Gradual nutrient buffering was enabled by high water holding capacity and cation

exchange ability of organic substrates such as cocopeat. In contrast, structural stability and aeration was provided by mineral substrates such as sand or gravel but lower nutrient retention capacity (5).

Commonly available, low-cost medium differing widely in aeration, water retention and nutrient buffering properties such as cocopeat, sand, gravel and pebbles were selected in this study (6). These substrates were evaluated to identify the optimal root-zone conditions for the rapid establishment of pineapple plantlets during hydroponic acclimatisation. Besides substrate properties, another crucial factor determining the success of acclimatisation is initial plantlet size (7). During hydroponic acclimatisation, larger plantlets have enhanced structural integrity, increased storage of assimilates, improved photosynthetic capacity in leaf and enabling faster canopy expansion.

The majority of hydroponic research has focused on vegetable crops such as tomato (8), lettuce (9) and strawberry (10) with limited information for fruit crops like pineapple especially regarding root and shoot morphological responses during early hydroponic acclimatisation. For scaling up propagation systems and ensuring uniform nursery performance, optimum substrate - plantlet combinations need to be identified. In this context present

study investigates the synergistic effects of initial plantlet height and hydroponic substrate properties on morphological development of bud induced pineapple plantlets under hydroponic cultivation. This study evaluates root growth, elongation of shoot, leaf formation, accumulation of biomass and related traits to determine the most suitable substrate plantlet combination for robust early development and successful acclimatisation.

Materials and methods

Collection of planting material

Pineapple cv. Mauritius plants with good quality fruits were tagged 10 days before harvest. After harvest, the plants were uprooted and leaves were removed from the stem. The axillary buds on the stem were exposed and the stems were placed in the soil under polyhouse. Dormant buds on the pineapple stems were induced and after 90 days plantlets were detached from stem sections and obtained plantlets were categorised according to their height before acclimatisation under hydroponics. The graded plantlets were evaluated for their adaptability and growth response when grown using different hydroponic medium.

Preparation of hydroponic solution

The hydroponic solution was prepared from commercial stock formulation, Green Loop LEAFY – 200 consisting of two stock solutions A and B (purchased from Amazon - online platform). Concentrated stock solution was diluted with water to obtain the required working concentration for solutions. The solution contained the following macro- and micronutrients: 23 % of calcium (Ca), 23 % of nitrogen (N), 7 % of phosphorus (P), 32 % of potassium (K), 32 % of magnesium (Mg) and trace elements such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), chlorine (Cl) and sodium (Na) each at a concentration of 0.7 % which ensures adequate nutrition throughout hydroponics. Perforated germinating trays (portrays) containing net pots filled with hydroponic medium were placed in plastic trays containing nutrient solution. Pineapple plantlets of varying heights were placed in the net pots

Experimental location

Pineapple plantlets of the Mauritius cultivar were obtained from Kanyakumari tracts of Tamil Nadu, India, a major pineapple growing region where year-round planting is done. This acclimatisation of plantlets produced from stem sectioning under hydroponics was conducted from October–December 2025 under controlled conditions. During the experimentation period, temperature of 28–30 °C, relative humidity of 70 % and photoperiod of 14 hr of light and 10 hr of dark was maintained under controlled conditions.

Treatment details and experimental design

Factorial completely randomized design (FCRD) with two factors was followed. Factor A plantlet height with four levels such as P₁: 2–5 cm, P₂: 6–8 cm, P₃: 9–11 cm, P₄: 12–15 cm whereas factor B hydroponic medium with five levels such as cocopeat (M₁), sawdust (M₂), sand (M₃), pebbles (M₄) and no medium (M₅). The interaction of these two factors yielded 20 treatments which were replicated three times. Experimental procedures followed and observations recorded are described below.

Water relation characteristics of hydroponic medium

Water relation characteristics of hydroponic medium such as bulk

density and particle density were measured using the Blake and Hartge method (11). Bulk density of the hydroponic medium was measured by oven drying a known volume of medium at 105 °C and calculated using the formula (12):

$$\text{Bulk density} \left(\frac{\text{g}}{\text{cm}^3} \right) = \frac{\text{Dry mass (g)}}{\text{Volume (cm}^3\text{)}}$$

Particle density was measured using the formula:

$$\text{Particle density} \left(\frac{\text{g}}{\text{cm}^3} \right) = \frac{\text{Oven dry mass (g)}}{\text{Volume of solids (cm}^3\text{)}}$$

Porosity was measured using the formula:

$$\text{Porosity (\%)} = \left(1 - \frac{\text{Bulk density}}{\text{Particle density}} \right) \times 100$$

Water holding capacity of hydroponic medium was determined by saturating with water, draining excess and weighing the wet sample, followed by oven drying and weighing the oven-dried sample (12). It is calculated using the formula:

$$\text{Water holding capacity (\%)} = \frac{\text{Wet weight - Dry weight}}{\text{Dry weight}} \times 100$$

Water in air dry substrate was calculated by weighing the air-dry sample followed by oven drying and reweighing and calculating the difference (12).

Water in air dry substrate = Weight of air dry medium - Weight of oven dry sample

Particle size distribution, volume of expansion and air capacity of hydroponic medium was calculated according to Morgan (12). Particle size distribution was determined via sieve analysis. Moisture content of hydroponic medium was calculated by weighing the initial mass and oven drying the medium (13).

Hydroponic parameters

Leaf area of pineapple plantlets after acclimatisation was measured using image analysis tool and expressed in square centimetre (cm²) (14). Number of new leaves produced on the 30th and 60th day after acclimatisation was counted and expressed in numbers.

Growth parameters

Shoots were weighed immediately after destruction and weighed after drying in oven. Plantlets of various heights were used and variation in plantlet height were observed on 30th and 60th day after hydroponic adaptation and expressed in centimetres (cm) (15).

Statistical analysis

The obtained data were statistically analysed using GRAPES (General R-based Analysis Platform for Experimental Statistics) software 1.1.0 developed by Dr. Pratheesh P Gopinath, Assistant Professor, Agricultural Statistics, Kerala Agricultural University (16). Graphical representation of the data was generated using Origin Pro, Version 2024 SR1 (17).

Results and Discussion

Bulk density, particle density and total porosity

Pebbles (M₄ - 5.373) followed by sand recorded highest bulk

density whereas lower as well as statistically similar values were recorded by cocopeat and sawdust. Similarly for particle density, maximum value was recorded by pebbles (M4 - 3.556) followed by sand while lower particle densities were exhibited by cocopeat (M1 - 0.629) as well as sawdust. In contrast, the highest porosity was exhibited by sawdust (M2 - 99.56 %) followed by sand and cocopeat (M1 - 94.93 %) while extremely low porosity was exhibited by pebbles (M4 - 2.21 %) (Fig. 1).

