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Optimising *Capsicum chinense* Growth in Cocopeat Media: The Effects of Pineapple Leaf Biochar and *Trichoderma* Biofertiliser

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ABSTRACT

The escalating demand for pineapples has led to a proportional increase in pineapple leaf waste, posing environmental challenges if not effectively managed. Numerous studies have explored the conversion of pineapple leaf waste into biochar to improve soil fertility. However, research on using pineapple leaf biochar (PLB) in cocopeat remains limited. Therefore, this study examines the effect of PLB and *Trichoderma* biofertiliser (TBF) on the growth, yield, and nutrient content of the *Capsicum chinense* plant grown in cocopeat media. Seven treatment groups were established: T0 = Control, T1 = Commercial organic fertiliser, T2 = 100% PLB, T3 = 100% TBF, T4 = 75% PLB + 25% TBF, T5 = 50% PLB + 50% TBF, and T6 = 25% PLB + 75% TBF. The *C. chinense* was planted in a polybag filled with cocopeat, placed in a rain shelter, and equipped with a fertigation system. The parameters measured included plant growth, yield, and nutrient content. Destructive sampling was done five months after treatment. The findings showed T4 emerged as an alternative to chemical fertiliser, as the results were comparable to T0 which helped boost plant growth, yield (403.69 g), biomass (156.13 g), and nutrient uptake (N: 9.33%, P: 1.68%, K: 13.20%) of *C. chinense* plant. Therefore, T4 is recommended as an organic amendment for cocopeat media.

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1 INTRODUCTION

As the global population continues to grow, it is significantly impacting agriculture and food security. As of 2024, the world population is about 8 billion, expected to reach 9.5 billion by 2050[1]. This increase in population heightens the pressure on land resources, leading to scarcity and soil degradation. As an alternative to conventional soil-based farming, soilless planting media are commonly used, including cocopeat, peat moss, and hydroponic systems. In Malaysia, cocopeat has gained popularity as an intensive production technique, especially for greenhouse cultivation[2] because of its superior physical properties, such as the capacity to retain water and essential nutrients like calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), and phosphorus (P)[3]. Recent studies by Felle et al.[4] and Ruli et al.[5] have shown the effectiveness of cocopeat in achieving higher yields under limited and adverse conditions, offering ideal growing conditions and protection against soil-borne diseases. For this reason, utilising cocopeat as a planting medium has become popular and is the main choice in various agricultural sectors. This trend includes many growers in Sarawak who are utilising cocopeat for the commercial production of chili. Among the crops benefiting from the cocopeat advantage, *Capsicum chinense* (*C. chinense*, henceforth) has gained attention due to its economic potential and increasing market demand[6].

C. chinense is well-known for its elevated spiciness level compared to other chili varieties[7]. The increasing consumer demand for *C. chinense* in local and global markets has led to its commercial expansion[8], with value-added processing such as hot sauces, powders, and seasonings contributing to its economic sustainability, longer shelf life, and catering to diverse consumer preferences[9]. While the growing demand for *C. chinense* presents economic opportunities, its intensive cultivation comes with agronomic and environmental challenges, particularly in terms of fertiliser dependency. The cultivation of *C. chinense* often requires high inputs of chemical fertilisers to achieve optimal yields. According to Susila et al.[10], fertigation is an efficient technique for increasing agricultural output, and the chemical fertilisers used are essential for providing the nutrients required for high yields. However, the extensive use of chemical fertilisers has several adverse environmental impacts, including soil degradation, nutrient leaching, and the disruption of microbial communities. These effects contribute to long-term soil infertility and ecological imbalances. To mitigate these environmental concerns and promote sustainable agricultural practices, researchers have explored alternative fertilisation strategies with a strong focus on organic production methods.

A study by Aythenew and Bore[11] investigated the potential of organic amendments to enhance soil fertility while reducing environmental harm. One such alternative is biochar, a carbon-rich material derived from biomass pyrolysis in the absence of oxygen. This carbon-rich substance has garnered significant attention for its role in improving soil health, enhancing nutrient retention, and promoting sustainable agricultural practices. Biochar not only improves soil structure and water retention but also enhances nutrient availability and microbial activity, counteracting the soil degradation caused by excessive chemical fertiliser use. The porous structure of biochar allows it to retain water and nutrients, promoting plant growth[12]. Despite its potential benefits, there are concerns about its long-term impact on soil health and ecosystem sustainability. Wang et al.[13] indicated that biochar may not be as effective in certain soil types and conditions, which can limit its benefits. In soilless cultivation systems, such as cocopeat, biochar improves water retention and nutrient availability, reducing leaching and enhancing root-zone conditions. In contrast, in soils with high organic matter or clay content, the benefits of biochar may be less pronounced, as these soils already possess good water-holding capacity and nutrient retention[14].

Additionally, Wang et al.[15] suggested that long-term impact of biochar on soil health and ecosystem sustainability depends on factors such as feedstock material. Wood-based biochar typically has high stability and carbon content, making it effective for long-term soil amendment and carbon sequestration. In contrast, biochar from crop residues such as pineapple leaves, often has higher nutrient content to enhance soil fertility but it is less stable over time[16]. Given these distinctions, pineapple leaf biochar (PLB) was selected in this study due to its potential to balance both stability and nutrient release. As a lignocellulosic agricultural byproduct, pineapple leaves contain both woody and fibrous components, which can contribute to moderate stability while still providing essential nutrients. Based on Bohari et al.[17], PLB contains 8.33%

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nitrogen (N), 0.39% phosphorus (P), and 48.32% potassium (K). A study by Jos et al.[18] indicated that incorporating PLB improved soil nitrogen retention, highlighting its potential as a sustainable and locally available resource for biochar production, particularly in regions like Sarawak, where pineapple cultivation is prevalent.

