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Research article

Effects of different substrates on the growth and yield of *Amorphophallus muelleri*

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ABSTRACT

Seven different substrates were prepared by mixing red soil, humus and river sand in different volume ratios and the growth and yield of *Amorphophallus muelleri* bulbils in different substrates was investigated. The growth of *A. muelleri* seedlings were tracked during the reproductive period, with measurements taken of indicators such as petiole length, petiole basal diameter and leaf size during the late period of leaf expansion. Number of surviving plants, weights and sizes of corms, and leaf bulbils were recorded after lodging. The results showed that there were differences in the physical and chemical properties of the seven substrates, but all met the growth requirements of *A. muelleri*. T1 (river sand), T2 (river sand: humus 1:1), T3 (humus), and T7 (river sand: humus: red soil 1:1:1) had higher emergence rates, reaching 95 %. T4 (humus: red soil 1:1) and T7 had better growth, with larger petiole and leaf sizes than other substrates. T3, T4, and T7 had higher yields, with a bulbil yield of 0.30 t hm^{-2} and a corm yield of 22.06 t hm^{-2}. Compared to the use of a single substrate, whether river sand, humus, or red soil, the proportional mixture of the three test materials improved the physical structure and chemical composition of the substrate, contributing to the growth of *A. muelleri*. T7 (river sand: humus: red soil 1:1:1) was was found to be the best nursery substrate for *A. muelleri*.

1. Introduction

Konjac (*Amorphophallus* Blume ex Decne.) is a common name for a genus of perennial, metamorphic underground stem herbaceous plants in the Araceae family [1]. They are mainly distributed in tropical and subtropical countries and regions in Asia and Africa between 16 and 24°N [2,3]. Konjac glucomannan (KGM) is a dietary fiber hydrocolloid polysaccharide isolated from konjac corms,

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which has the characteristics of water absorption, film formation, gelation, and moisturization, and has special physiological effects such as lowering blood pressure and blood lipids [4–6]. Due to the konjac being the only plant in nature that can extract large amounts of glucomannan, purified KGM has been widely used in food, medicine, chemical industry, agriculture, and environmental protection, with significant economic value [7].

Amorphophallus muelleri is one of the species of *Amorphophallus* with pearl-shaped aerial reproductive bulbils on the leaf surface (at the intersection of leaf veins), mainly found in the tropical regions of India, Bhutan, Nepal, Malaysia, Thailand, Bangladesh, Myanmar and China [8,9], and was first reported by Heterscheid et al. [10]. It has many advantages e.g. high content of glucomannan, high temperature and humidity tolerance for hot zone cultivation, short growth cycle, multi-seedling relay succession, high expansion coefficient, and strong resistance to soft rot disease, and it is a kind of bulbils konjac widely cultivated in Asia [11,12]. Unlike the more traditional species of *Amorphophallus heterophylla* and *Amorphophallus albus*, *A. muelleri* has triploid chromosomes [13], and the unique bulbils on the leaves are the main reproductive materials. The successful emergence and growth of newly planted bulbils can successfully germinate and grow depending on their absorptive capacity and access to adequate soil nutrients and water [14].

In Xishuangbanna, a state in China, farmers are planting the small bulbils directly in the local red soil. The red soil hardened and the nutrients supply was limited, resulting in a low emergence rate, and a waste of a large amount of bulbil resources. The quality of the substrate mainly depends on its physical and chemical properties. A good substrate provides sufficient water and nutrient supply for plant growth, and the nutrients in it are easily absorbed and utilized by plants. Meanwhile, it ensures inter-root gas exchange and provides support for plants [15,16]. The primary growth of konjac mainly depends on the nutrients of the implant. After growing into new corms, they mainly absorbs soil nutrients [17]. For smaller bulbils, due to their low nutrient storage and poor absorption capacity, they are not suitable for field planting directly. They need to be cultivated in a suitable substrate to become underground corms for field planting, in order to better avoid the waste of konjac resources and shorten the time from planting to harvesting. The substrate is not absorbed by plants, but plants absorb nutrients.

Wang [18]proposed that the prospects for konjac cultivation was good, but in the past 30 years, there has been few research on the substrate for konjac cultivation. The majority of the research only focused on konjac tissue culture seedling technology [19] and solid seed nursery [20] but few research on the substrate required for cultivation. Currently, many scholars have conducted studies on seedling substrates for different crops, e.g. *Cucumis sativus*, *Coffea arabica*, *Lycospersicon esukurentamu* [21–23]. In recent years, the planting area of konjac in many tropical and subtropical countries and regions has been continuously expanding and has a great application potential. However, smaller *A. muelleri* bulbils need to be cultivated as underground bulbs in suitable substrates before they can be used for field planting, the shortage of bulbils and corms has seriously restricted the development of the konjac industry [24,25].

In this study, the growth and yield of small konjac bulbils (individual bulbil mass < 2g) of *A. muelleri* in seven different substrates was investigated. The study screened out the substrate formulas suitable for large-scale and refined cultivation of small bulbils from seven tested substrates, providing technical support to improve the emergence rate and survival rate of bulbils for high bulbil yield at low cost. The findings provide references for the selection of field cultivation plots and soil improvement of *A. muelleri*.