Root zone aeration and water retention in hydroponic system was strongly influenced by the structural differences between organic and inorganic medium as evidenced by observed variation in bulk density, particle density and total porosity. Desirable physical characteristics for hydroponic plantlet acclimatisation such as enhanced root penetration, oxygen diffusion were promoted by lower bulk and particle densities of cocopeat and sawdust which indicates their high organic composition and loose structure (18, 19). Root improvement and hydroponic acclimatisation was supported by favourable physical properties such as low density and high porosity which is present in organic medium such as cocopeat (20, 21). In contrast, sand and pebble recorded very high densities which indicate compact, structure dominated by mineral with decreased water buffering capacity. Although pebbles provide excellent mechanical stability, their extremely low porosity results in poor moisture retention, limiting root hydration and nutrient availability (21,22). Plant growth and establishment can be enhanced by maintaining a balanced air-water ratio in rhizosphere using a moderate density hydroponic medium as demonstrated in previous studies on soilless culture substrates (5, 23). The current investigation reveals that organic substrates provide more favourable physical environment as compared to mineral hydroponic medium.

Water holding capacity, moisture content and volume of expansion

Among various hydroponic medium, water related parameters such as water holding capacity, moisture content and volume of expansion differed significantly. Higher water holding capacity was recorded by cocopeat (M1 - 100 %) followed by sawdust while lower capacity was recorded by sand as well as pebbles. A similar trend was observed with volume of expansion; maximum expansion was exhibited by cocopeat (M1 - 99.79 %) followed by sawdust whereas negligible expansion was exhibited by sand which is on par with pebbles. Significant differences were observed with cocopeat having highest moisture (M1 - 71.68 %) which is followed by sawdust, sand and pebbles (Fig. 2).

In hydroponic system, efficient absorption and gradual release of water is enabled in cocopeat due to its specific attributes such as fibrous structure, rich organic matter content and large internal pore space. Cocopeat has superior water holding capacity, expansion potential and moisture retention. Pineapple plantlet acclimatisation and growth were supported due to its ability to maintain stable root zone hydration and nutrient availability. Due to faster drainage and structural decomposition, sawdust exhibited a higher water holding capacity and lower moisture content (24). In contrast, very low expansion and moisture retention was exhibited by sand and pebble reflecting its limited pore connectivity and coarse mineral composition which restricts storage of water and increased risk of rapid drying around roots (25). Present findings suggest that more suitable substrates such as cocopeat and sawdust maintain favourable moisture dynamics during acclimatisation

of pineapple plantlets under hydroponics.

Water in air dry substrate, particle size distribution and air capacity

The characteristics such as water in air dry substrates, particle size distribution and air capacity differs significantly. Higher and statistically similar water in air dry substrate was recorded with sawdust (M2 - 25.32 %) and sand followed by cocopeat and lowest value was recorded by pebbles (M4 - 5.03 %). Greater particle size was recorded with pebbles followed by cocopeat (M1 - 7.97) while significantly smaller particle fractions was recorded with sawdust and sand. In contrast, higher air capacity was shown in pebbles (M4 - 30.30 %) followed by cocopeat and sand and lowest air capacity was recorded by sawdust (Fig. 3). Root zone aeration and moisture balance were influenced by the differences in the inherent structure of hydroponic medium. Pebbles exhibited higher air capacity due to coarse texture and large inter particle spaces which promotes oxygen diffusion and rapid drainage, but water retention was limited (26). During hydroponic acclimatisation, balance aeration was maintained along with moderate moisture retention which creates favourable air water equilibrium for root activity due to intermediate particle size and fibrous structure of cocopeat (27). More water was retained in the air-dry state yet their lower air capacity in sawdust. It may be due to restricted pore connectivity and reduced oxygen availability; it may impede respiration of root if excess moisture persists. Nutrient diffusion, root metabolism and plant establishment under hydroponic cultivation is regulated by the balance between aeration and water availability due to physical characteristics of hydroponic medium such as particle size distribution and pore geometry (28).

Leaf growth dynamics

Plantlet height and hydroponic medium significantly influence number of new leaves and leaf area of pineapple plantlets at 30 and 60 days after hydroponic acclimatisation. One month after acclimatisation, a greater number of new leaves were produced by taller plantlets (P4), particularly with cocopeat (M1 - 2.91), followed by pebbles (M4 - 2.81) and sand (M3 - 2.63) while fewer leaves were produced by pineapple plantlets grown without medium (M5) for smaller plantlets (P1 - 0.59). Better performance was shown by cocopeat (2.38) and pebbles (2.05) compared with other hydroponic medium. Similarly, after 30 days of acclimatisation, with increase in plantlet height, leaf area increased (Fig. 4a). Maximum leaf area was recorded in P4 × M1 (24.62 cm²), followed by P4 × M4 (24.39 cm²) while minimum leaf area was recorded in P1 × M5 (17.58 cm²). Overall, among hydroponic medium, greater leaf area was produced by cocopeat (23.10 cm²) (Table 1). Similar trend was observed 60 days after acclimatisation (Table 2). More leaves were produced in P4 × M1 (6.89), closely followed by P4 × M4 (6.72) and P4 × M3 (6.48), whereas less number of leaves were produced in plantlets grown without medium (P1 × M5: 4.21). In case of hydroponic medium, highest mean leaf number was produced in cocopeat (6.28), followed by pebbles (5.98), sand (5.70), sawdust (5.39) and without medium (4.78).