Sarawak, being the second-largest pineapple-producing state in Malaysia, cultivates approximately 8,429 hectares of pineapples and produces a significant amount of agricultural waste as production increases[19]. This non-commercial waste can be converted into biochar to enhance plant growth and yield. According to Bohari et al.[17], pineapple leaves have a high P content and a C/N ratio of 50 – 70%, supplying additional nutrients and improving soil fertility. Given the challenges of global warming and food insecurity, using PLB as an organic amendment can significantly enhance nutrient absorption and retention, leading to better plant growth[20]. The properties of pineapple leaf biochar make it well-suited for soil improvement, but its effectiveness is increased when used with biofertiliser. Hanyabui[21] found that combining PLB and compost boosts pineapple yield and fruit quality. Japakumar et al.[22] reported that combining biochar and biofertiliser enhances soil carbon content, improves soil structure, and promotes plant growth. While biochar has been extensively studied in soil-based media, its effects in cocopeat growing systems remains largely unexplored. Limited research has examined its effects on nutrient dynamics and crop yield in soilless cultivation. Specifically, the impact of PLB and TBF (*Trichoderma* biofertiliser) on the yield and nutrient uptake of *C. chinense* in cocopeat is yet to be investigated. Therefore, this study evaluates the effects of PLB and TBF on the yield and nutrient uptake of *C. chinense* plants grown in cocopeat.

2 MATERIALS AND METHODS

2.1 Site descriptions

The field study was conducted at Farm Unit, UiTM Sarawak Branch Samarahan Campus, Sarawak, Malaysia, at latitude 1°26'46.5" N and longitude 110°27'08.3" E (1.446256, 110.452313), from April – September 2022, under a fully enclosed rain shelter equipped with a fertigation system. The temperature at the study site ranged from 30 to 40 ºC, and the relative humidity was between 60 and 80%[6].

2.2 Planting materials and seed transplanting

The variety of *C. chinense* used in this study was the F1 (First Filial Generation) progeny of Cili Geronong Sarawak, a locally cultivated chilli variety. This progeny was commercially sourced from HFE Agro Resources Sdn. Bhd., (1225962D / 201701011797), Kuching, Sarawak, Malaysia, one of the leading *C. chinense* seedling suppliers for agricultural and research purposes.

The 2-month-old *C. chinense* seedlings, cocopeat, and chemical fertiliser (15-5-20) were also sourced from HFE Agro Resources Sdn. Bhd. The biochar used in this study was MD2 pineapple leaves from a local grower at Kampung Meranek, Samarahan, Sarawak, Malaysia. The TBF was obtained from Sungei Marong Agri Farm Company, Kota Samarahan, Sarawak, Malaysia while the commercial organic fertiliser, Indusol Premium, was obtained from the State Farmers' Organisation Sarawak.

The seedlings were acclimatised for seven days before transplanting. Then, healthy and uniform seedlings were transplanted into polybags (40 × 40 cm) filled with cocopeat. They were arranged on the research site with a planting distance of 60 × 90 cm.

2.3 Biochar production

The raw biomass of pineapple leaf waste was washed with tap water, cut into 2 to 3 cm, and air-dried for several days, followed by oven drying at 60 ºC until a constant weight was achieved[23]. The samples were crushed and ground into a size of about 2 mm using a heavy-duty grinder[24]. They were then placed into ceramic crucibles with tightly fitting lids and carbonised at 500 ºC for two hours in a large chamber muffle furnace (Daihan Scientific FH-14, Korea) at Block H Laboratory, UiTM Sarawak. The resulting

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biochar was then ground to pass through a 1 mm sieve and kept at room temperature before analysis[24]. After carbonisation, the weight of the samples was reduced by 50% to 65%.

2.4 Biochar characterisation

Biochar characterisation was conducted before its application to *C. chinense* plants based on the methods of Abdul Halim et al.[25].The physicochemical properties of PLB were assessed using the following instruments: surface area was determined by the Brunauer-Emmet-Teller (BET) method (Micromeritics Instrument Corporation; Norcross, GA); functional groups were identified by Fourier-transform Infrared Spectroscopy (FTIR) (Spectrum 100, Perkin Elmer, USA); thermal stability was analysed using a Thermogravimetric Analyser (TGA 4000, Perkin Elmer, USA); elemental composition was measured using a CHNS analyser (LECO Corporation, CHNS 628, St. Joseph, MI, USA); and surface morphology was examined using Field Emission Scanning Electron Microscopy (FESEM) (Hitachi SU8220, Japan).

2.5 Cocopeat, pineapple leaf biochar, and *Trichoderma* biofertiliser analysis

The determination of physicochemical properties of cocopeat, PLB, and TBF was performed at Block H Laboratory, Faculty of Plantation and Agrotechnology, and Block B, Faculty of Applied Science, UiTM Sarawak Branch. The samples were air-dried and sieved to pass through a 1 to 2 mm mesh before being stored in labelled plastic bags[26]. The cocopeat sample was analysed for pH, cation exchange capacity (CEC), organic carbon, N, P, K, Ca, and Mg. In contrast, PLB and TBF samples were analysed for pH, N, P, and K.

The pH values of cocopeat, PLB, and TBF were measured using the method described by Abdul Halim et al.[25]. A ratio of 10 g of sample to 25 mL of deionised water (1:2.5) was used. The sample was shaken for 90 minutes at 245 rpm on a Digital Orbital Shaker to ensure sample and solution equilibration, thus, obtaining accurate pH readings. The pH was measured using a digital pH meter (Hanna Instruments HI-83141-1 pH Meter).

As for the determination of the EC values, the method described by Bohari et al.[17] was used. A 10 g sample was immersed in 50 mL of distilled water (1:5 ratio), and the mixture was shaken for 60 minutes at 245 rpm on a Digital Orbital Shaker (Daihan SHO-1D, SHO-2D, Korea). An EC meter (Mettler Toledo, USA) was used to measure and record the EC by placing the electrode into the supernatant solution.

A chemical analysis, with modifications, was performed according to Motekar's[27] method to determine the N, P, and K contents in the samples. Nitrogen content was determined by using the Kjeldahls digestion and distillation method; phosphorus was measured using a UV-Vis spectrophotometer (Drawell, China); and potassium was determined using the flame photometric method.

2.6 Experimental design

The research was conducted using a Randomised Complete Block Design (RCBD) with seven treatments, each consisting of six plants and five replications, resulting in 210 experimental units. The composition of treatments is shown in Table 1.