2. Materials and methods

2.1. Regional setting

The study area is located in Jinghong City, Xishuangbanna Dai Autonomous Prefecture, Yunnan Province of China (22′00′51 N, 100′46′53E), with an altitude of 562 m. Climate data was collected through the use of a HOBO U30-NRC automatic weather station. In

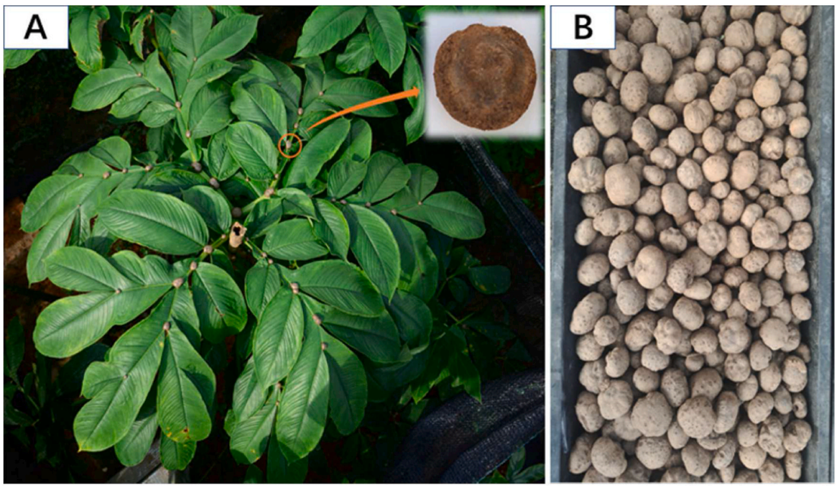

Fig. 1. *Amorphophallus muelleri.* (A) Bulbils on the leaves. (B) Bulbils after harvest.

2022, average relative humidity was 78.21 %, average annual temperature was 23.65 °C, with the hottest month (May) averaging 26.36 °C, and the coldest month (January) averaging 19.19 °C; frost-free all year round. The year spans dry and hot season, rainy season, and foggy and cool season. The experiment was conducted in the nursery of Yunnan Institute of Tropical Crops with a transparent polycarbonate board rain shelter of 2.3 mm above the experimental field, and a 60 % shading net under the shelter.

2.2. Sampling and analysis

2.2.1. Sampling

A. muelleri is widely cultivated in Asia, and our experimental institution has also conducted long-term breeding for the species (the breeding base is located in Jinghong, Yunnan).The bulbils used in our experiment were directly obtained from our cultivated individuals [Fig. 1 (A)]. The small bulbils collected from the leaves of *A. muelleri* in early December of 2021 were used as planting materials. The bulbils we stored in a cool and ventilated storage shed post-harvest [Fig. 1 (B)]. We randomly selected 2100 bulbils, each weighing less than 2g, flat and round, with uniform size and no surface damage. The thousand-grain weight of the selected bulbils was 1120g. The red soil (local soil type, with the 0–20 cm deciduous layer removed to take the subsoil below 20 cm), humus (a 50/50 mix of Pinch peat soil and Stanley coconut brick), and river sand (particles of 0.35–0.5 mm, sourced from the local Lancang River and rich in minerals, primarily clay, with a relatively compact texture) were mixed well in various volume ratios to create the breeding substrates (Table 1).

2.2.2. Determination of substrate physical and chemical properties

Physical properties were determined following the methods as described by Verdonck et al. [26]. Take the substrate in its original state and measure its physical properties e.g. bulk density, total porosity, aeration porosity and water-holding porosity. The detailed methods are as follows.

(1) Substrate bulk density = dry substrate mass in the ring knife/ring knife volume
(2) Total porosity = saturated water content × substrate bulk density × 100 %
(3) Water-holding porosity (capillary porosity) = capillary water content × substrate bulk density × 100 %
(4) Aerated porosity (non-capillary porosity) = total porosity - capillary porosity

Chemical properties were analyzed using the methods of substrate nutrient analysis in laboratory [27]. The substrate organic matter content was determined by the potassium dichromate-external heating method. The alkali hydrolyzed nitrogen content was determined by the alkali hydrolysis diffusion method. The available phosphorus content was determined by the continuous flow analyzer; and the available potassium was determined by the ammonium acetate extraction-flame photometry method [28,29]. The naturally air-dried substrate was filtered with distilled water, and then the pH value and EC values with a Mettler multi-parameter meter [30].

2.2.3. Planting and management

Twenty-one 1 m × 1 m standard plots were marked in a 1.1 m wide seedbed, and seven different substrates treatments were randomly set up, which were repeated for three times. The substrates were mixed evenly and put into the seedbed, watered and finally filled until flush with the edge of the seedbed, with a substrate thickness of 50 cm (greater than the root length of the small bulbils at full fertility).

The substrate was watered thoroughly 1 day before planting and drenched with 800-fold carbendazim solution [31]. 100 pits with a depth of 5 cm were dug per plot with a density of 10 cm × 10 cm, and small beads were planted. Three random plots were set up for each substrate treatment to replicate the experiment. The planting was at the same time on March 30, 2022. The plants were managed in a conventional way with watering 2–3 times a week to ensure adequate water supply and free from water stress during the growth growing period.

2.2.4. Growth performance observation

Each bulbil would grow a plant and the number of plants would be calculated for the emergence rate. The survival rate of plants, the time of leaf replacement, and the time of lodging were continuously observed and recorded in a cycle of 7 days. When the petiole no longer grew and the leaf length no longer changed, the base diameter of the entire plant was measured with a vernier caliper (accurate

Table 1
Seven treatments with different ratios of breeding substrates (volume ratio).

