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Optimising Pepper (*Capsicum Annuum* L.) Seedling Growth with the Synergistic Effects of Seaweed Waste Media and Beneficial Microbes Application

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ABSTRACT

In pepper cultivation, seed quality is the main factor affecting plant productivity. The study aims to determine the best composition of seaweed waste seedling media and the mycorrhizal application to enhance pepper seedling growth in the nursery. The study used a Completely Randomised Factorial design and four replications. The first factor is the composition of seedling media: (1) Control (soil + manure), (2) Seaweed waste seedling media without microbes, (3) Seaweed waste seedling media + microbes. The second factor is mycorrhizal application: (1) with mycorrhizal application, (2) without mycorrhizal. The research findings indicate that the application of mycorrhizal fungi across three types of seedling media, including standard operating procedure (SOP), non-microbial seaweed, and seaweed with microbes, can enhance pepper seedling growth, chlorophyll content, mycorrhizal infection in roots, and nutrient levels in the seedling media. There is a synergistic effect among microbial consortia, with the addition of mycorrhizae improving pepper seedling growth. Seaweed waste media combined with microbial consortia

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and applied with mycorrhizae is recommended as an adequate soil substitute for enhancing pepper seedling growth.

Keywords: Mycorrhizal, microbes, nursery, pepper, seaweed waste, seedling media

INTRODUCTION

Pepper (*Capsicum annuum* L.) is a horticultural commodity with many benefits and high economic value. Capsaicin is the main bioactive compound responsible for the spicy taste of pepper fruit. Capsaicin has various health benefits, including antirheumatic, antibacterial, anti-inflammatory, antirhinitis, and analgesic. Capsaicin also plays an essential role in improving immunity to manage diabetes, lowering cholesterol levels, high blood pressure, and obesity, inhibiting the spread of cancer, treating anaemia, improving eyesight, and supporting hair growth (Chakrabarty et al., 2017; Chung & Campbell, 2016; Idaryani et al., 2021; Saleh et al., 2018; Sanati et al., 2018).

In pepper cultivation, seed quality is a crucial factor that affects plant productivity. The process includes sowing, nursery, and field transfer. Each stage of seedling transfer increases stress, weakens seedlings, and inhibits growth. Efforts to overcome this include sowing pepper seeds in seedling media that can be directly transplanted to the field without disturbing the seedlings. Seaweed waste can be used as a seedling medium, reducing stress during seedling transfer and increasing seedling vigour in the seedling phase. Seaweed waste is an abundant natural resource but has yet to be optimally utilised. Seaweed waste from seaweed blooms and hydrocolloid extraction causes environmental pollution (Dang et al., 2023). The seaweed extraction industry produces liquid and solid waste, with an estimated 89% of the extracted seaweed's Weight ending up as solid waste. Solid waste from the extraction of *Gracilaria* sp. and *Sargassum* has excellent potential to be used as a seeding medium because it has a composition that includes perlite, cellulose, agar, micro and macro minerals, and growth regulators (auxin 191 ppm; GA3 509.5 ppm; cytokinin-kinetin 244.5 ppm, and cytokinin-zeatin 70.5 ppm) (Basmal et al., 2020; Basmal et al., 2019). Perlite itself consists of SiO_2 (75%), Al_2O (14.8%), Fe_2O (1.5%), CaO (0.9%), and K_2O (5.8%), Na_2O (2.9%), and MgO (0.1%) (Cojocaru et al., 2023). Seaweed extraction solid waste can also be a soil conditioner (Ammar et al., 2022; Shang et al., 2023). Application of *Gracilaria* sp. (Pramanick et al., 2016; Prihastanti & Haryanti, 2022) and *Sargassum* sp. (Yusuf et al., 2021) significantly increased plant growth and production. Cocopeat can be added as a filler to a planting medium to increase its water-holding capacity. Cocopeat has advantages such as its light, porous structure, high water holding capacity, neutral pH, natural sterility, and good nutrient retention capacity (Tiwari, 2015).