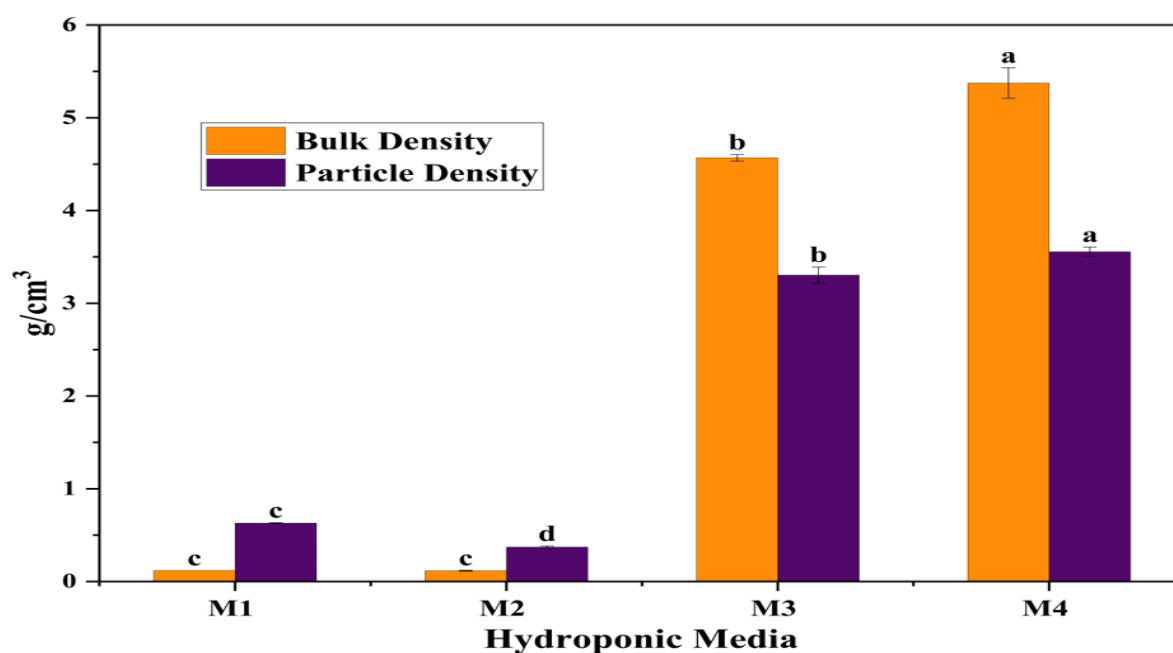
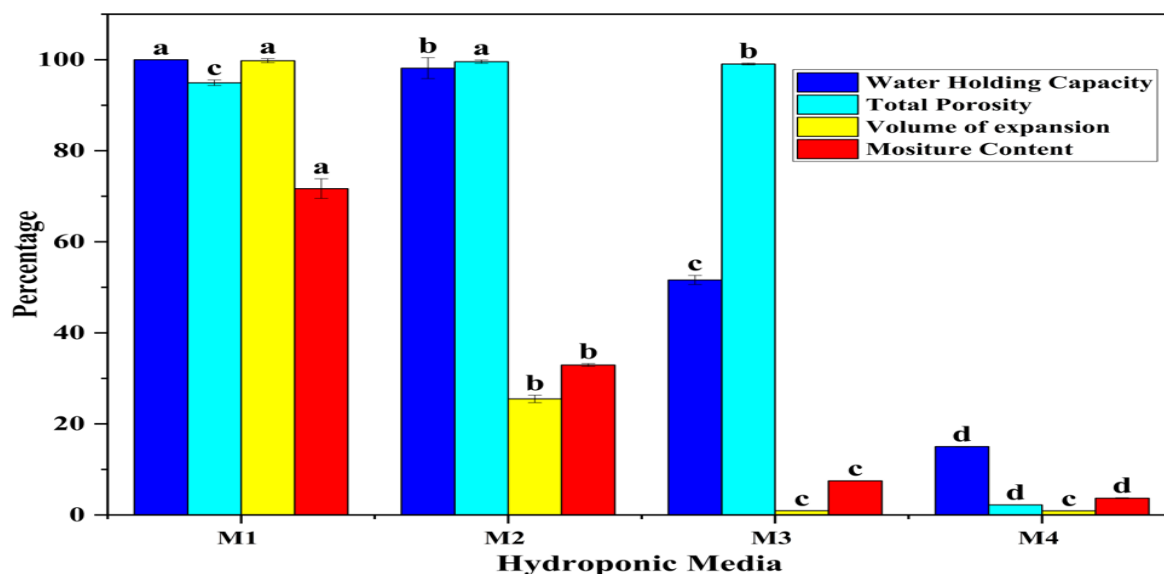
During transformation from *in vitro* environments to *ex vitro* or soilless environment, pineapple plantlets require advanced physiological adaptation for survival and development for acclimatisation under hydroponic conditions. Due to the fluctuations in humidity, light intensity and nutrition availability,

Table 1. Effect of hydroponic medium on leaf area 30th day after hydroponic acclimatisation

Treatments	Leaf area on 30 th day					Mean
	M ₁	M ₂	M ₃	M ₄	M ₅	
P ₁	21.28 ± 0.283 ^{fg}	18.75 ± 0.288 ^{kl}	19.67 ± 0.268 ^{ij}	20.53 ± 0.793 ^{ghi}	17.58 ± 0.098 ^m	19.56 ± 0.200 ^d
P ₂	22.36 ± 0.345 ^{de}	19.43 ± 0.820 ^{jk}	19.82 ± 0.051 ^{hij}	20.68 ± 0.243 ^{gh}	17.94 ± 0.423 ^{lm}	20.05 ± 0.248 ^c
P ₃	24.15 ± 0.351 ^{abc}	21.92 ± 0.000 ^{ef}	23.19 ± 0.397 ^{cd}	23.54 ± 0.850 ^{bc}	18.47 ± 0.716 ^{lm}	22.25 ± 0.319 ^b
P ₄	24.62 ± 0.514 ^a	22.84 ± 0.598 ^{cde}	23.71 ± 0.917 ^{abc}	24.39 ± 0.839 ^{ab}	22.11 ± 0.820 ^{ef}	23.53 ± 0.184 ^a
Mean	23.1 ± 0.245 ^a	20.74 ± 0.259 ^d	21.6 ± 0.299 ^c	22.29 ± 0.277 ^b	19.03 ± 0.290 ^e	21.35
	P		M		P × M	
SED	0.204		0.228		0.457	
CD at 5 %	0.413		0.462		0.923	

Table 2. Effect of hydroponic medium on leaf area 60th day after hydroponic acclimatisation

Treatments	Leaf area on 60 th day					Mean
	M ₁	M ₂	M ₃	M ₄	M ₅	
P ₁	61.30 ± 0.300 ^o	76.50 ± 0.300 ^f	57.20 ± 0.200 ^r	72.60 ± 0.200 ^h	82.30 ± 0.300 ^b	69.98 ± 9.711 ^a
P ₂	60.30 ± 0.200 ^p	68.30 ± 0.200 ^k	58.67 ± 0.306 ^q	77.30 ± 0.300 ^e	80.60 ± 0.200 ^c	69.03 ± 9.102 ^b
P ₃	62.80 ± 0.300 ⁿ	70.80 ± 0.300 ^j	55.50 ± 0.300 ^s	69.30 ± 0.300 ^j	84.50 ± 0.300 ^a	68.58 ± 9.968 ^c
P ₄	64.50 ± 0.300 ^m	66.20 ± 0.200 ^l	54.00 ± 0.200 ^t	74.30 ± 0.300 ^g	78.80 ± 0.300 ^d	67.56 ± 8.869 ^d
Mean	62.23 ± 1.674 ^d	70.45 ± 4.031 ^c	56.34 ± 1.847 ^e	73.38 ± 3.030 ^b	81.55 ± 2.212 ^a	68.79
	P		M		P × M	
SED	0.098		0.22		0.457	
CD at 5 %	0.199		0.445		0.923	

**Fig. 1.** Bulk density and particle density of hydroponic medium.**Fig. 2.** Water holding capacity, total porosity, volume of expansion and moisture content of hydroponic medium.