Treatment	River sand	Humus	Red soil
T1	1	0	0
T2	1	1	0
T3	0	1	0
T4	0	1	1
T5	0	0	1
T6	1	0	1
T7	1	1	1

to 0.1 mm), and the petiole length and leaf diameter were measured with a tape measure (accurate to 0.01 m). The plants were harvested 15 days after lodging, and the weight of the corms and bulbils of each plant was weighed separately. The number of bulbils on each leaf was different and was recorded.

2.2.5. Statistical analysis

The growth, yield data and time recording values of *A. muelleri* under different substrate treatments were entered into WPS Office 2019 for compilation and statistics. One-way analysis of variance (ANOVA) was used in SPSS 24.0 software to test the significance of differences among substrates, to perform do a comparative analysis of the physical and chemical properties of the substrates and the growth of *A. muelleri* between different substrate treatments. The principal component analysis was used to comprehensively evaluate the growth trait indicators of *A. muelleri*. SigmaPlot 14.0 and Origin 2022 were used for graphing.

3. Results

3.1. Physical and chemical properties of different substrates

The physical properties of the seven substrates prepared by mixing red soil, humus, and river sand in different volume ratios were varied (Table 2). A significant difference in bulk density was observed among different substrates ($P < 0.05$), ranging from 0.54 g cm^{-3} to 1.54 g cm^{-3}. The total porosity with the smallest being T1 (36.15 %) and the largest being T3 (74.77 %), which was significantly different from the other substrates. The aerated porosity with the smallest being T3 (0.80 %), which was significantly different from T1 and T7. The water-holding porosity varied in the order of T1 < T6 < T7 < T5 < T4 < T2 < T3, with the largest being T3 (73.45 %) and the smallest being T1 (21.45 %), which was significantly different from the other substrates. Generally, T1 (river sand) had the strongest air permeability and the weakest water-holding capacity; While T3 (humus) had the poorest air permeability and the strongest water-holding capacity.

The chemical properties of the seven substrates also differed (Table 2). The organic matter content varies greatly between different substrates, and the highest T3 (133.05 g kg^{-1}) was nearly 40 times that of the lowest T1 (3.41 g kg^{-1}). The highest content of alkali hydrolyzed nitrogen was T3, which was significantly higher than other substrates. The highest content of available phosphorus and available potassium were T3, which was significantly higher than other substrates. The pH showed that T1 (river sand) was the highest and alkaline (9.25), which was significantly higher than other substrates. T3 (humus) was weakly alkaline (pH 7.72) and T5 (red soil) was acidic (pH 4.45). The EC value with the smallest being T5 (33.10 μS cm^{-1}) and the largest being T3 (171.90 μS cm^{-1}), which was significantly different from the other substrates. The soluble salt content did not affect the osmotic pressure and was suitable for the growth of *A. muelleri*.

Compared with the T1 substrate, the bulk density of T7 substrate had decreased by 0.1 g cm^{-3}, the total porosity increased by 2.59 %, and the aeration porosity increased by 7.09 %. The substrate physical properties were considerably improved. Moreover, due to the addition of humus, the content of organic matter increased by 37.47 g kg^{-1} compared to that of single red soil, and the contents of alkali-hydrolyzable nitrogen, available phosphorus and potassium also increased to varying different degrees.

3.2. Comparing the growth of A. muelleri in seven substrates

After the completion of planting of bulbils of *A. muelleri* on March 31, 2020, the number of above-ground plants was continuously investigated once a week throughout the whole growth period, and their emergence and lodging period were recorded, and the emergence rate was calculated. It was found that the whole lodging of *A. muelleri* petiole ended 34 weeks after planting. T4 and T5 started to emerge relatively early (in the 4th week), and the overall emergence period was concentrated in the 4th and 5th weeks. Statistical analysis of the emergence of bulbils showed that T1, T2, T3, and T7 all reached a high emergence rate of 95 %, while the emergence rates of T4, T5 and T6 were 86 %, 87 % and 81 %, respectively. Different substrate treatments showed different trends in the time and rate of the lodging of *A. muelleri*. T5 was the earliest, while T7 was the latest to be lodging. T1 was the fastest lodging from the

Table 2
Comparison of physical and chemical properties of seven substrates were compared using analysis of variance (ANOVA).

Substrates	Bulk density/ (g.cm^{-3})	The total porosity/ %	Aerated pore space/%	Water holding pores/%	Organic matter/(g. kg^{-1})	Alkali-hydrolyzed nitrogen/(mg. kg^{-1})	Available Phosphorus/ (mg.kg^{-1})	Available Potassium/ (mg.kg^{-1})	pH	EC/(μS. cm^{-1})
T1	1.54a	36.37e	14.92a	21.45f	3.41f	25.10e	8.84b	24.16d	9.3a	55.50d
T2	0.85f	59.93b	6.01abc	53.92b	116.20b	40.64d	7.32BCE	137.53c	9.0b	75.30c
T3	0.54g	74.25a	0.80c	73.45a	133.05a	356.94a	20.57a	1041.27a	7.7d	171.90a
T4	0.95e	60.14b	8.66abc	51.48BCE	60.23c	119.19b	2.64d	210.04b	6.3f	45.50e
T5	1.24c	48.89c	4.45BCE	44.44cd	5.41e	35.49d	0.71d	16.12d	4.5g	33.10f
T6	1.39b	45.38d	10.81abc	34.57e	5.96e	40.30d	5.14c	23.36d	7.9c	96.00b
T7	1.14d	51.48c	11.54 ab	39.94de	42.88d	50.24c	5.63c	116.39c	7.3e	99.30b

Note: The different lowercase letters in the same column indicated significant differences in physical and chemical properties of seven substrates ($P <$ 0.05).