Adding a microbial consortium to seaweed seed media is one effort to increase the vigour of pepper seeds. The microbial consortium works synergistically to improve the balance of the soil ecosystem, nutrient availability, and plant resistance to disease and environmental stress. Phosphate- and potassium-solubilising bacteria that can dissolve P and K include *Pseudomonas cepacia*, *P. malei*, *Bacillus mycoides*, *B. subtilis*, *Azotobacter*, *Rhizobium*, *Cyanobacteria*, and *Escherichia*. These bacteria can also produce organic acids that dissolve phosphate and potassium, and enzymes such as phosphatase and phytase break down organic compounds containing phosphate (Patel & Patel, 2022; Rawat et al., 2021).

Arbuscular Mycorrhizal Fungi (AMF) are potential microbes that are widely used in cultivated plants to increase nutrient availability, production, and bioactive content of plants (Sharma et al., 2017; Singavarapu et al., 2024). Mycorrhizal inoculation of pepper plants with 75% irrigation conditions did not reduce pepper production (Calvo et al., 2024). Mycorrhiza increases the production of pineapple crown cuttings and improves seed quality, as measured by root dry Weight, chlorophyll content, root infection, and phosphatase enzyme activity (Putri et al., 2020). The provision of AMF to pepper plants can increase several growth parameters (number of leaves, height, stem diameter, dry Weight of the upper part of the plant) and production (number of fruits, fruit weight), root biomass, plant P content, and chlorophyll (Utari & Rachmawati, 2022) This study determines the composition of seaweed-waste seedling media and the optimal provision of mycorrhizal inoculum to increase the growth of pepper seedlings in the nursery.

MATERIALS AND METHODS

Preparation of Plant Materials and Seedling Media Formulation

The pepper seeds used were of the Kencana variety, suitable for lowland areas. The formulation materials for the seedling media included dried and ground agar-extraction waste (*Gracilaria* sp.) obtained using a hammer mill and dried *Sargassum* sp. cut into *Sargassum* chips. *Sargasum* contains various bioactive compounds, including perlite, cellulose, agar, micronutrients (potassium, nitrogen, phosphorus, calcium, magnesium), and macronutrients; plant growth regulators such as Auxin (191 ppm), GA3 (509.5 ppm), Kinetin (244.5 ppm), and Zeatin (70.5 ppm) (Basmal et al., 2019). The extraction of Gracilaria sp. had the macronutrients N (0.20%), P (0.12%), K (0.17%), C-organic (10.96%), Na (0.66%), Ca (0.61%), Mg (0.09%), CEC (13.5 me/100g), N/C ratio of 54:7, as well as the micronutrients Cu (4.80 ppm), Fe (0.24 ppm), Zn (8.42 ppm), Mn (57.58 ppm), B (32.32 ppm). Solid waste also contained growth hormones, including auxins (191 ppm), gibberellin/GA3 (509.5 ppm), kinetin (244.5 ppm), and zeatin (70.5 ppm) (Basmal et al., 2020). Other ingredients included fish meal, molasses, and hydrogel as components of the media mixture. Cocopeat, with a 10-12% moisture content, was used as the filler for the seedling's media.

Table 1
Seedling media formula from seaweed waste

No.	Seedling Media Materials (%)	Composition
1	Agar (*Gracilaria*) waste	40
2	*Sargassum*	51
3	Fish flour	7
5	Hydrogel	1
	Total	100

Preparation of *Bacillus* sp, *Pseudomonas* sp, and *Trichoderma* Microbes

The microbes used in this study are *Bacillus sp., Pseudomonas sp., and Trichoderma sp.* These are known to produce organic acids that solubilise phosphorus and potassium, synthesise phytohormones (Indole-3-acetic acid), secrete enzymes such as phosphatase and phytase, and exhibit antagonistic effects against soil-borne pathogens (Hernández-Rodríguez et al., 2008; Patel & Patel, 2022; Rawat et al., 2021; Yao et al., 2008). The microbes were propagated from a single lyophilised ampoule.

The microorganisms were dissolved in 50 ml of nutrient broth (N.B.) media for *B. subtilis* and *P. fluorescens* and incubated for 24 hours. For the propagation of *Trichoderma* sp., 50 ml of potato dextrose broth (PDB) media was used and incubated for 72 hours. The next stage involved propagating the microbes in a mixture of liquid Sargassum extract, fish silage, and molasses. This incubation lasted 15 days at room temperature (23-32°C). Subsequently, the microbes were mixed to form a microbial consortium, which was then added to the media formulation as presented in Table 1.