Through a fertigation system, 500 mL of commercial chemical fertiliser was applied daily to T0, as per common practice among local growers. The recommendation from the Department of Agriculture Sarawak (A. Shafiq, personal communication, 2021) was to dilute the commercial chemical fertiliser with water to achieve the required electrical conductivity (EC) level. According to the advice from the State Farmers' Organization Sarawak (D. Seraphina, personal communication, 2021), 50 g of commercial organic fertiliser was to be administered once every two weeks to the organic treatments (T1-T6). The quantities of nutrients applied to *C. chinense* seedlings were modified based on the findings of Rivitra et al.[28]. Meanwhile, the treatments consisting of PLB and TBF were applied in the second, seventh and tenth weeks after transplanting.

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Table 1. Composition of treatments

Treatment	Description	Fertiliser (per polybag)	PLB (g/polybag)	TBF (g/polybag)
T0	Commercial chemical fertiliser (Control)	500 mL *	0	0
T1	Commercial organic fertiliser	50 g**	0	0
T2	Commercial organic fertiliser and PLB	50 g**	50	0
T3	Commercial organic fertiliser and TBF	50 g**	0	50
T4	Commercial organic fertiliser, 75% PLB and 25% TBF	50 g**	37.5	12.5
T5	Commercial organic fertiliser, 50% PLB and 50% TBF	50 g**	25	25
T6	Commercial organic fertiliser, 25% PLB and 75% TBF	50 g**	12.5	37.5

Note. PLB = Pineapple leaf biochar; TBF = *Trichoderma* biofertiliser; *= applied daily following the standard recommended by the Department of Agriculture Sarawak; ** = applied biweekly following the standard recommended by State Farmers' Organization Sarawak.

2.7 Parameter measurement

Three plant growth parameters, that is, plant height, stem diameter, and SPAD chlorophyll content, were recorded monthly to evaluate the effects of applied treatment combinations. Plant height was recorded in centimetres from the plant's base to its apical point, while, the stem diameter was measured using a digital calliper (Fisherbrand TM TraceableTM Digital Calliper, USA) three centimetres above ground[29]. As for the SPAD chlorophyll content, the SPAD Chlorophyll Meter (SPAD-502 Konica Minolta, Japan) was used[22]. SPAD measurements were taken from three fully expanded leaves on the apical shoot of each chilli plant[30]. Thirty plants per treatment were sampled, with readings recorded from three leaves per plant. The average SPAD value per plant was calculated to enhance accuracy and ensure reliable treatment comparisons.

The yield parameter was recorded weekly. Fully ripe, red colour *C. chinense* fruits were harvested manually by hand-picking. The fruit weight was recorded as the yield, based on the total fruit weight (grams), using an electronic balance (Mettler Toledo SB16001, USA).

The *C. chinense* plants were destructively sampled for total plant biomass five months after treatment and partitioned into shoots, stems, and roots based on the method of Jaaf et al.[29]. The plant and cocopeat samples were placed into an oven and dried at 60 ºC until constant weight. Total plant biomass was recorded. Both samples were subjected to a chemical analysis to determine the N, P, and K content.

2.8 Statistical analysis

All data were analysed using the statistical software of Minitab 21 (Version 2.1). Analysis of variance (ANOVA) was conducted using individual data points from all replicates to assess the effects of different treatments. Duncan's Multiple Range Test (DMRT; $\alpha = 0.05$) was applied for mean separation.

3 RESULTS AND DISCUSSION

3.1 Biochar characterisation

Table 2 presents the characterisation of PLB produced at 500 °C. The results show that the PLB exhibited a BET surface area of 19.4152 $m^2\ g^{-1}$, with total pore volume (0.0098 $cm^3\ g^{-1}$) and micropore volume (0.0069 $cm^3\ g^{-1}$), indicating high porosity. FTIR analysis confirmed the presence of key functional groups, including O-H, C≡C, C=C, and C-O. The PLB demonstrated the lowest weight loss at 67.73% and had elemental compositions of C (59.90%), N (1.85%), and S (0.14%), reflecting its stable carbon-rich structure. Meanwhile, Fig. 1 shows the surface morphology of PLB pyrolysed at 500 °C. The morphological observations revealed numerous macropores and visible micropores on the PLB surface. Therefore, based on the findings, PLB produced at 500 °C was a promising organic amendment due to its porous structure, functional groups, and stable carbon content that enhance substrate quality and support soil microbial activity.

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Table 2. Characterisation of pineapple leaf biochar

Characterisation	Properties	Value/Bond
Surface area	BET surface area ($m^2 g^{-1}$)	19.4152
	Total pore volume ($cm^3 g^{-1}$)	0.0098
	t-plot micropore area ($cm^3 g^{-1}$)	0.0069
Functional group	alcohol	O-H
	alkyne	C≡C
	cyclic alkene	C=C
	secondary alcohol	C-O
Element composition	Carbon, C (%)	59.90 ± 0.20
	Nitrogen, N (%)	1.85 ± 0.07
	Sulfur, S (%)	0.14 ± 0.01

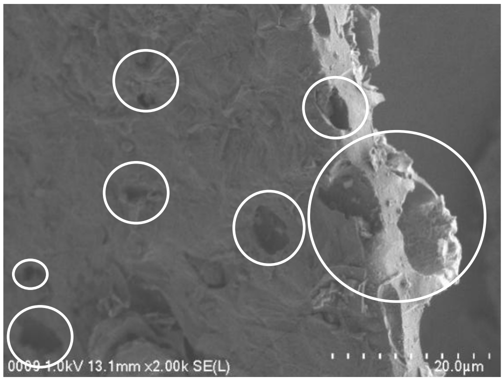

Fig. 1 Surface morphology of pineapple leaf biochar pyrolysed at 500 °C.

3.2 Initial nutrient analysis for cocopeat, pineapple leaf biochar and *Trichoderma* biofertiliser

The initial physicochemical analysis of cocopeat showed a slightly acidic pH value of 5.26. Its CEC was 93.13 cmol kg^{-1}, indicating a strong ability to retain and supply essential cations like K, Ca, and Mg. The bulk density was 0.14 g cm^{-3}. Cocopeat also contained 42.71% organic C, 0.60% N, 0.05% P, 0.30% K, 0.09% Ca, and 0.09% Mg.

