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Research Article

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Optimized substrate selection for enhanced orchid growth based on high-throughput lysimetric arrays

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Abstract: Orchids are highly valued ornamental plants whose growth conditions directly impact the economic returns of the horticultural industry. The substrate, acting both as a physical support and a nutrient reservoir, is critical for orchid development. Therefore, the careful selection of an appropriate growth substrate is of paramount importance. However, existing research on the relationship between orchid growth and substrate properties relies mainly on manual measurements of physiological indicators, with limited application of high-throughput phenotyping (HTP) platforms. In this study, we evaluated three distinct substrate types, peat soil mixed with perlite, pine bark, and river sand, which were applied to two orchid species, *Cymbidium goeringii* and *Cymbidium faberi*. Using the high-throughput Plantarray lysimetric system, we continuously recorded environmental parameters (photosynthetically active radiation, humidity, and temperature) as well as key growth metrics (biomass accumulation, canopy conductance, and transpiration rate). This platform enabled precise and rapid quantification of orchid growth indicators. The results show that the type of substrate significantly affects orchid growth. Under controlled conditions, mixed substrates that provide balanced nutrition and excellent drainage enhanced orchid growth compared to other substrates. Additionally, when the data obtained from the HTP platform were compared with those from traditional manual measurements, the automated system showed higher reliability and accuracy. This study not only provides practical guidance for selecting cultivation substrates for orchids, but also establishes a robust scientific framework for integrating advanced phenotyping technologies into orchid cultivation practices.

Key words: Orchid; Cultivation substrate; Phenotypic platform; Plantarray; High-throughput monitoring

1 Introduction

Orchids are among the most diverse and evolutionarily successful flowering plant families on earth, with over 28 000 species (Zhang et al., 2024). Within this taxonomically complex group, the genus *Cymbidium* stands out as a particularly species-rich cluster, encompassing about 50–70 recognized species distributed across tropical and subtropical regions of Asia. Beyond their striking aesthetic appeal, characterized by a zygomorphic floral architecture and specialized pollination mechanisms, orchids hold profound cultural significance in societies worldwide. They are deeply embedded in artistic traditions and symbolize values ranging from luxury and elegance to moral virtue. The commercial importance of orchids as ornamental plants continues to grow, with the global orchid trade now constituting a multibillion-dollar horticultural industry.

As one of the top ten famous flowers in China, orchids occupy a pivotal position in the traditional Chinese flower market. With the expansion of the global economy and rising living standards, these iconic plants have gained increasing popularity worldwide. Countries such as the USA, the Netherlands, Japan, and Republic of Korea have been actively developing the orchid industry, driving its continuous growth and cementing orchids as both culturally resonant symbols

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and economically significant commodities (Yang et al., 2017).

The cultivation substrate is a critical medium for plant growth, playing a pivotal role in the development and overall health of orchids. It serves multiple functions: anchoring the root system; supplying essential water and nutrients; and directly influencing the plant morphology, physiological functions, and growth quality (Blok et al., 2021). Orchid roots, being thick and fleshy, thrive in fertile, well-drained, and well-aerated substrates. However, challenges associated with these substrates include susceptibility to decomposition and acidification, limited availability, and rising costs. Mosses, commonly used as the main substrates for *Phalaenopsis* orchids, offer excellent water retention, efficient nutrient retention, strong adaptability, and natural resistance to pests and diseases. Alternative materials like peat, coconut coir, and bark have also been evaluated. For instance, substrates composed of pine bark, sphagnum moss, peat fibers, and coconut husk chips differ significantly in physical characteristics, impacting water retention and aeration (Criscione et al., 2022). In particular, coconut coir offers high water-holding capacity and structural stability but requires buffering to address its high salt content, which is a concern when used alone (Conrad and Hansen, 2007). However, the practical application of these substrates presents challenges, such as incompatibility with mechanical potting operations and tidal irrigation systems, which can limit their broader application. Most studies have focused on agronomic species, with few systematic comparisons of ornamental orchids across multiple substrate types, indicating a gap in horticultural substrate research (Mirani et al., 2017; Wang et al., 2022, 2024). As such, selecting a substrate that balances functionality, sustainability, and adaptability to modern cultivation techniques remains a key consideration in orchid horticulture.