20th week. T2 and T7 lodged the slowest. T2, T3, and T4 had the longest duration of growth, reaching 34 weeks, followed by T7 (33 weeks). The growth period of T1 and T6 was the shortest, only 31 weeks (Fig. 2).

Different substrates had a significant effect on the growth of *A. muelleri*. After the leaves were fully expanded, the leaf length, the petiole length and diameter of the *A. muelleri* under different substrates were measured (Fig. 3).

The leaf of T7 (28.9 cm) was the longest, which was approximately 3 times that of T1 (10.46 cm), and no significant difference was observed between T7 and T4. The length of petiole ranged from 9.33 cm to 52.79 cm, and the variation range is large. The highest length of petiole was T7, which was significantly higher than other substrates and about 5.6 times that of T1. Followed by T4, which was about 5 times that of T1. T1 had the shortest petiole length, with an average of only 9.33 cm.

The mean value of petiole basal diameter ranged from 2.78 mm to 9.76 mm, and its variation trend (T1 < T6 < T3 < T2 < T5 < T4 < T7) was similar as that of leaf length. The petiole diameter of T1 was significantly smaller than those of the other substrates. T7 had the largest petiole diameter (9.76 mm), which was significantly higher than other substrates, and was about 3.5 times that of T1 (2.78 mm).

3.3. Comparing the yield of A. muelleri in seven substrates

After half a month of lodging, *A. muelleri* were collected and the individual corm diameters, corm weight and bulbil weight under seven substrate treatments were measured (Fig. 4).

The results of corm size among different substrates showed that the mean of corm diameter with the largest T7 (44.36 mm) being about 3 times that of the smallest T1 (15.68 mm). The corm diameter of T5 (29.99 mm) was about twice that of T1. The average weight of the harvested corms was 25.57 g, with the largest being 140.5 g. Corms under T7 treatment (29.48 g) was the most suitable and economical for field cultivation.

The number of harvested bulbils was smalland the average number of bulbils per plant was increasing in the order of T5 (0.13) $<$ T6 (0.30) $<$ T5 (0.40) $<$ T2 (1.10) $<$ T4 (1.13) $<$ T3 (2.03) $<$ T7 (2.47). The average weight was low (0.85 g). The bulbils under T7 treatment had the largest average weight (1.30 g), which was equivalent to the size of the bulbil used for the experiment, but it could not be directly used as a field bulbils resource.

The yield of *A. muelleri* was statistically calculated from the harvested bulbils and corms, and it was found that different substrates treatments had an impact on the yield of *A. muelleri* bulbils and corms (Fig. 5). The total yield varied in the order of T1 < T6 < T5 < T2 < T3 < T4 < T7, which was similar to the corms yield, while the bulbils yield (T1 < T6 < T5 < T2 < T4 < T3 < T7) was inconsistent with total yield. The yield of T1, T5, and T6 was relatively low. The corms yield of T1 (0.55 t hm^{-2}) plus the bulbils yield (0.01 t hm^{-2}) was still significantly lower than the bulbils yield of T7 (0.96 t hm^{-2}). Although the total yield of T3 (22.44 t hm^{-2}) was lower than that of T4 (22.74 t hm^{-2}), the bulbils yield (0.38 t hm^{-2}) was higher than that of T4 (0.30 t hm^{-2}). Generally, T7 had the highest yield of bulbils and corms, so the total yield was also the highest among the seven substrate treatments.

3.4. Comprehensive evaluation of A. muelleri growth

The principal component analysis to the 13 growth indicators of *A. muelleri* was conducted (Table 3). Two principal components were extracted with characteristic values greater than 1, and the cumulative contribution rate was 87.10 %. This indicated that these two principal components played a dominant role in the growth of *A. muelleri* and comprehensively reflected the growth status of *A. muelleri*.

The characteristic value of the first principal component was 9.05, which contained 69.61 % of the original information. Except for the negative effect of the minimum bulbil weight on the first principal component, the other 12 indicators all had positive effects, and the loading values were all greater than 0.60, with the largest value (0.98) being the maximum corm weight. The characteristic value of the second principal component was 2.27. The positive loading weights of the maximum bulbil weight, minimum bulbil weight,

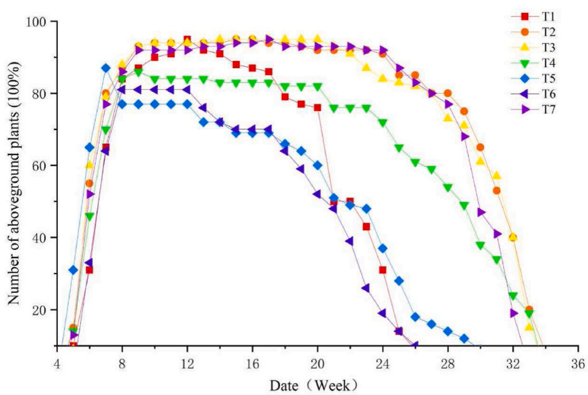

Fig. 2. Emergence and lodging of *Amorphophallus muelleri* under seven substrates.