Mixing seedling media

All the ingredients for the seedling media formulation (Table 1) were mixed until homogeneous. For the microbial seedling media, *Bacillus sp*. (5.4 x 10^7 CFU/ml), *Pseudomonas sp*. (2.35 × 10^8 CFU/ml), and *Trichoderma sp*. (2.15 x 10^4 CFU/ml) were added to the mixture and stirred until well combined. Each medium was then mixed with cocopeat as a filler in a 10:90 ratio and stirred until homogeneous. The physical properties, nutrient content, and plant growth regulators (PGRs) of the seedling media are presented in Table 2.

Forming the seedling media

The seedling media is placed in gauze and then compacted using a hydraulic press with a pressure of 3-4 tons until the dimensions are 1.58 cm in diameter and 9 cm in height.

Table 2
Physical characteristics, nutrient content, and plant growth regulators (PGR) for seaweed seedling media

No	Physical characteristics, nutrient content, and PGR for seaweed seedling media	Value
1	Water Content (%)	35.03
2	Ash Content (%)	11.07
3	Water Holding Capacity (%)	7.83
4	Evaporation (%)	29.95
5	Protein (%)	1.71
6	N Content (%)	1.05
7	P_2O_5 Olsen (ppm)	566.50
8	K_2O Morgan (ppm)	9047.0
9	K (cmol c/kg)	16.92
10	Auxin (mg /l)	0.111

Propagation of Mycorrhizal Consortium

Mycorrhizal consortium cultivation and harvesting refer to Patil et al. (2022) and Cahyani et al. (2022), with modifications in zeolite preparation. The zeolite media was washed repeatedly until the rinse water was clear. Corn seeds were planted in the zeolite in polybags sized 15 cm × 30 cm, then inoculated with a mixture of three mycorrhizal genera: *Glomus*, *Gigaspora*, and *Acaulospora*, which have been tested and are compatible and able to enhance the vigour and growth of pepper plants. The inoculum was applied to a depth of approximately 5 cm in the planting holes. The corn plants were maintained until approximately 3 months old. Low-phosphorus liquid fertilisers (organic and inorganic) were applied with watering. Harvesting was performed when the plant's vegetative growth was at its maximum, and the early generative phase was achieved by cutting off the top of the plant and then drying it for approximately 2 weeks. The dried roots were separated from the stem base, cut into pieces, and mixed with the seedling medium, which already contained the mycorrhizal population.

Sowing and Maintenance in the Nursery

Pepper seeds are soaked in water for 2 hours to promote germination. The seedling medium, prepared according to the treatment, is dipped in water for approximately 10 seconds, thereby expanding it up to 4 times its initial volume. After that, one pepper seed is sown in each seedling media hole to a depth of 3 cm. For the control treatment, seeds are sown in polybags with a soil and manure mixture (2:1). Mycorrhiza application is given at 25 grams of Mycorrhiza + carrier (300 spores) according to the treatment after the seeds have been sown. The seedlings are placed on nursery racks in the nursery shed until the plants are 1.5 months old. Watering is done as needed.

Research Design

The study uses a Completely Randomised Design (CRD) in a factorial arrangement with 4 replications. The first factor is three seedling media compositions: K= Control (soil + manure), B0= Seaweed waste seedling media without microbes, B1= Seaweed waste seedling media with microbes.

The second factor is two mycorrhiza applications: M0 = Without Mycorrhiza, and M1 = Mycorrhiza consortium. The number of samples per experimental unit is 10, resulting in a total of 240 plants.

Observations

The parameters observed include plant height, number of leaves, leaf length and width, stem diameter, root length, wet and dry root weight, wet and dry plant weight, chlorophyll content (SPAD), mycorrhizal infection in the roots, and nutrient content of the media at the end of the observation using a Palintest device. The obtained data will be analysed using an F-test at a 5% significance level. If the calculated F-value exceeds the F-table value, the analysis will proceed with Duncan's Multiple Range Test (DMRT) at a 5% significance level.