Table 3. Initial physicochemical properties for cocopeat, PLB and TBF samples

Properties	Cocopeat (Values)	PLB	TBF
pH	5.26	10.80	5.7
CEC (cmol kg^{-1})	93.13	-	-
Bulk density (g cm^{-3})	0.14	-	-
Organic carbon (%)	42.71	-	-
N (%)	0.60	1.85	2.20
Total P (%)	0.05	0.29	2.14
Total K (%)	0.30	2.23	3.64
Total Ca (%)	0.09	-	-
Total Mg (%)	0.09	-	-

Measuring the pH of the planting media was fundamental, as it directly influenced the growth and development of plants by affecting nutrient availability and microbial activity[31]. Due to the slightly acidic conditions, when cultivating plants that prefer neutral or slightly alkaline conditions, minor pH adjustments through the application of lime and balanced fertilisation were recommended for cocopeat. As *C. chinense* thrives in slightly acidic to neutral soils with an ideal pH range of 6.0 to 7.5[32], pH adjustment is required. The application of dolomitic lime at a rate of 2 to 4 g L^{-1} to cocopeat was recommended to gradually increase the pH[33]. Proper pH regulation enhanced the availability of essential nutrients such as P, Ca, and Mg, preventing nutrient lock-up and promoting healthier growth and development of *C. chinense*. Based on a study conducted by Hussain and Farooq[34], it is concluded that cocopeat is an efficient growth medium,

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which makes it promising for growing chillies due to its favourable physical properties and nutrient-retention capacity.

In addition to pH, the CEC value of growth media also needed to be measured as it affected nutrient retention and supply capacity. Based on the findings outlined in Table 3, the higher CEC of cocopeat allowed it to act as a nutrient reservoir over time, reducing the frequency of fertilisation and supporting optimal plant growth[35,36]. The high CEC of cocopeat helped meet the nutrient needs of *C. chinense* at different growth stages by retaining and gradually releasing essential nutrients. This was especially important during flowering and fruiting, when the plants required more K, as well as Ca and Mg for healthy growth. By holding nutrients for longer periods, cocopeat reduced the need for frequent fertilisation while ensuring a steady supply of nutrients. This supported strong vegetative growth, improved fruit formation, and enhanced yield and quality. According to Ilahi and Ahmad[37], the bulk density of cocopeat falls within the general range of 0.09 – 0.2 g cm^{-3}. Bulk density depends on the composition and processing method for cocopeat production. With a bulk density of 0.14 g cm^{-3}, the cocopeat is considered a suitable medium for various crops. Cocopeat generally offers good physical structure that could support the overall growth of the plant, such as good aeration, high water retention and nutrient holding capacity, and good compatibility with other amendments[38-40].

The high organic C content of cocopeat significantly benefited *C. chinense* by enhancing root development, nutrient uptake, and stress tolerance. Organic C improved the physical properties of the growing medium, such as aeration and water-holding capacity, which were crucial for healthy root growth[41]. Enhanced root systems facilitated more efficient nutrient absorption, leading to robust plant development. Furthermore, incorporating TBF into cocopeat further amplified these benefits was known to promote plant growth by increasing nutrient availability and enhancing soil microbial activity. A study by Zhang et al.[42] demonstrated that applying TBF led to improved plant biomass, likely due to altered soil chemistry and microbial community structures that favour nutrient cycling. The interaction between high organic carbon content and TBF created a synergistic effect, enhancing nutrient retention and promoting beneficial microbial populations. This synergy supported optimal nutrient uptake and improved stress resilience in *C. chinense*, leading to healthier plants and potentially higher yields.

Despite organic C, N was one of the essential nutrients required by plants, playing an important role in photosynthesis and protein synthesis. The findings revealed that the N content in cocopeat was relatively low. However, minor adjustments with additional fertiliser could be performed to meet the requirements of specific crops. The moderate P content (0.05%) in cocopeat supported *C. chinense* by promoting early root development and enhancing flowering, as P was essential for energy transfer, cell division, and root formation. Meanwhile, the high K content (0.30%) played a crucial role in regulating water balance, enzyme activation, and photosynthesis, which was vital for fruit development and stress tolerance. As cocopeat naturally provided moderate P and high K, it served as a suitable growing medium for *C. chinense*, supporting plant structure and metabolic functions. Additionally, the incorporation of PLB further enhanced nutrient availability by improving P retention and K release, ensuring a steady supply throughout different growth stages[43,44]. This optimised nutrient balance promoted stronger root systems, improved flowering, higher fruit yield, and better resilience to environmental stress. Nevertheless, based on the results outlined, the Ca and Mg were almost two times higher than the K content. Ca was vital in cell wall formation and stability, while Mg was a crucial nutrient of chlorophyll, which was necessary for plant photosynthesis. The balanced availability of these nutrients in cocopeat promoted the growth and development of the plants, and this finding is supported by Kusparwanti et al.[3].

The N, P, and K content in the PLB and TBF samples is listed in Table 3. The PLB had a pH of 10.8, indicating a highly alkaline condition which resulted in nutrient lockout, where essential nutrients became less available to plants. Alkaline stress decreased nutrient availability for plant growth and physiological processes, such as Fe, Mn, and P, which played important roles in metabolic functions[45], especially in *C. chinense*. However, when PLB was applied to the slightly acidic cocopeat, it helped to improve the pH to become more neutral and, therefore, favourable for *C. chinense*. This adjustment enhanced nutrient availability, allowing the plant to absorb essential nutrients more efficiently. On the other

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hand, N (1.85%) in PLB provided a moderate amount of this essential macronutrient, which was involved in protein synthesis and chlorophyll production. However, the high pH might limit N uptake[46]. The P (0.29%) content was relatively low, which could limit plant growth and productivity because it was vital for energy transfer and root development. Meanwhile, the K (2.23%) content was relatively higher than that of P, which was beneficial for various plant physiological processes, including enzyme activation and water regulation. However, the high pH might have affected K uptake for the *C. chinense* plant[47].