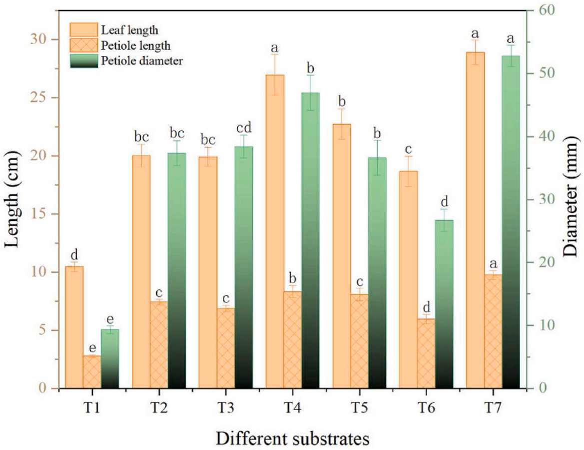

Fig. 3. The growth of *Amorphophallus muelleri* in seven substrates
Note: Different lowercase letters within the same illustration denote significant differences in plant growth indices among the seven substrates ($P < 0.05$).

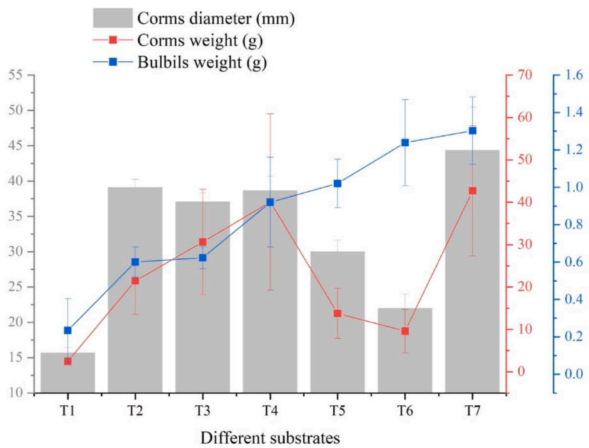

Fig. 4. The growth of *Amorphophallus muelleri* in different substrates.

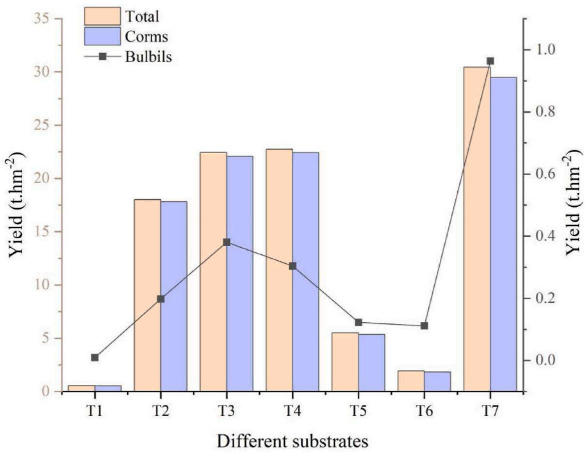

Fig. 5. Comparison of *Amorphophallus muelleri* yield under different substrates.

Table 3
Principal component analysis of growth traits of *Amorphophallus muelleri*.

Factors		Principal component	
Numbering	Specific indicators	1	2
X_1	Bulbils number	0.86	−0.38
X_2	Bulbils yield	0.9	−0.01
X_3	Maximum bulbil weight	0.82	0.4
X_4	Minimum bulbil weight	−0.01	0.84
X_5	Bulbils average weight	0.62	0.71
X_6	Corms number	0.69	−0.67
X_7	Corms yield	0.91	−0.36
X_8	Maximum corm weight	0.98	−0.1
X_9	Minimum corm weight	0.79	0.3
X_{10}	Corm average weight	0.93	−0.14
X_{11}	Petiole diameter	0.93	0.13
X_{12}	Petiole length	0.97	0.01
X_{13}	Crown width	0.93	0.24
X_{14}	Characteristic value	9.05	2.27
X_{15}	Contribution rate	69.61	17.49
X_{16}	Cumulative contribution rate	69.61	87.1

bulbil average weight, and minimum corm weight were relatively large, with values of 0.40, 0.84, 0.71, and 0.30, respectively. However, the negative loading weights of the number of bulbils, number of corms, and corm yield were relatively large, with values of −0.38, −0.67, and −0.36, respectively.

The principal component analysis was performed on all substrate treatment. Based on the variance contribution rate and the factor score coefficients of the first and second principal components and the comprehensive evaluation model coefficients could be obtained. After normalization, the expression of the comprehensive evaluation score model for each index could be obtained as follows:

$$Y_1 = 0.29X_1 + 0.30X_2 + 0.27X_3 + 0.01X_4 + 0.21X_5 + 0.23X_6 + 0.30X_7 + 0.33X_8 + 0.26X_9 + 0.31X_{10} + 0.31X_{11} + 0.32X_{12} + 0.31X_{13}$$

$$Y_2 = - 0.25X_1 - 0.01X_2 + 0.26X_3 + 0.55X_4 + 0.47X_5 - 0.45X_6 - 0.24X_7 - 0.07X_8 + 0.20X_9 - 0.09X_{10} + 0.08X_{11} - 0.01X_{12} + 0.16X_{13}$$

Substitute each indicator into the comprehensive evaluation model, the ranking of comprehensive scores of the seven substrates were shown in Table 4.