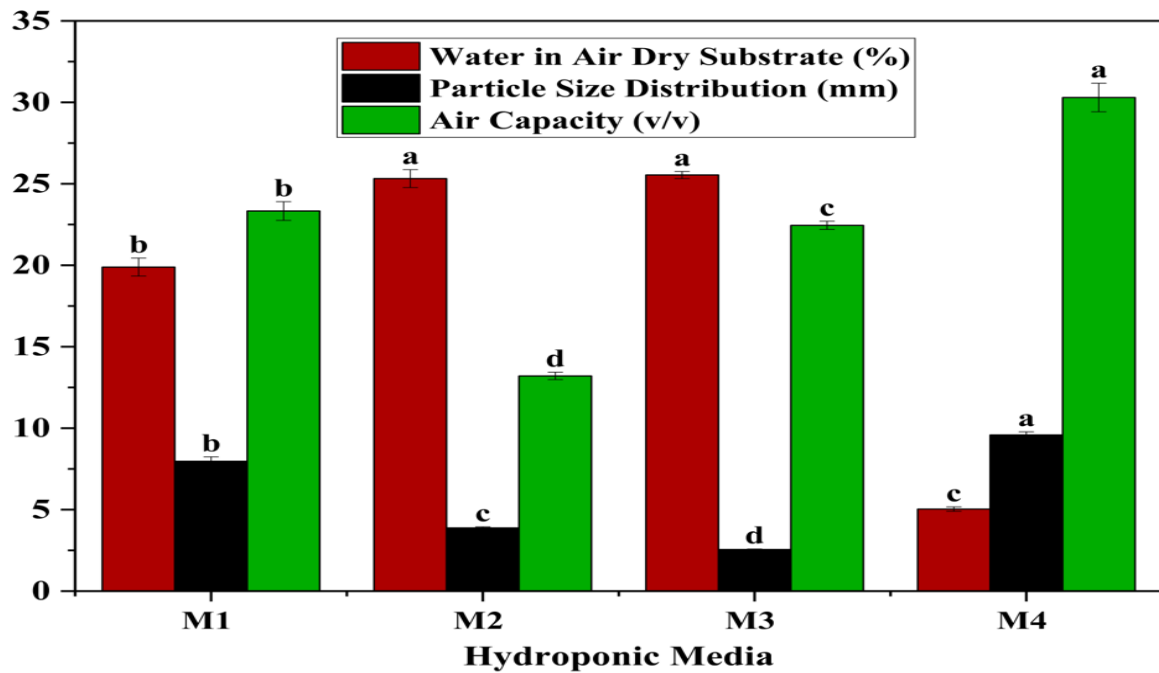


Fig. 3. Water in air dry substrate, particle size distribution and air capacity of hydroponic medium.

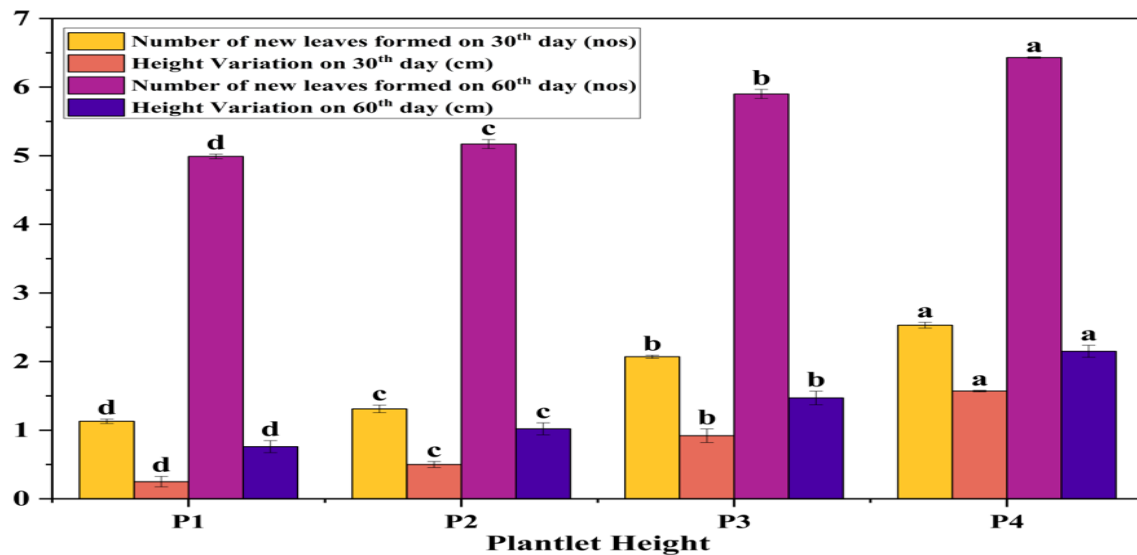


Fig. 4a. Effect of plantlet height on number of new leaves produced and height variation at 30th and 60th day after acclimatisation.