As for the TBF, the results showed the pH (5.7) was slightly acidic and fell within the optimal range for most plants, as it improved the availability of essential nutrients and supported a healthy rhizosphere microbial community, thereby enhancing nutrient uptake and overall plant health[48]. The N (2.20%), P (2.14%), and K (3.64%) contents in TBF were higher than in PLB. Higher N provided a better nutrient supply for vigorous vegetative growth. While P was essential during the flowering and fruiting stages. The slightly acidic pH enhanced P availability, making it more accessible to plants[49]. The high content of K supported stronger stem and root development, improved drought resistance, and enhanced overall plant health. The slightly acidic pH facilitates better K availability, making it suitable for *C. chinense* growth. However, the application of TBF alone in cocopeat would not be ideal as the pH of the cocopeat itself was slightly acidic. Therefore, applying PLB to the cocopeat medium would help to increase and buffer pH levels to an optimal range for plant growth. This combination ensured consistent nutrient availability and reduced the need for frequent pH adjustments.

3.3 Effect of pineapple leaf biochar and *Trichoderma* biofertiliser in the growth performance of *C. chinense* plant

All treatments showed positive responses across all measured parameters, with improvements observed each month. Fig. 2 (a-c) illustrates the effects of PLB and TBF on the growth performance of *C. chinense* for 5 months after treatment. In Fig. 2 (a), T0 recorded the highest increase in plant height from 20.08 cm in the first month to 141.02 cm in the fifth month. Treatment T1 exhibited the least growth, starting at 14.23 cm and reaching 66.43 cm in the fifth month. However, treatment T4 demonstrated the leading performance among the organic treatments (T2-T6) with an initial height of 15.13 cm in the first month, reaching 102.52 cm in the fifth month. These results suggest that this treatment combination may offer optimal nutrients for promoting vertical growth.

The data revealed that all treatments showed an increase in stem diameter over time (Fig. 2 (b)). The degree of stem diameter growth varied significantly among the treatments, with T0 increasing steadily from 0.39 cm in the first month to 2.26 cm in the fifth month. Meanwhile, for T1, the stem diameter was the lowest among the treatments, starting at 0.28 cm in the first month and reaching only 1.21 cm in the fifth month. Treatment T4 showed the highest stem diameter among the organic treatments (T2-T6), with an initial of 0.31 cm in the first month and reaching 1.75 cm in the fifth month. This finding suggests that the treatment combination supports greater plant height and enhanced stem diameter.

As for the SPAD chlorophyll meter readings, Fig. 2 (c) shows a varied recorded data in chlorophyll content in *C. chinense* plant. These results indicate that chlorophyll content in *C. chinense* plant changed but did not consistently increase over time. Based on the data presented, T0 and T4 displayed a similar trend, with these two treatments recorded a steady increase in chlorophyll content during the first four months and then started to decrease in the fifth month. In contrast, T1 showed an increase in the first three months and started to decrease in the fourth month. For T5 and T6, the chlorophyll content increased in the first three months, decreased in the fourth month, and then picked up again in the fifth month. Interestingly, T2 and T3 displayed a steady increased over the five months. This showed that a single application of either PLB or TBF can improve the chlorophyll content. The findings concluded that the combination of PLB and TBF produced a trend and effect similar to that of chemical fertiliser[21,22,32].

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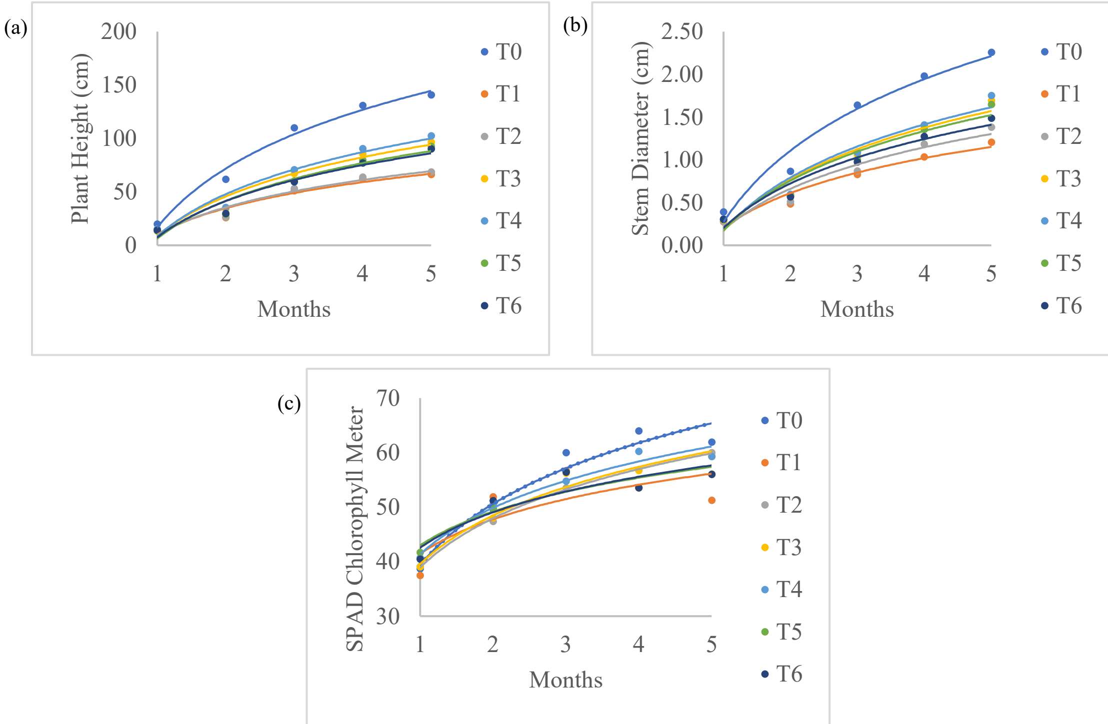

Fig. 2. Effects of pineapple leaf biochar and *Trichoderma* biofertiliser on (a) plant height, (b) stem diameter, and (c) SPAD chlorophyll content of *C. chinense* for 5 months after treatment. Note. T0= Commercial chemical fertiliser (Control), T1= Commercial organic fertiliser, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

The findings provided deeper insights beyond the expected trend of increasing plant growth parameters over time by identifying specific time periods where certain treatments exhibited superior performance. Notably, while all treatments showed growth increments, T4 consistently outperformed other organic treatments (T2-T6) in both plant height and stem diameter, particularly from the third to fifth month, indicating its effectiveness in supporting sustained vegetative growth. Additionally, the chlorophyll content trends revealed distinct patterns among treatments, with T0 and T4 showing a steady increase up to the fourth month before declining, while T2 and T3 displayed continuous improvement over five months. This suggested that single applications of PLB or TBF may have provided prolonged benefits in chlorophyll content compared to combination treatments. These variations highlighted the differential impact of treatments at various growth stages, emphasising the importance of selecting optimal nutrient combinations for maximising plant development at critical periods.