4. Discussion

The physical and chemical properties of different substrates directly influence plant growth [32]. Research on the indicators of plant growth (plant height, basal diameter, leaf area) and yield is the most direct method to test and evaluate substrates [33,34]. In this study, the substrates were mixture of different volume ratios of river sand, red soil and humus. The seven substrates showed difference in bulk density, total porosity, aerated porosity, water-holding porosity and organic matter content, river sand had strong air permeability but poor water-holding capacity, with a pH value of alkaline. Humus had the highest contents of organic matter, available nitrogen, phosphorus, potassium, showing the highest fertility, but with a weakly alkaline pH value. Red soil had poor air permeability with an acidic pH value. These factors may affect the growth and yield of bulbils.

In this study, the differences in the yield, corm size and plant growth of *A. muelleri* under different substrate treatments were not completely consistent. The relationship between corm size and yield was analyzed and it was found that the corm size under different substrates did not respond well to the difference in corm yield mainly due to the large difference in plant deficiency rate of *A. muelleri* among different substrates. From a comprehensive analysis of plant growth and yield, it was found that the growth of bulbils with T7 treatment were the greatest, and which also showed the best yield of bulbils and corms. T1, in contrast, showed the worst growth and yield; T5 showed no significant difference in growth with T2 and T3, but showed a significant difference in yield. The potential reason is that the substrate of T5 may have been more conducive to the initial growth of *A. muelleri*, but it may have lacked the essential nutrients required for the later expansion and growth of *A. muelleri* corms. This deficiency could have limited the provision of nutrients throughout the entire growth cycle of *A. muelleri*. Additionally, the inherent tendency of the brick red soil to slump may have impeded the proper expansion of the corms underground during the later stages [35–37], leading to reduced nutrient accumulation and potentially contributing to the early lodging observed. Therefore, it was necessary to carry out in-depth research on the nutrient requirements of *A. muelleri* at different growth stages, and explore the impact of different planting densities on growth and yield to provide high-yield and high-quality cultivation and breeding for *A. muelleri*.

Among the seven substrates, rriver sand had the greatest air permeability but the weakest water-holding capacity, while humus was the opposite, and both pH values were weakly alkaline. The substrate of T2 was made of humus with highest nutrient content and river sand with the greatest permeability, the yield of which should be the highest, but the result showed that the highest yield was achieved in T7 treatment made of river sand, humus, and red soil, and the difference in yield between T2 and T7 was significant. One reason might be the addition of alkaline river sand and humus to the acidic red soil, which regulated the pH value of the substrate [38], making it more suitable for the growth of *A. muelleri*. Another reason might be that red soil contained a large amount of iron and other

Table 4
The comprehensive evaluation scores of the seven substrates.

	Different substrates						
	T_7	T_4	T_3	T_5	T_2	T_6	T_1
Comprehensive score	4.04	1.44	0.18	−0.28	−0.38	−1.06	−3.94
Order	1	2	3	4	5	6	7

macro elements and trace elements such as nitrogen, phosphorus, potassium [39–41], which were exactly the elements required for the growth of *A. muelleri*. Therefore, further research on the effect of substrate physical and chemical properties on the yield of *A. muelleri* was necessary to explore the types and amounts of fertilizer needed for *A. muelleri* in depth to provide technical support for high-yield cultivation.

In the future research, the gradient ratios of the three substrates in this study could be adjusted to explore substrate formulas with higher seedling efficiency. However, the substrates used in this study were relatively homogeneous, and locally available tree residues such as mixed wood sawdust, coconut leaf stems/petioles, coconut fiber waste, rubber logs sawdust, etc. could be added as substrates [42]. Materials with lower cost, such as rice husks, compost, peat soil, etc. could also be explored as research materials [43–45]. Different substrates with different formulas and ratios could be set up for further research to explore low-cost and efficient substrates for cultivation of *A. muelleri* with greater precision.

5. Conclusions

This study has demonstrated that the growth and yield of *Amorphophallus muelleri* bulbils are significantly influenced by the physical and chemical properties of seven substrates, which are composed of varying ratios of red soil, humus, and river sand. The emergence rate of *Amorphophallus muelleri* was particularly high in substrates T1, T2, T3, and T7, reaching 95 %, indicating a favorable environment for seedling establishment. Furthermore, T4 and T7 exhibited superior vegetative growth, characterized by larger petiole and leaf sizes. Yield analysis revealed that T7 achieved the highest bulbil and corm yields of 0.30 t hm^{-2} and 22.06 t hm^{-2}, respectively.

Compared to the use of a single substrate, whether river sand, humus, or red soil, the proportional mixture of these three test materials improved the physical structure and chemical composition of the substrate, making it more suitable for the growth of *Amorphophallus muelleri*. Among seven different substrates, T7 (river sand: humus: red soil 1:1:1) was the most suitable substrate for the growth of *Amorphophallus muelleri* bulbils. In summary, the study emphasized the importance of substrates formulation in optimizing the growth and yield of *Amorphophallus muelleri*. It is also helpful to promote the substrate selection and management practice of *Amorphophallus muelleri* cultivation, and has an impact on sustainable agriculture and horticulture.