The integration of interdisciplinary research in plant sciences has elevated the importance and urgency of plant phenomics, a field that bridges genetic complexity with environmental interactions to define phenotypic traits (Wu et al., 2024). These traits, which are critical for taxonomic classification and species identification, have long relied on traditional physiological analyses that are inherently limited by their labor-intensive nature, low throughput, high error rates, and restricted scope—often confined to single leaves or specific organs (Haworth et al., 2023). In contrast, the emergence of high-throughput phenotyping (HTP) technologies, collectively termed phenomics, has transformed phenotypic analysis by enabling automated, scalable, and precise data collection (Kumari et al., 2025). These technologies not only reduce time and labor costs but also enhance measurement accuracy, allowing researchers to capture dynamic plant responses across diverse environmental conditions. Recent innovations in spectroscopy, robotics, computer vision, and high-performance computing have expanded the applicability of phenomics from controlled laboratory settings to natural field and greenhouse environments (Wang et al., 2015). For instance, Enders et al. (2019) used RGB imaging to analyze wheat traits under low-temperature stress and recovery under laboratory conditions. Herrero-Huerta et al. (2020) combined data from multiple optical sensors to predict soybean yield. Lazarević et al. (2021) used CropReporter photosynthetic phenotypic imaging and three-dimensional (3D) multispectral scanning technology to assess differences in the phenotypic traits of basil plants subjected to drought and saline-alkali stress. Similarly, Griffiths et al. (2022) leveraged HTP technology to investigate wheat root architecture and nitrate uptake efficiency, identifying key nitrate transporter factors in wheat roots. These advancements underscore how phenomics is redefining plant research by enabling holistic, scalable, and environmentally relevant assessments of plant traits. As phenotyping technologies continue to evolve, their capacity to bridge genotype-to-phenotype gaps will become increasingly vital for addressing challenges in agriculture, conservation, and climate resilience.

Despite significant advances in cultivation substrate research, most studies have focused on crops, with limited attention given to substrates for ornamental plants, particularly orchids (Brown and Klett, 2020; Ortiz-Delvasto et al., 2023). Additionally, current research on orchid cultivation substrates often relies on manual measurements of physiological phenotypic data, and high-throughput physiological phenotyping platforms have yet to be widely applied in this field. To address these limitations, in this paper we introduce the Plantarray physiological phenotypic platform, a high-throughput, multi-sensor system developed by Plant-DiTech. This platform enables non-invasive, continuous monitoring of plant water balance, biomass gain, and environmental parameters, such as soil volumetric water content (VWC), photosynthetically active radiation (PAR), and vapor pressure deficit (VPD), at high resolution. By capturing dynamic water flux in the soil-plant-atmosphere continuum (SPAC), the Plantarray platform provides precise, whole-plant-scale measurements that correlate strongly with field yield results. This technology allows for a comprehensive analysis of orchid growth and development dynamics under different substrates, helping identify environmentally friendly, cost-effective, and compatible substrates for various orchid species. The integration of Plantarray with ecological and physiological models also offers insights into genotype-specific traits, such as transpiration sensitivity to radiation and VPD, which are critical for optimizing orchid cultivation practices. By leveraging this advanced phenotyping platform, this study aimed to provide a robust scientific foundation for sustainable orchid cultivation, supporting industry growth and enhancing the commercial viability of the horticultural sector.

2 Materials and methods

2.1 Research object and matrix selection

The experimental orchid species were *Cymbidium goeringii* Rchb. F. and *Cymbidium faberi* Rolfe, both sourced from the Zhejiang Academy of Agricultural Sciences, Hangzhou, China. *C. goeringii* is characterized by fleshy roots, spherical pseudobulbs, and a compact growth habit. It produces 4–6 slender, narrow leaves with fine serrations along the edges and thrives in a humid environment with about 70% air humidity during its growth period, requiring relatively low light levels. In contrast, *C. faberi* has a thick, short root system and exhibits strong upright growth. It features a taller stature with 5–9 broad, typically green leaves with coarse serrations along the edges, and lacks prominent pseudobulbs.

The experiment used three substrate types: pine bark; a mixture of peat soil and perlite at a 3:1 ratio (referred to as peat soil); and river sand. Peat or peat moss is widely distributed, rich in organic matter, trace elements, and fiber content, and is typically weakly acidic or neutral (Chen et al., 2014; Schafer and Lerner, 2022). However, its poor aeration and water permeability necessitate combination with other substrates. Pine bark offers good aeration, contains organic matter, and maintains a stable pH; however, its widespread use is limited by high costs and significant environmental impacts due to the long growth cycle of pine trees. River sand provides excellent aeration and looseness, facilitating orchid growth and development. It is readily available and cost-effective but lacks essential nutrients and has an unstable pH.