3.4 Effects of pineapple leaf biochar and *Trichoderma* biofertiliser on the total yield and plant biomass of *C. chinense* plant

The mean yield (g) of *C. chinense* under different treatments (T0 to T6) over 10 weeks is shown in Table 4.

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Table 4. Yield performance of *C. chinense*

Harvesting week	Mean yield (g) for each treatment by week						
	T0	T1	T2	T3	T4	T5	T6
1	3.75[a]	0.00[b]	0.43[b]	0.32[b]	0.64[b]	0.29[b]	0.88[b]
2	71.6[a]	1.25[b]	2.47[b]	6.62[b]	14.72[b]	3.18[b]	3.80[b]
3	41.17[a]	0.58[b]	4.70[b]	9.16[b]	32.04[a]	9.97[b]	11.87[b]
4	56.43[a]	4.59[c]	8.73[c]	13.60[bc]	34.49[ab]	12.46[bc]	18.21[bc]
5	42.25[ab]	2.23[d]	11.30[cd]	21.54[bcd]	44.45[a]	16.43[cd]	29.97[abc]
6	73.74[a]	8.67[d]	21.10[cd]	23.46[cd]	50.99[b]	18.67[cd]	31.91[c]
7	60.31[a]	16.43[c]	34.89[b]	32.10[b]	60.12[a]	29.98[b]	32.50[b]
8	60.44[ab]	18.16[d]	41.70[bc]	40.13[c]	67.44[a]	32.07[cd]	33.52[cd]
9	47.95[ab]	17.93[d]	37.73[bc]	30.10[cd]	59.78[a]	36.71[bc]	25.10[cd]
10	36.05[ab]	14.60[d]	30.64[abc]	21.78[cd]	39.03[a]	27.10[bc]	24.86[cd]

Note. Means with the same letter at a given parameter are not significantly difference ($p>0.05$) according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$; values are the means of five replicates; n=210. T0= Commercial chemical fertiliser (Control), T1= Commercial organic fertiliser, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

In the study, general trends were observed. In the first week, T0 showed the highest initial yield, 3.75 g, compared to other treatments with negligible yields, which were close to 0 g. This indicated that the *C. chinense* plant supplied with commercial chemical fertiliser was initially more favourable for yield production than the other treatments that received organic fertiliser. In the subsequent weeks, T0 consistently exhibited high yields, noticeably in the second (71.6 g), third (41.17 g), fourth (56.43 g), sixth (73.74 g), and seventh (60.31 g) weeks. Nonetheless, T4 often outperformed T0 in yield, particularly in the fifth (44.45 g), eighth (67.44 g), ninth (59.78 g), and tenth (39.03 g) weeks, indicating potentially high efficacy of the treatment used. However, T1 consistently showed the lowest yields among all treatments throughout the study period, suggesting it was the least beneficial. This finding aligned with a study by Hanyabui et al.[50] that applying PLB and compost as organic amendments can increase pineapple yield and improve fruit quality.

As for specific observations, there was a significant fluctuation in yield for T0 compared to other treatments, with yield jumping from 3.75 g in the first week to 71.6 g in the second week and then dropping to 41.17 g in the third week. A similar trend was recorded in the fourth to eighth weeks, and it began to decline in the ninth week. However, the yield for T4 consistently increased from the first week until the eighth week and only started to decrease in the ninth week. This result suggested that the combination of organic fertiliser with PLB and TBF released nutrients gradually over time, and it was affirmed by the response of *C. chinense* when the yield produced was delayed. It also showed an effective response to the treatment when it resulted in a consistent increasing yield production. The other treatments such as T2, T3, T5, and T6, also showed yield improvements but not as consistently or significantly as T4. Overall, T0 recorded higher yields during most of the harvest weeks, indicating that the chemical fertiliser was consistently favourable from the first to the seventh week. However, in the eighth, ninth, and tenth weeks, both T0 and T4 showed high yields, with T4 often exceeding T0 in consistency and performance.

The weekly yield data of *C. chinense* collected in this study provided practical insights for optimising agricultural management practices, particularly in nutrient application timing and harvest schedule. By analysing yield fluctuations over time, growers can identify critical periods when nutrient application may have the greatest impact on crop productivity. For instance, if yield trends indicated significant increase after specific fertilisation events, this can be the best practice for nutrient scheduling. Besides, these findings can aid in determining the optimal harvest window by identifying peak yield periods, thereby maximising both yield quantity and quality.

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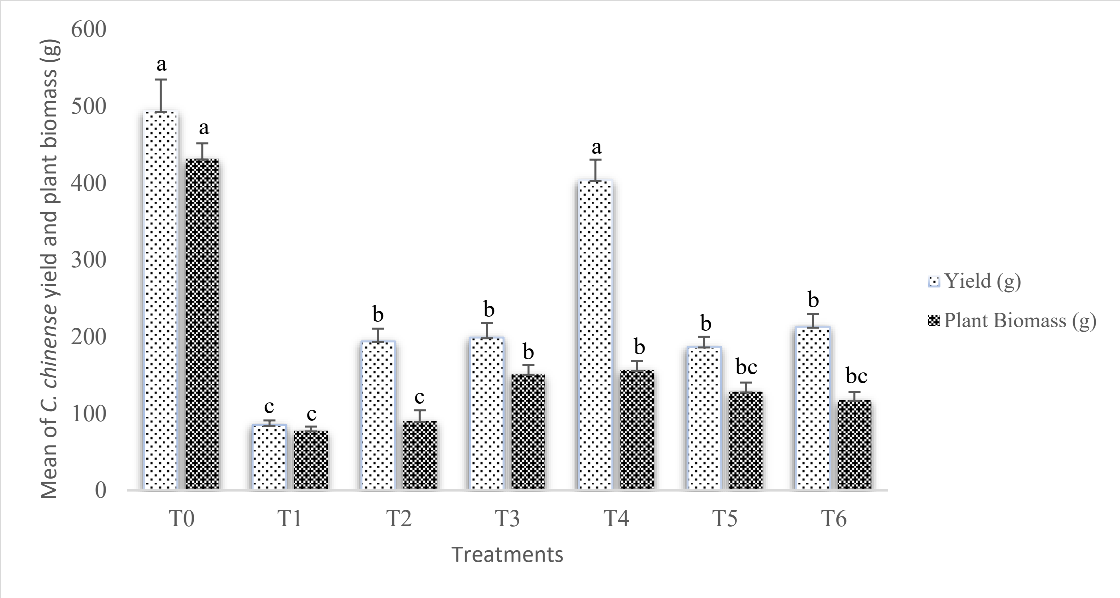