Ethical approval

The plant collection and use was in accordance with all the relevant guidelines.

Originality

The authors declare the work described was original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part.

Data availability statement

The datasets used and analyzed during the study are available from the corresponding author upon request.

CRediT authorship contribution statement

Rui Xu: Writing – original draft, Methodology, Funding acquisition. **Xiaofeng Zheng:** Writing – original draft, Software. **Chao Chen:** Software, Resources. **Maobiao Li:** Writing – review & editing. **Jinwei Li:** Methodology, Formal analysis. **Huiping Zhou:** Resources. **Yanxiong Gong:** Resources. **Xiangshuai Yan:** Supervision, Data curation. **Changming Wang:** Supervision.

Declaration of competing interest

The authors declare no competing interests.

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References

[1] S.J. Mayo, J. Bogner, P.C. Boyce, The Genera of Araceae, Royal Botanic Gardens, Kew, 1997.
[2] M. Chua, T.C. Baldwin, T.J. Hocking, K. Chan, Traditional uses and potential health benefits of *Amorphophallus konjac* K. Koch ex N.E.Br, J. Ethnopharmacol. 128 (2010) 268–278.
[3] N. Cusimano, et al., Relationships within the Araceae: comparison of morphological patterns with molecular phylogenies, Am. J. Bot. 98 (2011) 654–668.
[4] J. Wu, S.S. Peng, Comparison of hypolipidemic effect of refined konjac meal with several common dietary fibers and their mechanisms of action, Biomed. Environ. Sci. 10 (1997) 27–37.
[5] L. Yuan, et al., Effects of deacetylation of konjac glucomannan on the physico-chemical properties of surimi gels from silver carp (Hypophthalmichthys molitrix), RSC Adv. 9 (2019) 19828–19836.
[6] K. Meng, et al., Rheological and microstructural characterization of wheat dough formulated with konjac glucomannan, J. Sci. Food Agric. 101 (2021) 4373–4379.
[7] D. Yang, et al., A review on konjac glucomannan gels: microstructure and application, Int. J. Mol. Sci. 18 (2017) 2250, https://doi.org/10.3390/ijms18112250.
[8] D. Zhang, Q. Wang, Z. Duan, K. Mi, Mechanism of relay multi-seedling release *Amorphophallus bulbifer* and its application in Southeast Asia, Resour. Dev Mkt. 25 (2009) 682–684+710.
[9] F.J. Zhang, H.L. Liu, J. Zhang, Y. Niu, S.L. Zhang, Research progress of *Amorphophallus bulbifera* resources, South Chin. Agric. 7 (2013) 64–67.
[10] W. Hetterscheid, S. Ittenbach, Everything you always wanted to know about *Amorphophallus*, but were afraid to stick your nose into, Aroideana. 19 (1996) 13–16.
[11] Z. Xue, et al., A high trans-zeatin nucleoside concentration in corms may promote the multileaf growth of *Amorphophallus muelleri*, Front. Plant Sci. 13 (2022) 964003, https://doi.org/10.3389/fpls.2022.964003.
[12] M.C. Gui, et al., Effects of plant growth regulators on tissue culture by leafstalk of *Amorphophallus bulbifer*, North. Hortic. 7 (2020) 20–26.
[13] C. Pouchon, J. Gauthier, C. Pitteloud, C. Claudel, N. Alvarez, Phylogenomic study of *Amorphophallus* (Alismatales; Araceae): when plastid DNA gene sequences help to resolve the backbone subgeneric delineation, J. Syst. Evol. 61 (2023) 64–79.
[14] S.C. Grossnickle, Importance of root growth in overcoming planting stress, New For 30 (2005) 273–294.
[15] V. Zoes, H. Dinel, T. Paré, A. Jaouich, Growth substrates made from duck excreta enriched wood shavings and source-separated municipal solid waste compost and separates: physical and chemical characteristics, Bioresour. Technol. 78 (2001) 21–30.
[16] V.M. Montoya-Jasso, V.M. Ordaz-Chaparro, G.S. Benedicto-Valdés, A. Ruiz-Bello, J.M. Arreola-Tostado, Chemical and physical characterization of substrates enriched with minerals and compost, Terra Latinoamericana 39 (2021) 601, https://doi.org/10.28940/terra.v39i0.601.
[17] P.Y. Liu, J.F. Chen, Studies on the morphological development and growth trend of tuber of elephant-foot yam (*Amorphophallus rivieri* durieu and a. albus p.y.liu et j.f.chen), Acta Hortic. 4 (1986) 263–270.
[18] C.X. Wang, *Amorphophallus konjac* seed seedling has a good prospect, Sichuan Agric. Sci. Technol. 6 (1986) 34–35.
[19] D. Li, M.A. Mohammadi, Y. Qin, Z. Zhang, Somatic embryogenesis and indirect in vitro plant regeneration in *Amorphophallus konjac* K. Koch by one-step seedling formation, Horticulturae 7 (2021) 497, https://doi.org/10.3390/horticulturae7110497.
[20] J.W. Li, X.S. Yan, H.P. Zhou, H.F. Yuan, Y.H. Tian, Effects of different seed treatments on the growth of bulbil-yellow konjac, Trop. Agric. Sci. Technol. 45 (2022) 36–40.