2.2 Settings and operations of Plantarray

The Plantarray platform, based on the principle of evapotranspiration, integrates multiple sensors and the SPAC analysis software to enable real-time monitoring of water content parameters in plants and their surrounding environment (Mupambwa et al., 2017). Prior to the experiment, each test unit underwent calibration using a level gauge and standard weights to enhance the signal-to-noise ratio. The initial mass of each component, including the drainage basin, soil probe, combined irrigation drip head, and plastic film, was recorded. The drainage basin was positioned in the trough of each test unit, and the plants were placed on top. The soil probe and combined irrigation drip head were inserted into the soil of the potted plants, and the soil surface was covered with plastic film to minimize water evaporation. Once all the units were assembled, the configurations were implemented within the SPAC software (Hajiaghaei Kamrani et al., 2019).

Nutrient solution supplementation was managed by an automated phenotyping irrigation system, which delivered three doses of 120 s each at 1:00 a.m., 2:00 a.m., and 3:00 a.m. daily, repeated every five days. This systematic approach ensured precise control over irrigation schedules and nutrient delivery, supporting consistent experimental conditions.

2.3 Experimental environment control

The experiment was conducted from October to November 2024 in a glasshouse at the Huaiyin Agricultural Science Research Institute, located in the Xuhuai Region of Jiangsu Province (Huai'an City, Jiangsu Province, China). The glasshouse measured 10 m×5 m×4 m (length×width×height) and was constructed with 4-mm thick tempered glass on the roof and 4-mm float glass on the sides and partitions. The light transmittance exceeded 87%, and the facility was equipped with heating, air circulation, ventilation, and shading systems.

To ensure uniform growth conditions, only healthy and pest-free orchid seedlings were selected. These seedlings were transplanted into 1.5-L plastic pots (upper diameter: 16 cm; lower diameter: 13 cm; height: 18 cm) on October 11, 2024. The physicochemical properties of the matrix used are shown in Table 1 and were measured using standard soil analysis methods (Klute and Dirksen, 1986; Wright, 1986). Apart from variations in substrate composition, all other cultivation conditions, including water and fertilizer management, were maintained consistently. After a 4-d acclimatization period, four pots with uniform growth characteristics were selected from each experimental group for physiological phenotype analysis on October 15. The nutrient solution used was "Zhonghua Nanyan Series" water-soluble macroelement fertilizer (Zhonghua Chemical Fertilizer Holding Co., Ltd., China) at a concentration of 2 g/L. Pest and disease management followed standard production protocols.

2.4 Data monitoring and collection

Simultaneously, low-throughput growth indicators of orchids were routinely measured. The experiment site was set up in the greenhouse of China Jiliang University (Hangzhou, China), where the temperature and relative humidity (RH) were maintained at levels comparable to those of the Huai'an phenotypic group experiment. Healthy orchid plants exhibiting uniform growth and free from pests or diseases were selected and transplanted into pots with a diameter of 16 cm using different substrate mixtures. The experimental setup consisted of the same six substrate combinations as those in the Huai'an phenotypic group experiment, with three replicates per group. Fertilizer and water management practices were standardized, and manual irrigation was performed every five days. The measured physiological growth indicators included plant height, leaf length (L, measured from the base to the tip of the leaf), and leaf width (D, measured at the widest point of the leaf). The leaf surface area (S) was calculated using the formula (Lin et al., 2007):

$$S=0.8343\times L^{0.9895}\times D^{1.0427}.$$

2.5 Data analysis

In this study, the Plantarray platform was used to automatically collect high-resolution data on various environmental and soil parameters for all test units in the array, with measurements recorded every 3 min. The monitored parameters included system mass, PAR, ambient temperature (T), RH, and VWC. Secondary characteristics, such as the real-time dynamic transpiration rate (TR), daily TR, and growth rate under saturated irrigation conditions, were analyzed using SPAC data analysis software. Physiological traits, including plant height and leaf area, were directly measured with calibrated instruments. Data processing and analysis were conducted using Excel 2019, while graphical representations were generated using Origin 2022. For statistical analysis, analysis of variance (ANOVA) was performed using SPSS (version 27). The results are presented as mean±standard error of the mean (SEM), with significant differences indicated by different letters above the bars in the bar charts. Statistical significance was set at $P<0.001$.