Fig. 3. Comparison of the effects of pineapple leaf biochar and *Trichoderma* biofertiliser on the mean yield and plant biomass of *C. chinense* for 5 months after treatment. Note: Means with the same letter at a given parameter are not significantly difference (p>0.05) according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$; values are the means of five replicates; n=210. T0= Commercial chemical fertiliser (Control), T1= Commercial organic fertiliser, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF.

Based on Fig. 3, statistical analysis confirmed that T0 (493.71 g) and T4 (403.69 g) illustrated mean total yields that were significantly higher than those of the other treatments, supporting the effectiveness of these treatments. These mean values showed a significant difference compared to other treatments, notably T1 (84.43 g) demonstrating the lowest mean value. The highest mean value for the yield recorded by T0 might be influenced by the chemical fertiliser used, which was in liquid form and easily absorbed by the plant. Although T0 recorded the highest mean total yield based on statistical analysis, there was no significant difference compared to T4, with only an 18.23% difference. This finding indicated that the application of PLB and TBF has shown to positively affect the total yield per cycle of *C. chinense*. The nutrient analysis for PLB in this study showed that the K content (2.23%) was higher compared to N (1.85%) and P (0.29%). The higher K content in PLB most probably improved the nutrient content of the medium, thus increasing the yield of *C. chinense*. Potassium was essential for enzyme activation, water balance, and photosynthesis, all of which directly contributed to fruit development and overall plant productivity[51]. It enhanced the movement of sugars from leaves to developing fruits, promoting higher fruit yield and quality. Additionally, K improved plant resistance to abiotic stresses such as drought and temperature fluctuations, ensuring steady growth under varying environmental conditions[52]. Compared to N and P, which primarily supported vegetative growth and root development, respectively, K was particularly important during the reproductive stage, ensuring optimal flowering and fruit set. Moreover, the main role of PLB was to improve the physical properties of the substrate which included enhancing the nutrient retention capacity. Meanwhile, the purpose of the addition of TBF was to enhance nutrient uptake by promoting root growth, thus increasing the efficiency of nutrient adsorption. Therefore, the presence of PLB may enhance the effectiveness of TBF to give better yields than a single application of organic amendment.

Findings reported by Sifton et al.[53] found that biochar combined with biofertilisers significantly increased growth and nutrient uptake in silver maple grown in urban soil by enhancing both macronutrient and micronutrient availability. Although they used cocopeat in their study, the effects aligned with the high yields observed in T4 treatments for *C. chinense*, which might possibly reflect optimal nutrient conditions.

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Irawan et al.[54] and Yan et al.[55] further clarified that the use of *Trichoderma sp*. inoculum was found to significantly increase the decomposition rate of pineapple litter, resulting in better compost quality with lower organic C content and C/N ratio. Partial substitution of chemical fertiliser with TBF improved N use efficiency and plant growth in wolfberry, indicating enhanced N stabilisation and carbon fixation respectively. These findings may help to explain the superior yields seen in T4, which combined 75% PLB and 25% TBF, significantly enhanced substrate health, nutrient availability, and plant growth, and providing a sustainable alternative. The results indicated that T4 can be a potential combination for long-term agronomic strategies.

As for total plant biomass, T0 (431.60 g) recorded the highest mean value among the treatments with a difference of 63.82% in total compared to T4 (156.13 g). This might be due to the nutrient being supplied in a form readily available for the plant roots to absorb. In addition, liquid chemical fertiliser is the most popular commercial fertiliser used because it can be easily monitored in terms of nutrient supply[56]. Therefore, the amount of nutrients supplied to the *C. chinense* plants was sufficient, as the liquid chemical fertiliser contained a balanced mixture of essential macro and micronutrients that were crucial for their growth and biomass accumulation. Unlike organic fertiliser that was supplied in solid form, the nutrient was slowly released and absorbed by the plants. Thus, it led to lower total plant biomass for *C. chinense*. The findings revealed that applying PLB and TBF could have improved both yield and plant biomass because they were organic amendments that boosted media fertility and increased overall plant growth. Pineapple leaf biochar increased water retention, improved nutrient availability, and balanced soil pH, creating a better environment for plant growth. *Trichoderma* biofertiliser supported root development by helping plants absorbed nutrients more efficiently and producing growth-promoting hormones. It also protected plants from harmful pathogens, reducing stress and improving overall growth. Together, PLB and TBF enhanced nutrient cycling, strengthened root systems, and boosted plant resilience, leading to higher yields and healthier plants. These findings were supported by O'Laughlin and McElligott[57], who reported that the addition of biochar could increase plant growth so that it can grow optimally due to biochar's ability to bind carbon, produce extremely porous fiber and charcoal, and hold nutrients and water in the media. Situmeang et al.[58] also found that applying biochar can increase C levels, retain water and nutrients, and restore media fertility. The findings concluded that the higher total plant biomass recorded for T0 may be related to all the nutrients were utilised to produce plant leaves, stems, and roots, whereas, in T4, it was assumed that the plant's uptake of the nutrient was mainly for the yield.