RESULTS

Plant Growth and Chlorophyll Content

Table 3 shows an interaction between seedling media composition treatments and mycorrhizal application on pepper plant growth (plant height, number of leaves) and chlorophyll content 1.5 months after sowing. The best plant height and number of leaves were achieved with the combination of soil + manure media with mycorrhizal application

Table 3
Interaction between seedling media composition and mycorrhizal application on plant height, number of leaves, and chlorophyll content of 1.5-month-old pepper plants

Treatment	Plant Height (cm)	Number of leaves	Chlorophyll Content (SPAD)
KM0	11.70 c	9.74 c	53.72 b
KM1	20.39 a	14.95 a	62.75 a
B0M0	4.26 e	3.37 e	27.73 c
B0M1	17.20 b	12.63 b	51.89 b
B1M0	8.10 d	6.69 d	31,95 c
B1M1	17.49 b	12.76 b	56,44 b
CV (%)	5.989	7.759	6.554

Note. Numbers followed by the same letter in the same column are not significantly different according to the Duncan 0.05% test

(KM1), followed by the combination of seedling media seaweed waste (microbial consortium) with mycorrhizal application (B1M1) and the combination of seaweed waste media (without microbes) with mycorrhizal application (B0M1). The application of microbial consortium (*Bacillus* sp*., Pseudomonas* sp., and *Trichoderma* sp.) (B1M0) alone on seaweed media without the addition of mycorrhiza did not affect the growth of pepper seedlings. Combining seaweed-waste seedling media and a microbial consortium with mycorrhizal inoculation at planting significantly increased pepper growth compared with the control (KM0). These results indicate compatibility among consortium microorganisms, thereby synergistically enhancing growth.

Table 4 shows that leaf length, leaf width, stem diameter, and root length were not affected by the interaction between media composition and mycorrhizal application. However, these variables were influenced by individual factors, namely media composition and mycorrhizal application. Regarding media composition alone, the soil + manure media (K) yielded the best results for leaf length, leaf width, stem diameter, and root length compared to the seaweed waste media without microbes (B0) and the seaweed waste media with a microbial consortium (B1). The soil + manure media (K) significantly improved the growth of leaf length, leaf width, stem diameter, and root length of pepper seedlings in the nursery, attributed to the larger media volume compared to the seaweed waste media, which ensures that essential macro-nutrients for the plants remain high until the plants are 1.5 months old.

Table 4
The influence of a single factor of seedling media composition and mycorrhizal application on leaf length, leaf width, stem diameter, root length, and root wet Weight

Treatment	Leaf length (cm)	Leaf Width (cm)	Stem diameter (mm)	Root length (cm)	Roots Dry Weight (g)
Seedling media composition					
K	4.89 a	2.45 a	2.03 a	11.10 a	0.05
BO	3.77 b	1.82 c	1.59 b	8.89 b	0.04
B1	4.16 b	2.11 b	1.69 b	8.36 b	0.03
Mycorrhiza application					
M0	3.03 b	1.59 b	1.21 b	7.30 b	0.019 b
M1	3.53 a	2.67 a	2.33 a	11.61 a	0.063 a
CV (%)	10.783	9,685	11.711	12.793	41.920

Note. Numbers followed by the same letter in the same column are not significantly different according to the Duncan 0.05% test

Table 5 shows that mycorrhizal application on each type of seedling media, whether soil + manure (KM1), seaweed waste media without microbes (B0M1), or seaweed waste media with microbes (B1M1), improves both wet and dry weights of pepper plants. The mycorrhizal application significantly enhances root nutrient uptake across all media compositions.