3 Results

3.1 Monitoring results of orchid environmental parameters

Using the high-precision monitoring capabilities of the Plantarray platform, key environmental parameters influencing orchid growth were recorded (Fig. 1). Throughout the experimental period, the RH and temperature within the greenhouse showed distinct sequential changes, following cyclical patterns influenced by diurnal environmental dynamics. The RH levels fluctuated between 20% and 80%, occasionally approaching 90% (Fig. S1). These substantial daily variations highlight the strong influences of solar radiation and temperature on humidity levels. Notably, during the latter stages of the experiment, the amplitude of the RH fluctuations diminished, likely due to reduced solar intensity and lower ambient temperatures. Greenhouse temperatures ranged from about 10 to 40 ℃,

Table 1 Physical and chemical properties of different substrates

Substrate	pH	Electrical conductivity (S/m)	Water retention (%)	Drainage rate (cm^3/h)
Peat soil	6.42	0.0746	76.34	92
Pine bark	5.09	0.0147	53.41	153
River sand	7.36	0.0247	17.39	102

displaying clear diurnal cycles. The temporal patterns of temperature fluctuations closely mirrored those of the RH, suggesting a strong inverse relationship between the two variables (Fig. S2). This correlation underscores the interdependency of microclimate conditions in controlled environments and their collective impact on orchid physiology.

The PAR and VPD showed a strong positive correlation throughout the experimental period (Fig. 2). Elevated PAR levels, corresponding to periods of high light intensity, were consistently associated with increased VPD, indicating air approaching saturation with water vapor. Conversely, reduced PAR levels, reflecting lower light intensity, were paralleled by decreased VPD, indicating reduced atmospheric water vapor content. This synchronized variation underscores the stable and coordinated relationship between light intensity and air humidity within the greenhouse environment. Such stability is critical for maintaining optimal conditions for photosynthesis and transpiration in orchids.

3.2 Monitoring results of orchid moisture content parameters

The VWC is another critical factor influencing the growth of orchids (*C. goeringii* and *C. faberi*). Following irrigation, the VWC showed a marked increase across all the substrate groups. However, once watering ceased, the VWC gradually decreased, due mainly to continuous water uptake by the plants through transpiration and evaporation from the soil surface (Fig. 3). Significant differences in VWC were observed among the tested substrate types. Notably, when pine bark was used as the substrate, its VWC remained relatively low, with a much smaller increase in water content than the other substrates did, even after irrigation. This can be attributed to the superior

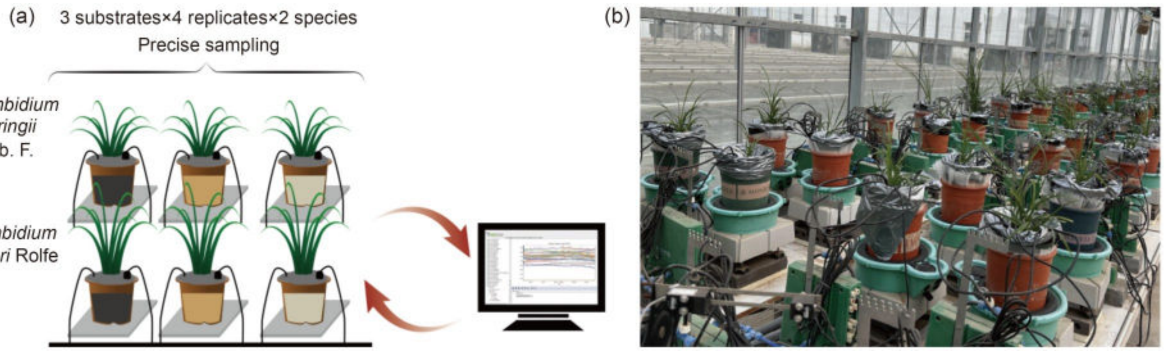

Fig. 1 Structure of the experimental units in the Plantarray functional physiological phenotyping system (a) and the experimental scenario (b). The lysimetric system where a randomized experimental array consisting of multiple measuring units loaded with orchids was set up. The system was designed to monitor and analyze various physiological parameters of plants under controlled conditions. The experimental units were arranged in a specific configuration to facilitate precise measurements and data collection.