3.5 Effects of pineapple leaf biochar and *Trichoderma* biofertiliser on nutrient content in *C. chinense* and cocopeat media

The mean comparisons for N, P, and K in the *C. chinense* plants shown in Table 5 indicated significant differences (p<0.05) among the treatments. The results revealed that T0 (9.64%) and T4 (9.33%) exhibited the highest N content in *C. chinense* plants, suggesting that these treatments were most effective in promoting N absorption. In contrast, T1 (6.58%) showed the lowest N content, indicating its limited effectiveness. Similarly, the absorption of P was highest in T0 (3.03%) and T4 (1.68%) and lowest in T1 (1.07%), highlighting the greater capacity of T0 to improve P absorption. Potassium content followed a similar trend, with T0 (15.13%) and T4 (13.20%) being the most effective, while T1 again displayed the lowest content (7.67%), further suggesting its inefficiency in nutrient uptake. Meanwhile, in the cocopeat medium, T0 (0.77%; 0.94%) recorded the lowest N and P content respectively, while T4 recorded the lowest K (1.05%) content, indicating that the nutrients were highly absorbed by the plants. Furthermore, T1 (2.20%) showed the highest N content, indicating poor plant absorption. Treatment T3 (1.52%) showed the highest P content, suggesting reduced absorption by the plants, while T2 (6.22%) showed the highest K, also indicating decreased plant absorption.

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Table 5. Nitrogen, phosphorus, and potassium content in *C. chinense* plant and cocopeat samples

	Nutrient elements	Treatment						
		T0	T1	T2	T3	T4	T5	T6
Plant	N (%)	9.64[a]	6.58[g]	7.30[f]	7.78[e]	9.33[b]	8.90[c]	8.18[d]
	P (%)	3.03[a]	1.07[f]	1.31[e]	1.33[e]	1.68[b]	1.54[c]	1.44[d]
	K (%)	15.13[a]	7.67[g]	8.75[f]	9.25[e]	13.20[b]	11.05[d]	11.12[c]
Cocopeat	N (%)	0.77[g]	2.20[a]	1.86[b]	1.82[c]	0.86[f]	0.90[e]	1.61[d]
	P (%)	0.94[e]	1.15[c]	1.23[b]	1.52[a]	1.11[d]	1.11[d]	1.15[c]
	K (%)	1.44[f]	4.93[c]	6.22[a]	5.82[b]	1.05[g]	3.23[d]	2.74[e]

Note. Means with the same letter at a given parameter are not significantly difference (p>0.05) according to Duncan's Multiple Range Test (DMRT) at α = 0.05; values are the means of five replicates; n=210. T0= Commercial chemical fertiliser (Control), T1= Commercial organic fertiliser, T2= 100% PLB, T3= 100% TBF, T4= 75% PLB + 25% TBF, T5= 50% PLB + 50% TBF, and T6= 25% PLB + 75% TBF

These findings were congruent with studies by Hanyabui[21] and Japakumar et al.[22], that is, the combination of biochar with compost enhanced nutrient content in plants. In this study, combination of PLB and TBF treatments was found to enhance the nutrient content in *C. chinense* plants, with T4 producing the second-highest plant nutrient content after T0. These results indicated that the use of 75% PLB combined with 25% TBF application was the most effective combination to improve nutrient uptake by *C. chinense*. The combination of PLB and TBF significantly improved nutrient availability and plant absorption compared to single amendments. Pineapple leaf biochar enhanced soil nutrient retention and structure, while TBF actively mobilised and solubilised nutrients, leading to higher nutrient-use efficiency, improved root growth, and greater disease resistance. A recent study conducted by Atluri et al.[59], stated that the co-application of biochar along with biofertiliser showed better performance of crops and nutrient uptake. This study indicated that the incorporation of PLB with TBF could improve nutrient retention in the substrate. Furthermore, this result aligned with findings by Lehmann et al.[60] on the potential of biochar as a plant growth promoter and nutrient retention agent in media by reducing rapid nutrient leaching during irrigation, especially organic N, and finally increasing yields.

Based on the results, T0 and T4 consistently showed the highest nutrient levels in plants, however, the nutrient levels in cocopeat were relatively low. The relatively lower nutrient levels in cocopeat suggest efficient absorption by plants, revealing effective nutrient uptake by *C. chinense*. Treatment T1 generally showed the lowest nutrient content in plants but higher levels in cocopeat, indicating inefficient nutrient uptake by plants. The data suggested that the combination of PLB and TBF improved nutrient uptake compared to a single organic amendment[21,22]. Employing a combination of treatments that balanced nutrient availability and uptake can lead to better plant health and yields. The results also showed the highest yield recorded in T4 (Fig. 3) and the lowest nutrient levels in cocopeat (Table 5) compared to other organic treatments, which indicated effective nutrient absorption by *C. chinense*. An integrated approach ensured that all essential nutrients were adequately supplied and utilised. The addition of both organic amendments into the media positively impacted nutrient retention, minimising nutrient leaching while making it continuously available to plants. Based on the overall findings, T4 is recommended as an alternative to chemical fertilisers and could improve substrate fertility as a sustainable agricultural practice.

4 CONCLUSION

This study evaluates the effects of PLB application with TBF on *C. chinense* growing in cocopeat media. The outcome suggests that 75% PLB, with 25% TBF is the ideal combination to enhance the agronomic performance of *C. chinense*. The results confirm that these organic amendments significantly increases the growth, yield, and nutrient content of *C. chinense*. It also highlights the potential of producing *C. chinense* using a sustainable method by promoting the use of organic amendments instead of chemical fertilisers. The findings reveal that the inferred ratios can effectively reduce dependence on chemical fertilisers while improving or sustaining crop productivity.

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CONFLICT OF INTEREST

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

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Methodology: S. Mahdian, N. Rosli & S. Jos
Formal analysis: S. Mahdian & S. Jos
Visualisation: S. Mahdian & S. R. Basri
Software: S. Mahdian & S. R. Basri
Writing (original draft): S. Mahdian
Writing (review and editing): H. Mohidin, R. Abdullah & K. Khalid
Validation: H. Mohidin, R. Abdullah & K. Khalid
Supervision: H. Mohidin
Funding acquisition: S. Mahdian & H. Mohidin
Project administration: S. Mahdian

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