Table 5
Interaction between the composition of the seedling medium and the application of Mycorrhiza to wet weight (roots, stems) and dry weights (stems, leaves)

Treatments	Wet Weight (g)				Dry Weight (g)		
	Root	Stem	Leave	Total	Stem	Leave	Total
KM0	0.21 c	0.26 cd	0.46 c	0.98 c	0.03 c	0.06 c	0.10 c
KM1	0.75 a	1.43 a	2.46 a	5.32 a	0.15 a	0.31 a	0.56 a
B0M0	0.07 c	0.10 d	0.08 d	0.28 d	0.03 c	0.03 c	0.08 c
B0M1	0.69 ab	0.93 b	1.51 b	3.37 b	0.13 b	0.19 b	0.37 b
B1M0	0.19 c	0.31 c	0.51 c	1.12 c	0.02 c	0.04 c	0.07 c
B1M1	0.52 b	0.86 b	1.40 b	3.11 b	0.12 b	0.17 b	0.34 b
CV (%)	26.496	16.867	15.345	16.053	15.145	14.878	12.049

Note. Numbers followed by the same letter in the same column are not significantly different according to the Duncan 0.05% test

The effect of mycorrhizal application on seaweed waste media with microbes on plant and root growth of pepper seeds can be seen in Figure 1. The seedling media with mycorrhizal inoculation supported greater plant and root growth than the control media without mycorrhizae.

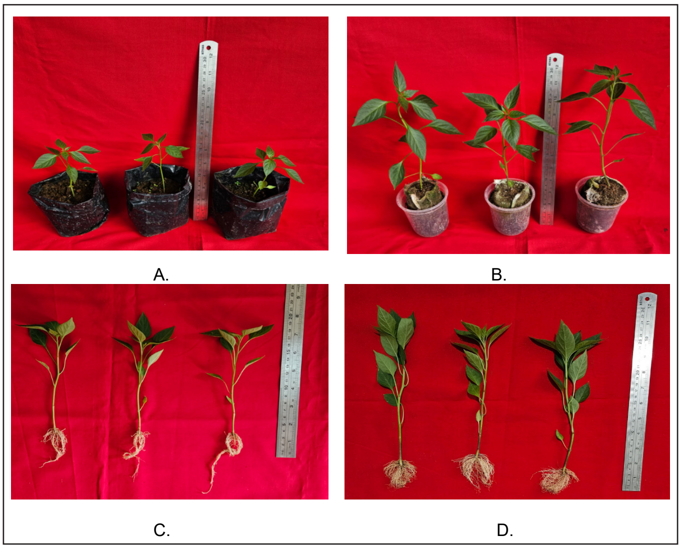

Figure 1. Plant and root growth of pepper peppers aged 1.5 months with (A and C) Soil + manure (control) seedling media, (B and D) Seaweed + consortium microbial seedling media, with mycorrhizal application

Mycorrhizal Infection Percentage

Figure 2 illustrates that the addition of Mycorrhiza significantly increased the percentage of roots infected with Mycorrhiza. The figure also demonstrates that chilli roots can naturally be infected by Mycorrhiza, as observed in the KM0 treatment. In contrast, no root infections were found in plants grown in seaweed medium. In the soil + manure medium without added Mycorrhiza, 5% of chilli roots were naturally infected. The presence of indigenous Mycorrhiza can slightly inhibit the growth and infection of introduced Mycorrhiza, as they are well-adapted to the local environment (Verbruggen et al., 2013). This adaptation results in a smaller increase in the percentage of infected roots in soil media (37.5%) compared to seaweed media (56.3% and 72.9%).

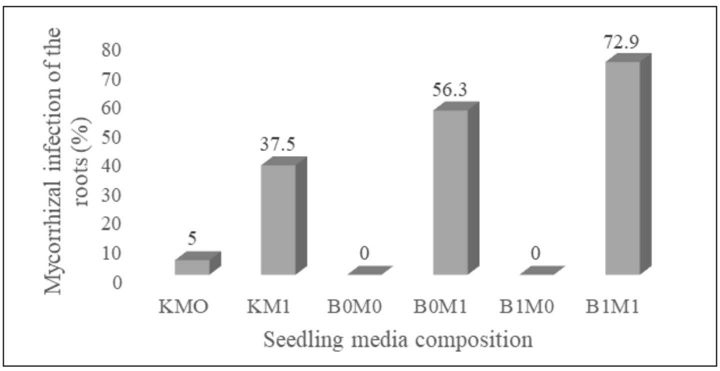

Figure 2. Percentage of mycorrhizal infection in the roots of pepper seeds aged 1.5 months