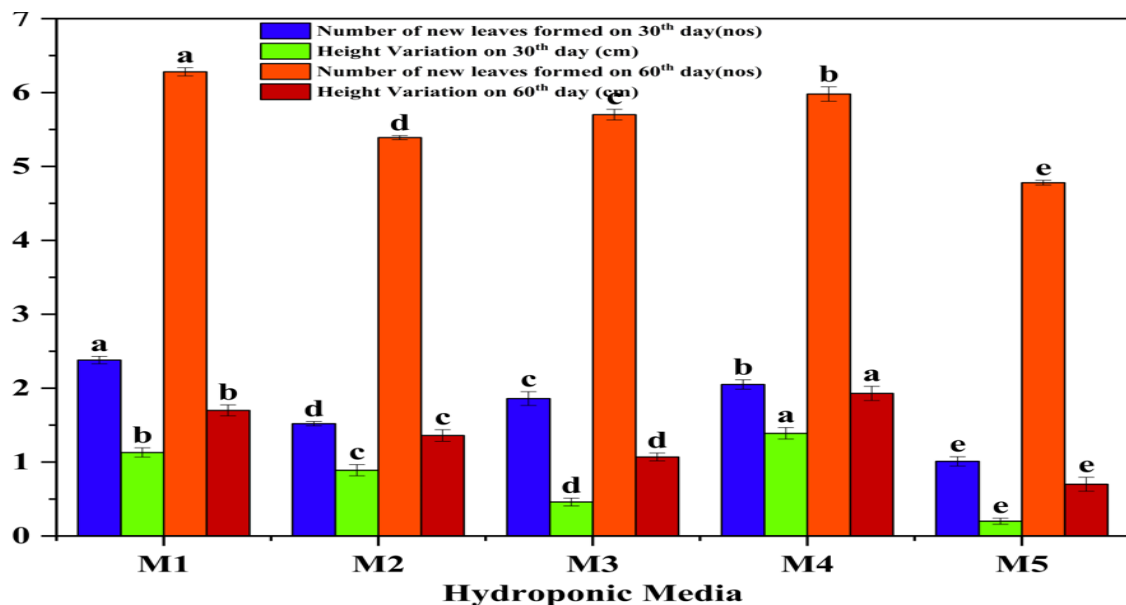


Fig. 4b. Effect of hydroponic medium on number of new leaves produced and height variation at 30th and 60th day after acclimatisation.

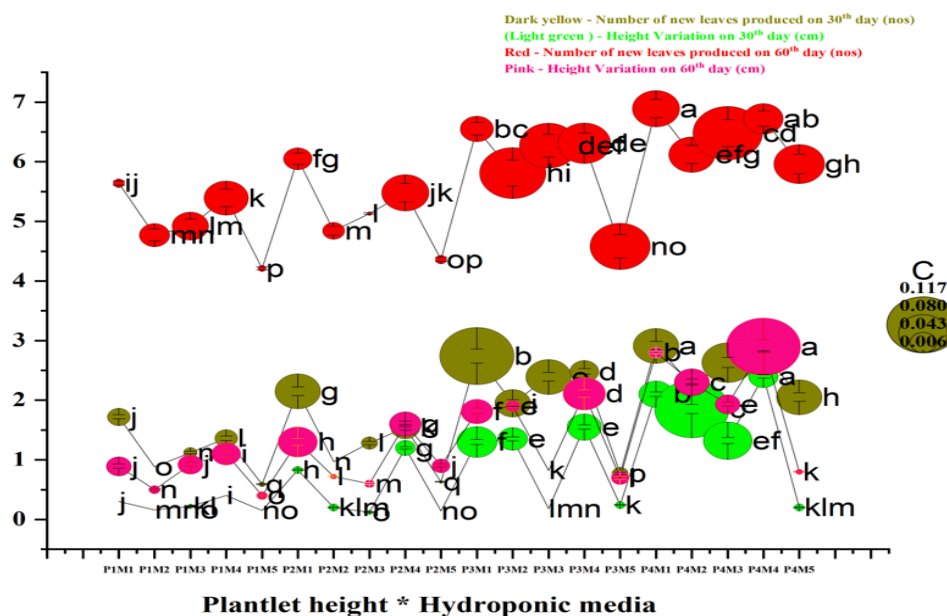


Fig. 4c. Effect of plantlet height and hydroponic medium on number of new leaves produced and height variation at 30th and 60th day after acclimatisation.

stress is induced in acclimatised plantlets which ultimately affects water relations, photosynthetic metabolism and growth (29, 30). Pineapple plantlets alter their mesophyll structure, cuticular properties and stomatal behaviour to adapt to changed environment and to optimise the water use efficiency and carbon uptake (31). Duration of new leaf production, number of new leaves produced and leaf area expansion in pineapple plantlets is affected by plantlet height and hydroponic medium. Overall productivity of the plantlet is determined by the temporal sequence of leaf initiation, expansion and functional development.

Frequency of leaf emergence, the cumulative number of leaves emerged and the leaf area depends on the exposed surface area for photosynthesis (32). Leaf growth dynamics of pineapple plantlets are influenced by the plant characteristics such as developmental stage of the plant, initial growth vigour as well as external factors such as light, nutrient supply and water status (33). Plantlets possessing increased reserves of carbohydrates and nutrients from the *in vitro* stage make the acclimatised plantlets more physiologically active to initiate leaf growth. Due to more vigorous root - shoot balance and higher photosynthetic activity higher rate of leaf formation was promoted in larger plantlets (34).

Enhanced water availability and nutrition under hydroponics along with greater leaf proliferation was driven by well developed, leaf growth and meristem activity. Taller plantlets generates more number of new leaves due to the fact that greater initial biomass resulted from continued meristematic activity and enhanced photosynthetic activity in leaf expansion. Overall elongation and increased photosynthetic activity were promoted by leaf area which signifies the cumulative benefits of physiological status as well as ideal condition in the root zone of pineapple plantlets (35, 36). Larger plantlets produce larger leaf laminae due to higher rate of cell division and expansion results in well developed vascular systems and leaf primordia.

Earlier adaptation of plantlets under hydroponic system was attributed by the hydroponic medium such as coco peat and pebbles which have superior aeration and water holding capacity which ultimately leads to quicker leaf initiation (37). Quick

establishment is fostered by porous and well aerated hydroponic medium. More average leaf production is due to the consistent nutrient absorption and moisture retaining ability of cocopeat medium (38). Similar results emphasised by characteristics of hydroponic medium like providing anchorage, maintaining water and nutrient balance which act as nutrient source (39).

In hydroponic tomatoes, root growth was promoted and leaf area was developed by the beneficial physical characteristics of cocopeat (40). Root development and hydraulic conductivity critically influence success of acclimatisation. Root morphogenesis and formation of effective vascular connections was aided by using hydroponic medium which enhances root oxygenation and moisture availability. Photosynthesis and shoot growth were sustained by promoting essential nutrient and water uptake (41).

In addition to the interaction effect, vigour of plantlet at establishment and physical characteristics of substrate influence the rate and degree of leaf growth. Regulation of hormones such as cytokinin, auxin, carbon uptake and water availability was influenced by the rooting environment and plantlet size ultimately leading to greater leaf production and expansion. Dynamics of leaf growth under hydroponics were controlled by both internal reserves and external environments which is coordinated by water nutrient availability, hormonal signalling and carbon adsorption essential for leaf initiation and expansion (33). Selection of appropriate plantlets and medium is essential for maximising growth and photosynthetic efficiency. This is influenced by the synergistic effect of plantlet developmental stage and hydroponic medium. In comparison to soil based conventional methods, hydroponics enhances environmental control through nutrient delivery, aeration and moisture availability. These factors will reduce the duration taken for emergence of new leaves; increased number of leaves produced and expanded the area of leaves produced (37, 42). The success of pineapple plantlet acclimatisation is facilitated by physiological transitions, enhanced photosynthetic performance and improved root development.