[21] M. He, et al., Effect of differences in substrate formulations on cucumber growth under soilless bag culture in greenhouse, Soil Sci. Plant Nutr. 49 (2003) 763–767.
[22] H.R. Silveira, et al., Growth effects of water excess on coffee seedlings (Coffea arabica L.), Acta Sci-agro. 36 (2014) 211–218.
[23] Y.L. Che, Y.M. Li, Q.C. Yang, R.F. Cheng, Q.S. Fan, Application of biogas residue of distiller grains in tomato substrate seedling, J. Agric. Sci. 26 (2021) 88–98.
[24] S.S. Behera, R.C. Ray, Konjac glucomannan, a promising polysaccharide of *Amorphophallus konjac* K. Koch in health care, Int. J. Biol. Macromol. 92 (2016) 942–956.
[25] R.D. Devaraj, C.K. Reddy, B. Xu, Health-promoting effects of konjac glucomannan and its practical applications: a critical review, Int. J. Biol. Macromol. 126 (2019) 273–281.
[26] O. Verdonck, R. Penninck, M. De Boodt, The physical properties of different horticultural substrates, Acta Hortic. 150 (1984) 155–160.
[27] G.S. Liu, Physio-Chemical Analysis of Soils and Descnption of Soil Profiles 266-269, Chinese standard press, Beijing, 1996.
[28] S.D. Bao, Soil and Agricultural Chemistry Analysis, vols. 30–56, Chinese Agriculture Press, Beijing, 2000.
[29] S. Du, Z.X. Gao, Technical Specification for Soil Analysis 9-67, Chinese Agriculture Press, Beijing, 2006.
[30] S.R. Guo, Soilless Culture, vols. 423–425, China Agricultural Press, Beijing, 2003.
[31] Q.Y. Gao, et al., Screening of disinfectant for seedling substrates with plasmodiophora brassicae, Chin. Veg. 359 (2019) 32–36.
[32] M. Roehrdanz, T. Greve, M.D. Jager, R. Buchwald, M. Wark, Co-composted hydrochar substrates as growing media for horticultural crops, Sci. Hortic. 252 (2019) 96–103.
[33] E.M. Waters, M.A. Watson, Live substrate positively affects root growth and stolon direction in the woodland strawberry, Fragaria vesca, Front. Plant Sci. 6 (2015) 814, https://doi.org/10.3389/fpls.2015.00814.
[34] R.R.S. da Silva-Matos, et al., New organic substrates and boron fertilizing for production of yellow passion fruit seedlings, Arch. Agron Soil Sci. 62 (2016) 445–455.
[35] S. Altikat, A. Celik, The effects of tillage and intra-row compaction on seedbed properties and red lentil emergence under dry land conditions, Soil Tillage Res. 114 (2011) 1–8.
[36] Y.B. He, L.R. Lin, J.Z. Chen, Maize root morphology responses to soil penetration resistance related to tillage and drought in a clayey soil. J, Agric. Sci. 155 (2017) 1137–1149.
[37] S.J. Lyczak, J.M. Kabrick, B.O. Knapp, Long-term effects of organic matter removal, compaction, and vegetation control on tree survival and growth in coarse-textured, low-productivity soils, For. Ecol. Manag. 496 (2021) 119428, https://doi.org/10.1016/J.FORECO.2021.119428.
[38] Y. Shen, Z. Zhang, Y. Xue, Study on the new dynamics and driving factors of soil pH in the red soil, hilly region of South China, Environ. Monit. Assess. 193 (2021) 304, https://doi.org/10.1007/s10661-021-09080-4.
[39] C.L. Tu, T.B. He, C.Q. Liu, X.H. Lu, Y.C. Lang, Accumulation of trace elements in agricultural topsoil under different geological background, Plant Soil 349 (2011) 241–251.
[40] G. Chen, K.J. Shah, L. Shi, P.C. Chiang, Z. You, Red soil amelioration and heavy metal immobilization by a multi-element mineral amendment: performance and mechanisms, Environ. Pollut. 254 (2019) 112964, https://doi.org/10.1016/j.envpol.2019.112964.
[41] J. Bai, et al., Nitrogen, water content, phosphorus and active iron jointly regulate soil organic carbon in tropical acid red soil forest, Eur. J. Soil Sci. 72 (2021) 446–459.
[42] G. Thiribhuvanamala, A.S. Krishnamoorthy, Evaluation of different lignocellulosic substrates for cultivation of medicinal mushroom Ganoderma lucidum, J. Environ. Biol. 42 (2021) 1314–1319.
[43] J.S. Buck, M.R. Evans, Physical properties of ground parboiled fresh rice hulls used as a horticultural root substrate, Hortscience 45 (2010) 643–649.
[44] A.L. Shober, C. Wiese, G.C. Denny, C.D. Stanley, B.K. Harbaugh, Plant performance and nutrient losses during containerized landscape shrub production using composted dairy manure solids as a peat substitute in substrate, HortTechnology 21 (2011) 240–245.
[45] G. Atzori, C. Pane, M. Zaccardelli, S. Cacini, D. Massa, The role of peat-free organic substrates in the sustainable management of soilless cultivations, Agronomy 11 (2021) 1236, https://doi.org/10.3390/agronomy11061236.