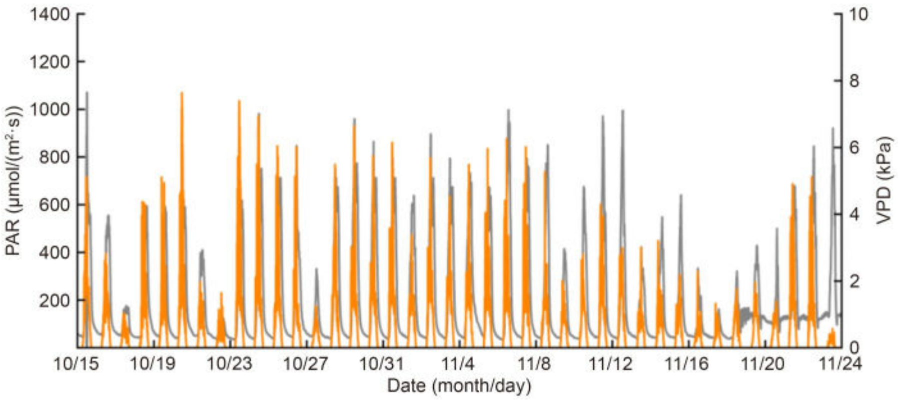

Fig. 2 Environmental parameters of orchid accessions as recorded by the Plantarray physiological phenotyping system. PAR: photosynthetically active radiation; VPD: vapor pressure deficit.

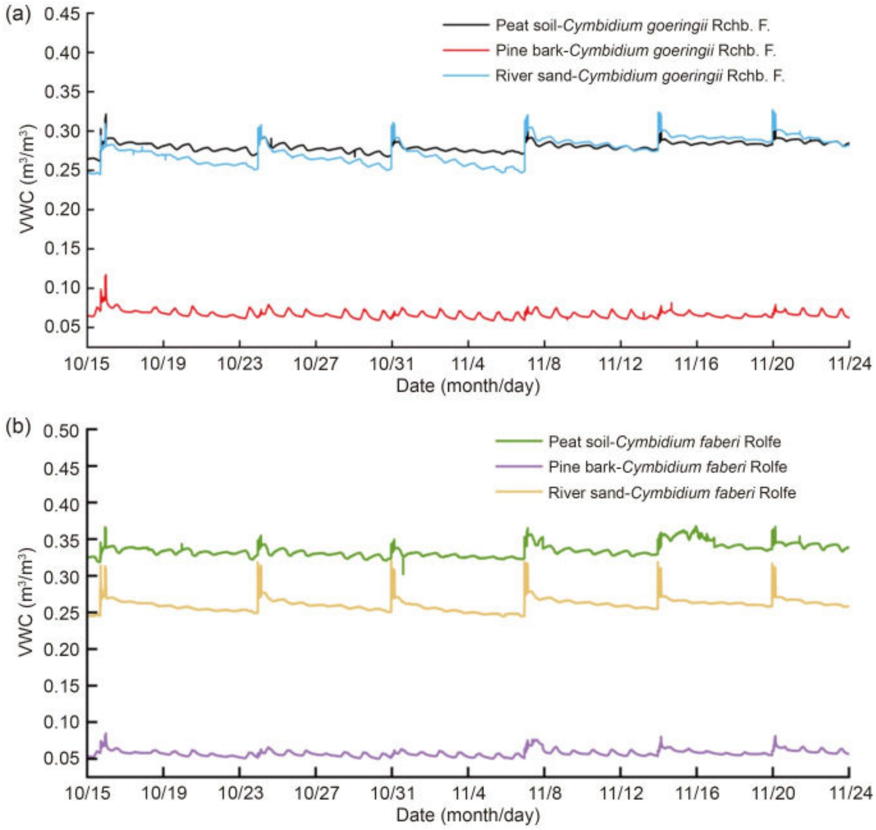

Fig. 3 Soil parameters of orchid accessions captured by the Plantarray physiological phenotyping system. Dynamics of soil volumetric water content (VWC) during the test period of *Cymbidium goeringii* (a) and *Cymbidium faberi* (b).

aeration and drainage properties of pine bark, which promote rapid water infiltration into deeper soil layers, thereby reducing surface water retention and subsequent evaporation. By minimizing surface moisture while maintaining adequate soil hydration, pine bark effectively reduces the risk of root rot caused by waterlogging. This balance between moisture retention and proper drainage makes pine bark an exceptionally suitable substrate for orchid cultivation, supporting healthy root development and overall plant vigor.