Height variation

Plantlet height, inert medium and their interaction significantly

influenced shoot growth and biomass accumulation of hydroponically acclimatised pineapple plantlets after 30 and 60 days respectively. One month after hydroponic acclimatisation, increase in height of plantlets was observed with taller plantlets (P4) when grown with pebbles (M4: 2.4 cm) followed by cocopeat (M1: 2.1 cm) (Fig. 4a) whereas reduced growth of plantlets was recorded when smaller plantlets grown without medium (M5) (Fig 4b).

A trend similar to height variation was observed with shoot fresh and dry weight after 30 days with more biomass accumulation in P4 × M1 (3.92 g fresh; 0.91 g dry) and P4 × M4 (3.75 g fresh; 0.88 g dry) whereas less biomass was produced when smaller plantlets were grown without medium (Fig. 4c). After 60 days of hydroponic acclimatisation, height increment is more evident. Increased height variation was observed in P4 × M4 (2.9 cm) closely followed by P4 × M1 (2.8 cm) whereas reduced height increment with M5 treatment. Increased shoot fresh weight after 30 and 60 days observed with P4 × M1 (9.92 g) and P4 × M4 (9.48 g), while decreased weight with P1 × M5 (3.41 g) (Table 3 and 4). Similarly maximum dry weight was observed in P4 × M1 (2.91 g), followed by P4 × M4 (2.83 g) and P4 × M3 (2.67 g) while minimum in smaller plantlets grown without medium (Table 5 and 6). Overall mean values suggest that highest biomass and growth was

consistently produced when grown with coco-peat medium followed by pebbles and sand, while lowest with plantlets grown without medium.

Hydroponic medium and plantlet height influence the varied shoot biomass and height variation.

Taller plantlets utilised more nutrients and developed faster. Under soilless cultivation, shoot elongation was determined by the initial plantlet vigour (43). Healthy growth and appropriate nutrient intake were indicated by the complete transformation of raw biomass into structural tissue indicated by increase in dry weight. A favourable correlation established between initial plantlet vigour and biomass accumulation indicates consistent increase in plantlet height (P3 and P4).

Similarly, relationship between enhanced shoot dry matter in hydroponics and increased capacity for carbon uptake and nutrient uptake efficiency also established (44). Improved photosynthetic uptake and assimilate partitioning of assimilates to shoot tissue under suitable conditions of fertiliser and water availability causes a consistent rise in shoot biomass. A well-balanced nutritional composition in hydroponic medium enhances the shoot biomass accumulation in pineapple plantlets

Table 3. Effect of hydroponic medium on shoot fresh weight on 30th day after hydroponic acclimatization

Treatments	Shoot fresh weight on 30 th day					
	M ₁	M ₂	M ₃	M ₄	M ₅	Mean
P ₁	2.15 ± 0.046 ⁱ	0.92 ± 0.010 ^o	1.28 ± 0.015 ^m	1.73 ± 0.015 ^k	0.58 ± 0.000 ^p	1.33 ± 0.580 ^d
P ₂	2.64 ± 0.087 ^g	1.12 ± 0.026 ⁿ	1.56 ± 0.046 ^j	1.94 ± 0.015 ^j	0.64 ± 0.021 ^p	1.58 ± 0.713 ^c
P ₃	3.67 ± 0.154 ^b	2.39 ± 0.046 ^h	3.11 ± 0.026 ^e	3.28 ± 0.129 ^d	0.87 ± 0.015 ^o	2.66 ± 1.028 ^b
P ₄	3.92 ± 0.171 ^a	2.81 ± 0.046 ^f	3.46 ± 0.046 ^c	3.75 ± 0.057 ^b	2.47 ± 0.057 ^h	3.28 ± 0.580 ^a
Mean	3.1 ± 0.766 ^a	1.81 ± 0.843 ^d	2.35 ± 0.989 ^c	2.68 ± 0.898 ^b	1.14 ± 0.810 ^e	2.21
	P		M		P × M	
SED	0.025		0.028		0.057	
CD at 5 %	0.051		0.057		0.115	

Table 4. Effect of hydroponic medium on shoot fresh weight on 30th day after hydroponic acclimatization

Treatments	Shoot fresh weight on 60 th day					
	M ₁	M ₂	M ₃	M ₄	M ₅	Mean
P ₁	6.42 ± 0.226 ⁱ	4.26 ± 0.051 ^m	5.14 ± 0.026 ^j	5.97 ± 0.216 ^k	3.41 ± 0.108 ^o	5.04 ± 1.146 ^d
P ₂	7.56 ± 0.015 ^g	4.53 ± 0.180 ⁿ	5.68 ± 0.180 ^k	6.08 ± 0.154 ^j	3.65 ± 0.046 ^{no}	5.5 ± 1.390 ^c
P ₃	9.13 ± 0.273 ^c	6.73 ± 0.262 ^h	8.21 ± 0.262 ^e	8.76 ± 0.262 ^d	3.87 ± 0.171 ⁿ	7.34 ± 1.997 ^b
P ₄	9.92 ± 0.108 ^a	7.84 ± 0.262 ^f	9.05 ± 0.087 ^{cd}	9.48 ± 0.309 ^b	7.29 ± 0.021 ^g	8.72 ± 1.042 ^a
Mean	8.26 ± 1.429 ^a	5.84 ± 1.578 ^d	7.02 ± 1.728 ^c	7.57 ± 1.653 ^b	4.56 ± 1.662 ^e	6.65
	P		M		P × M	
SED	0.068		0.076		0.153	
CD at 5 %	0.138		0.154		0.308	

Table 5. Effect of hydroponic medium on shoot dry weight on 30th day after hydroponic acclimatization

Treatments	Shoot dry weight on 30 th day					
	M ₁	M ₂	M ₃	M ₄	M ₅	Mean
P ₁	0.53 ± 0.010 ^j	0.34 ± 0.006 ^m	0.42 ± 0.010 ^k	0.48 ± 0.021 ^j	0.23 ± 0.010 ^p	0.4 ± 0.110 ^d
P ₂	0.67 ± 0.021 ^f	0.37 ± 0.447 ^j	0.45 ± 0.507 ^k	0.51 ± 0.260 ^j	0.26 ± 0.860 ^o	0.45 ± 0.144 ^c
P ₃	0.86 ± 0.580 ^b	0.58 ± 0.000 ^h	0.74 ± 0.010 ^e	0.79 ± 0.036 ^d	0.29 ± 0.010 ⁿ	0.65 ± 0.211 ^b
P ₄	0.91 ± 0.026 ^a	0.72 ± 0.026 ^e	0.82 ± 0.015 ^c	0.88 ± 0.010 ^b	0.63 ± 0.010 ^g	0.79 ± 0.109 ^a
Mean	0.74 ± 0.159 ^a	0.5 ± 0.164 ^d	0.61 ± 0.185 ^c	0.67 ± 0.184 ^b	0.35 ± 0.169 ^e	0.57
	P		M		P × M	
SED	0.006		0.007		0.014	
CD at 5 %	0.012		0.014		0.027	