Nutrient Content of Media

The macro-nutrient content of various seedling media at the end of the seedling stage is shown in Table 6. The table indicates that the Control and seaweed waste seedling media

Table 6
Macronutrient content in various compositions of seedling media at the end of the pepper plant nursery was measured by the Palintest

Nutrient (mg/l)	KM0	KM1	B0M0	B0M1	B1M0	B1M1
N	1.5	0.3	Ttd	3.1	2.6	2.6
NO_3	6.6	1.3	Ttd	13.7	11.5	12.4
P	38.5	57	21.5	10.5	23	16
K	430	360	445	385	455	455
$CaCO_3$	915	931	722,5	868	751	938.75
Mg	222.5	238	175	211	183	231.25
S	45	16.5	0	35	10	10

contain essential macronutrients for plant growth. At the end of the seedling stage, the seedling media seaweed waste, especially the B1M1, had higher levels of macro-nutrients (N, K, Ca, and Mg) compared to soil and manure media. These nutrients are crucial for promoting pepper seedling growth in the nursery**.**

DISCUSSION

Applying mycorrhiza in each type of seedling media in soil and manure (control), and seaweed waste media without or with microbes can increase plant height and the number of chilli leaves. Table 3 shows that the application of mycorrhiza significantly increased plant height, leaf number, and chlorophyll content in chilli plants, both in soil and in seaweed media. Nutrients in the seedling media support plant growth, while mycorrhizal fungi increase the absorption of root nutrients; this was observed across all media compositions. These findings indicate that adding mycorrhiza facilitates the formation of a beneficial symbiosis with chilli roots. Mycorrhizal fungi colonise plant root systems and form an extensive hyphal network, producing an external mycelial layer around the roots. This condition increases contact between plant roots and the growing medium. Mycorrhizal fungal hyphae can expand their network widely throughout the soil, allowing fungi to access nutrients outside the root area (Shi et al., 2023). Arbuscular mycorrhizal fungi (AMF) have the ability to increase the surface area of roots by effectively producing intraradical and extraradical mycelium for better utilisation and effective transportation of nutrients and water (Tyagi et al., 2017). The hyphal diameter ranges from 2 to 20 μm, with the capacity to absorb nutrients from an area of 25 cm around the roots for translocation (Jansa et al., 2008). In addition, mycorrhizal fungal hyphae form a linear surface that goes across soil pores, increasing the pathway for water flow, thereby enhancing the plant's ability to absorb groundwater (Allen, 2007).

The results of the study showed that AMF significantly increased total nitrogen (N) by 0.03%-0.13% and available phosphorus (P) in ultisol soil from 9.00 ppm to 17.50 ppm. The positive role of Mycorrhiza applied to eggplant plants at 20 g per polybag was reported to provide better eggplant plant growth (Ferdi et al., 2023). In cayenne pepper plants with a dose of 10 g in sandy media for 3.5 months, it was reported to increase plant height 3.3 times and leaf area 4.5 times compared to plants without Mycorrhiza (Yudaswara et al., 2018). In addition, application to plants using Andisol soil media with a mycorrhizal dose of 10 g per plant produced the highest plant height, stem diameter, and number of productive branches at the age of 45 days (Matondang et al., 2020).

Leaf chlorophyll is an essential indicator of leaf greenness and is commonly used to assess nutrient deficiencies and monitor changes in chlorophyll levels (Ali et al., 2016). High chlorophyll content indicates that nutrient availability in the seedling medium is well maintained during the seedling and nursery stages. Increased chlorophyll formation in leaves indicates increased photosynthetic activity, so plant growth (height and number of leaves) increases. The highest chlorophyll content in chilli leaves was obtained in plants using a combination of soil and manure media with the provision of mycorrhiza (KM1), followed by a combination of seaweed waste media and microbial consortium with the provision of Mycorrhiza (B1M1). However, this is equivalent to combining seaweed-waste media without microbes with mycorrhiza media (B0M1) and to soil- and manure-based media without mycorrhiza (KM0). The highest results in the number of leaves, plant height, number of fruits, fruit weight, and leaf chlorophyll content in large chilli plants were reported to be produced by applying 15 g of Mycorrhiza with daily watering intervals and mycorrhiza inoculation at a dose of 100 g per plant increased leaf chlorophyll content, higher than the control, due to increased plant metabolic processes where the absorption of nitrogen and phosphorus in the leaves increased (Astiari et al., 2021).