Table 6. Effect of hydroponic medium on shoot dry weight on 60th day after hydroponic acclimatization

Treatments	Shoot dry weight on 60 th day					
	M ₁	M ₂	M ₃	M ₄	M ₅	Mean
P ₁	1.73 ± 0.036 ^h	0.95 ± 0.010 ^j	1.28 ± 0.026 ^k	1.57 ± 0.036 ^j	0.83 ± 0.021 ⁿ	1.27 ± 0.360 ^d
P ₂	2.14 ± 0.087 ^f	0.99 ± 0.036 ^j	1.42 ± 0.026 ^j	1.64 ± 0.072 ^j	0.86 ± 0.015 ^{mn}	1.41 ± 0.478 ^c
P ₃	2.79 ± 0.098 ^b	1.88 ± 0.026 ^g	2.47 ± 0.010 ^d	2.54 ± 0.046 ^d	0.92 ± 0.000 ^{lm}	2.12 ± 0.695 ^b
P ₄	2.91 ± 0.000 ^a	2.36 ± 0.051 ^e	2.67 ± 0.103 ^c	2.83 ± 0.072 ^{ab}	2.08 ± 0.021 ^f	2.57 ± 0.323 ^a
Mean	2.39 ± 0.507 ^a	1.55 ± 0.626 ^d	1.96 ± 0.644 ^c	2.15 ± 0.577 ^b	1.17 ± 0.550 ^e	1.84
	P		M		P × M	
SED	0.018		0.02		0.041	
CD at 5 %	0.037		0.041		0.083	

(45). Physical characteristics of hydroponic medium such as water holding capacity and aeration facilitates increased nutrient assimilation, root growth and decreased physiological stress ultimately shoot extension and accumulation of biomass was triggered (36, 38).

Due to inadequate mechanical support and reduced root zone aeration in the treatment which is grown without hydroponic medium resulted in poor growth and impaired shoot development. Maximum pineapple growth performance was observed by the usage of good quality starting material and environment displays better shoot development dynamics by taller plantlets. Greater diversity in plantlet height and biomass accumulation is encouraged by using larger plantlets and nutrient supporting medium like cocopeat and pebbles. For sustainable soilless cultivation, these factors should be optimised for pineapple proliferation efficiency (42, 38). Stomatal opening throughout the day may accelerate the growth of these crassulacean acid metabolism (CAM) plantlets under hydroponic conditions. Better nutrient uptake and water availability must be ensured for successful hydroponics (46). Increased plant biomass resulted by improving the water potential, promoting stomatal opening and enhancing the rate of carbon uptake through Rubisco (47).

Principal component analysis

Principal component analysis (PCA) yielded ten independent components, which accounted for 99.8 % of the total variance. Major variation among various traits was explained by PC1 with positive correlation from leaf area on 30th day, number of new leaves produced on 30th and 60th day, shoot fresh and dry weight on 30th and 60th day which indicates its contribution for the enhanced biomass performance. On the other hand, leaf area on 60th day had a strong positive correlation in principal component 1 and 2 whereas PC 3 shows positivity with leaf area on 30th day and negativity with height variation on 30th and 60th day (Fig. 5). Overall better performance among the observations was shown by P4M1, P4M4, P3M4 and P3M1, while negative principal component score was revealed by P1M5, P2M5 and P3M5 which indicates lower performance of such traits. Overall principal component analysis indicates that principal component 1 effectively separates better and lower performance of traits based on growth factors.

Correlation analysis

Leaf area on 30th day had a strong positive and had a significant correlation with number of new leaves produced on 30th ($r = 0.974$) and 60th ($r = 0.967$), shoot fresh weight on 30th ($r = 0.974$) and 60th ($r = 0.968$), shoot dry weight on 30th ($r = 0.973$) and 60th ($r = 0.973$), height variation on 30th ($r = 0.756$) and 60th ($r = 0.787$). On the other hand, leaf area on 60th day have significant negative correlation