Several other studies have mentioned a significant correlation between chlorophyll and leaf nitrogen content in various crops (Kalacska et al., 2015; Wang et al., 2014). Fertiliser application, especially nitrogen, positively impacts chlorophyll content, leaf area index (LAI), and leaf dry weight. Bassi et al. (2018) observed that fertilisation could increase nitrogen remobilisation in low nitrogen availability to support safflower growth, accelerate leaf ageing, and reduce chlorophyll content. As seen in Table 3, the control treatments (KM0 and KM1) showed the highest values for plant height, number of leaves, and chlorophyll content compared to the seaweed waste media treatment, which was predicted due to the difference in media volume. In the control treatment, the media volume was 10 x 15 cm, whereas in the seaweed-waste media treatment, it was 5 x 10 cm. As a result, at the end of the observation period (1.5 months after sowing), the nutrient content in the control media was still sufficiently available.

Meanwhile, treatment of seaweed waste media with a smaller volume resulted in nutrient levels that were insufficient for the 1.5-month observation period, both with a microbial consortium (M1) and without microbes (M0) and did not increase growth. Another possible cause of suboptimal growth is the high tannin content of the cocopeat used as a filler in the seaweed-waste media. Cocopeat has the advantage of having a high water retention capacity and slow degradation (V. D. S. Handayani et al., 2023). Water is gradually released from the planting medium, providing nutrients to plants over an extended period. However, cocopeat also contains toxic tannins and can inhibit plant root growth. Efforts to reduce tannins in cocopeat by soaking it in clean water before use as a plant nursery medium are suboptimal.

The single factor of mycorrhizal application significantly affected the growth of leaf length, leaf width, stem diameter, and root length in chilli seedlings (Table 4). Mycorrhizal fungi enhance plant growth by facilitating nutrient and water uptake, particularly under stressful environmental conditions such as drought. Mycorrhizal hyphae can explore soil pores beyond the reach of root hairs, thereby increasing water absorption by plants and ultimately increasing productivity in water-deficient conditions (Calvo et al., 2024). Direct contact between the seedling media and mycorrhizae in the planting hole can increase root infection by mycorrhizae and the absorption of phosphorus (P), which is very important for plant growth (Ginting et al., 2018). The statistical analysis showed an interaction between media composition and mycorrhizal application on wet Weight (roots, stems, leaves, total) and dry Weight (stems, leaves, total biomass). The best results for fresh Weight (roots, stems, leaves, total biomass) and dry Weight (stems, leaves, total biomass) were achieved with a combination of soil and manure media with mycorrhizal application (KM1), followed by seaweed waste media without microbes with mycorrhizal application (B0M1), and seaweed waste media and microbial consortium with mycorrhizal application (B1M1) (Table 5).

A new mycorrhizal infection can be observed in the roots of chilli plants two weeks after inoculation. The percentage of mycorrhizal infection in chilli seedlings aged 1.5 months after planting in various seedling media showed the highest value in the B1M1 treatment (72.9%), followed by B0M1 (56.3%) and KM1 (37.5%) (Figure 2). The percentage of mycorrhizal infection in B0M1 and B1M1 showed a high level of root expansion by mycorrhizae (51 - 75%). Root infection with mycorrhizae is considered more effective in nutrient-poor soils, where its presence benefits plants (Adetya et al., 2019; Ginting et al., 2018). B1M1 treatment combines mycorrhizal consortium application with other microbial consortia, including *Bacillus subtilis*, *Pseudomonas fluorescens*, and *Trichoderma* sp., to enhance phosphorus and potassium uptake. This treatment is classified as a Plant Growth-Promoting Rhizobacteria (PGPR) treatment. *Bacillus subtilis* plays a role in IAA production, phytase activity, and antibiotic production (Yao et al., 2008). *Pseudomonas fluorescens* plays a role in IAA production and shows antagonism to *Fusarium verticillioides* (Hernández-Rodríguez et al., 2008b).

Mycorrhizal fungi can interact with various bacterial species, and this interaction occurs in the root zone and within fungal hyphae. The mycorrhizosphere can expand the rhizosphere by increasing the extent of fungal mycelium. This expanded area helps increase nutrient absorption, soil stability, and water retention efficiency (Ramasamy et al., 2011). The nutrient source in the B1M1 planting medium is seaweed and coconut coir (cocopeat). The addition of a microbial consortium (including *Bacillus* sp., *Pseudomonas* sp., *Trichoderma* sp., and *Mycorrhiza*) synergistically improves soil ecosystem balance, increases nutrient availability, and enhances plant resistance to disease and environmental stress. *Bacillus* sp. and *Pseudomonas* sp. produce organic acids that dissolve phosphate and potassium and enzymes such as phosphatase and phytase that break down organic compounds containing phosphate, thereby increasing nutrient availability. *Trichoderma* spp. are biological agents and plant growth stimulants. This mechanism involves a symbiotic relationship with plant roots, mediated by direct interactions between fungal hyphae and fungal conidia. These conidia grow around the root system and are planted in the surrounding area (Charisma et al., 2012). Arbuscular Mycorrhiza Fungi and *Trichoderma harzianum* have been shown to increase the growth of mustard greens in clay and sandy soils (Ginting et al., 2018).

Seaweed extract enhances cold resistance, improves nutrient uptake, controls phytopathogenic fungi, stimulates seed germination and root growth, and increases nutrient absorption (Brownlee et al., 2012; Čmiková et al., 2024; Lomartire et al., 2021; Nabti et al., 2017). Cocopeat, comprising 75% of the media mix, has proven to be the most effective medium for the growth and performance of *Chrysanthemum* in pots. Its aggregate stability and potassium content make cocopeat an ideal alternative potting medium for chrysanthemums (Singh et al., 2015). Combining cocopeat with other composts is also identified as an excellent growing medium, serving as a nutrient source and soil substitute for vegetable crops (Utari & Rachmawati, 2022). Based on this study, seaweed waste combined with coconut coir (cocopeat) can be used as a soil substitute for seeding media. Seaweed provides essential micronutrients and growth hormones (auxin, cytokinin, gibberellin) that stimulate root and shoot growth. Cocopeat contributes high water-holding capacity, good aeration, and stable physical structure, making it ideal for root development. The combination of seaweed and cocopeat creates a growth medium that is a nutrient-rich, lightweight, and water-retentive medium, ideal for seedling growth, which improves root development, nutrient availability, and water holding capacity, leading to enhanced seedling growth (Handayani et al., 2004; Singh et al., 2015; Tiwari, 2015). Adding a microbial consortium can maximise its function as a nutrient-rich planting medium. In addition, it can be packaged in compact, lightweight containers, facilitating transport, storage, and use.

CONCLUSION

The results of this study demonstrate that using seaweed waste combined with mycorrhizae as a planting medium leads to optimal seedling growth, as indicated by enhanced pepper seedling development, increased chlorophyll content, higher mycorrhizal root infection, and improved nutrient levels in the growing medium. There is a synergistic effect among microbial consortia, with the addition of mycorrhiza improving pepper seedling growth. Additionally, seaweed-waste media combined with microbial consortia and mycorrhizae are recommended as a suitable soil substitute to enhance pepper seedling growth.

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AUTHOR CONTRIBUTIONS

Devi Rusmin, Ireng Darwati, Jamal Basmal, Octivia Trisilawati, Melati, and Eliza Mayura conceived the idea of research; Rudi Suryadi, Muchamad Yusron, Raden Vitri Garvita, and Rinta Kusumawati assisted in field and laboratory studies; Devi Rusmin, Ireng Darwati, Jamal Basmal, Rudi Suryadi, Eliza Mayura and Melati analysed the data and wrote the manuscript; and Devi Rusmin, Jamal Basmal, Rinta Kusumawati, Octivia Trisilawati, Rudi Suryadi and Melati were involved in language improvement and final editing of the manuscript.

DATA AVAILABILITY

Data will be made available on request.

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