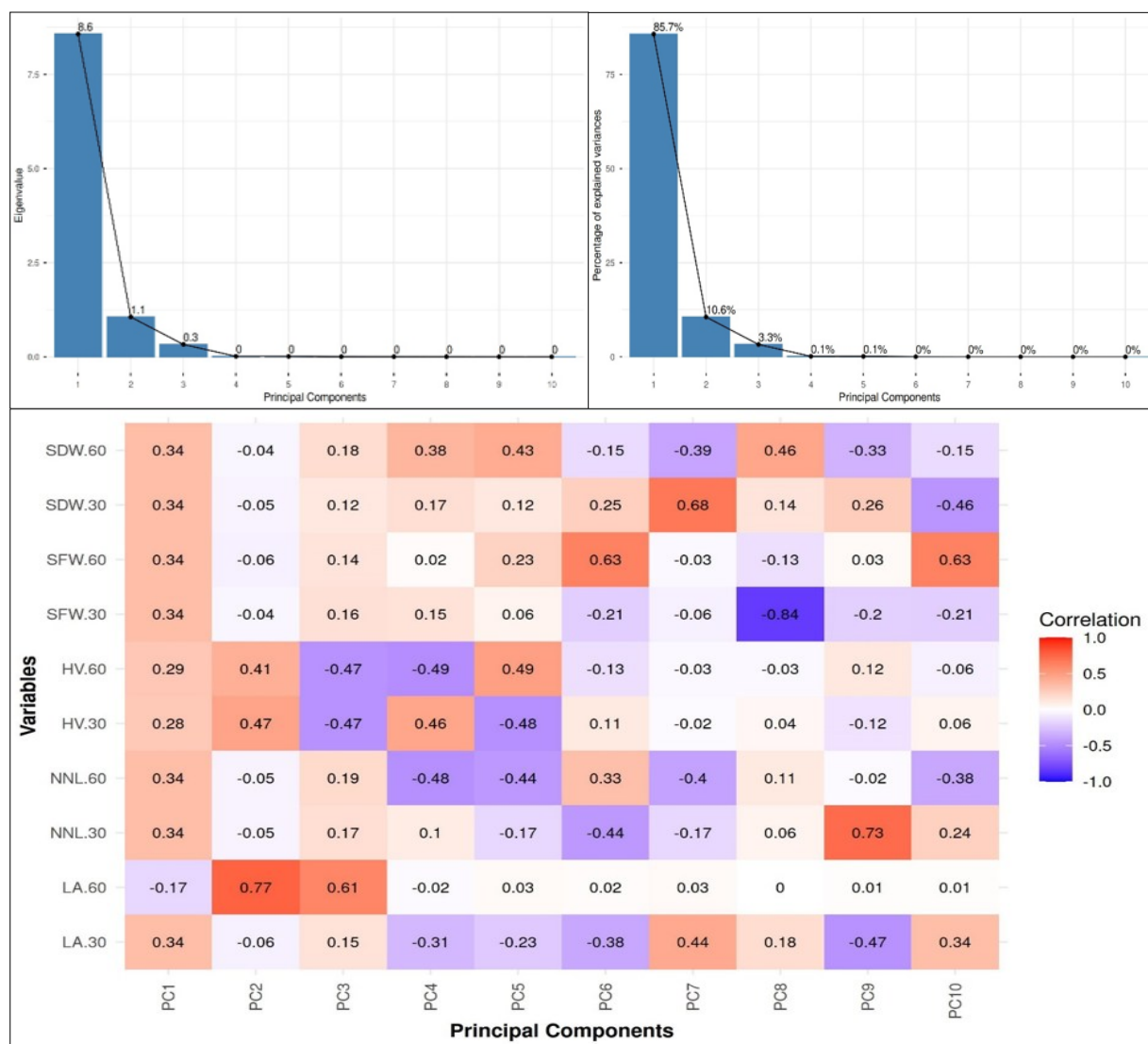


Fig. 5. Heat map of principal component analysis.

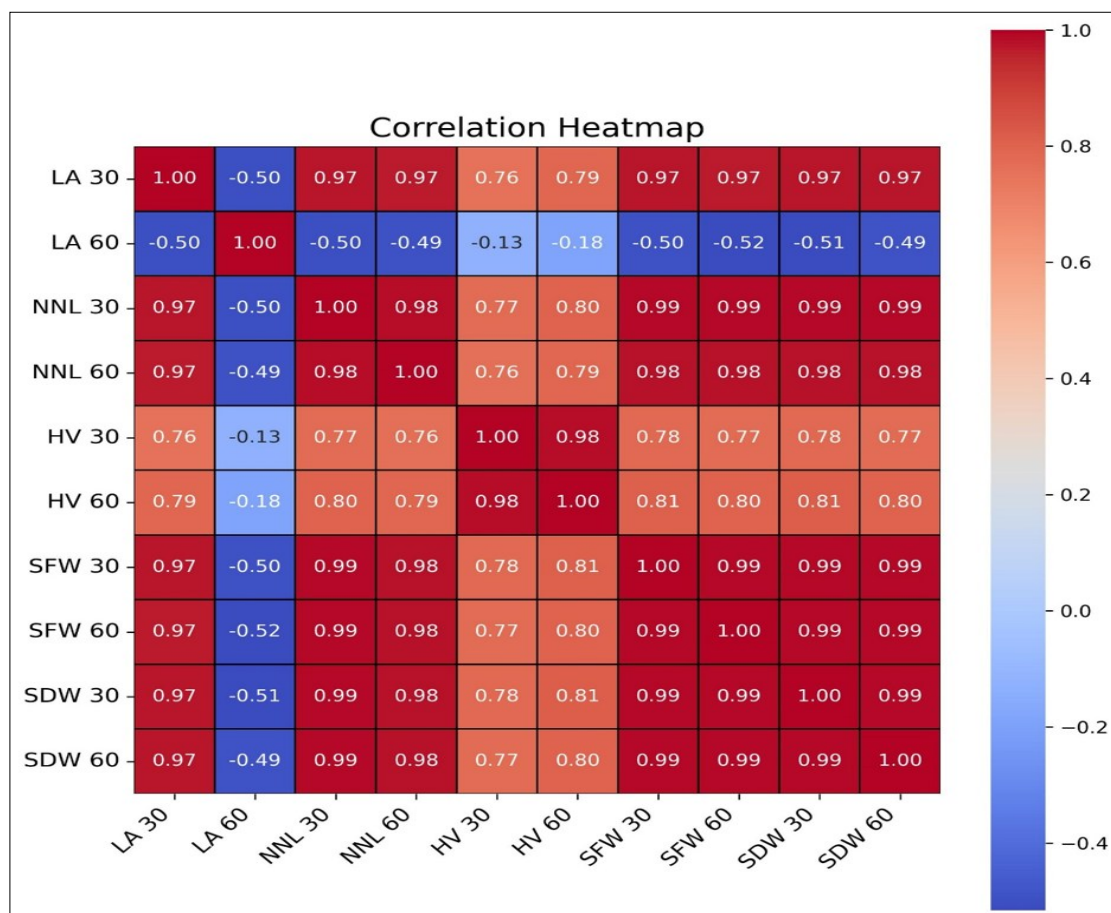


Fig. 6. Heat map of correlation studies.

with shoot fresh weight on 30th ($r = -0.496$) and 60th ($r = -0.516$), shoot dry weight on 30th ($r = -0.511$) and 60th ($r = -0.492$), number of new leaves produced on 30th ($r = -0.499$) and 60th ($r = -0.492$) and leaf area on 30th day ($r = -0.499$) and a non-significant negative correlation with height variation on the 30th ($r = -0.185$) and 60th days ($r = -0.185$) which indicates strong relationship among shoot biomass attributes but shows inverse relationship with leaf area on 60th day with overall growth attributes (Fig. 6).

Conclusion

This study reveals that during acclimatisation, shoot development and water relations were regulated by the physical structure of hydroponic medium. Cocopeat medium had balanced porosity, bulk density, moisture retention and aeration of cocopeat and pebbles created favourable environment for root zone which supported biomass accumulation, leaf formation, plant height increase and better canopy expansion across both observation stages. In contrast due to suboptimal air-water balance limited the shoot growth when grown in substrates with either excessive compaction or poor water buffering. For ensuring stable hydration, sufficient oxygen supply and vigorous shoot establishment, selecting a suitable medium with optimum physical characteristics is essential for improving the efficiency of hydroponic acclimatisation systems for pineapple propagation. The findings of the study were placing taller plantlets under hydroponics with cocopeat as anchoring medium is optimal for production of good quality planting material of pineapple. Elucidation of physiological mechanism responsible for plantlet establishment improvement and validation of optimised hydroponic medium under commercial nursery conditions should

be focused in future studies.

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Authors' contributions

ARS performed the field, laboratory experiments, statistical data analysis, interpretation and prepared the draft of the manuscript. SS conceptualised and supervised the research. SMS contributed to data analysis and manuscript editing. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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