3.3 Monitoring results of physiological parameters of orchids

TR, a critical physiological phenotypic indicator, was measured during the growth process of the orchids. The results revealed that this parameter was significantly influenced by external environmental factors, particularly substrate type and irrigation practices (Fig. 4). For *C. goeringii*, the TR showed a dynamic pattern under different substrate conditions, with irrigation playing a key role in its fluctuation. Among the three tested substrates, river sand showed the most pronounced response: a sharp increase in transpiration occurred immediately after watering, followed by a rapid decline on the second day. This fluctuation was significantly greater in river sand than in the other substrates (Fig. 4a). This pattern highlights the critical role of substrate properties in modulating orchid physiology, particularly in relation to water availability and drainage dynamics.

C. faberi, characterized by a larger plant body and broader leaf area, showed a consistently higher TR than *C. goeringii*. However, like its counterpart, its transpiration dynamics were strongly influenced by irrigation. Notably, fluctuations in transpiration were most dramatic in the river sand substrate (Fig. 4b). This finding suggests that the physical and chemical properties of river sand, such as rapid water infiltration and reduced surface retention, may amplify post-irrigation water dynamics, thereby driving significant changes in TR.

In addition to irrigation, weather conditions play a critical role in regulating transpiration. Under cloudy

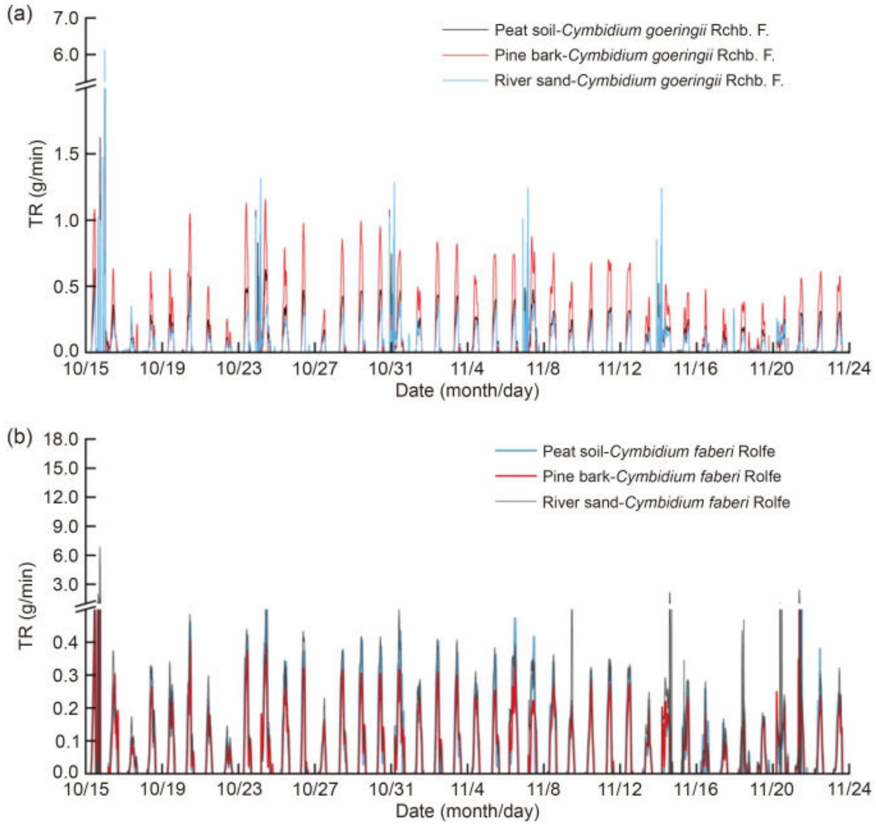

Fig. 4 Dynamics of transpiration rates (TRs) of orchids. TR fluctuates due to irrigation, light intensity, air humidity, and other factors. These data help to understand how orchids respond to environmental changes and their water use efficiency.

or rainy conditions, reduced PAR and lower temperatures led to decreased TR. As the temperatures dropped, the VPD approached saturation, further suppressing transpiration. These results underscore the complex interplay of light, temperature, and humidity in governing orchid transpiration. They also emphasize the importance of substrate selection in optimizing water management and highlight the environmental dependencies of this physiological process.

3.4 Relationship between orchid growth and substrate

Continuous real-time monitoring of orchid physiological parameters using the Plantarray platform revealed significant differences in weight dynamics across different substrates during two consecutive watering periods (Fig. 5a). In the river sand substrate, both *C. goeringii* and *C. faberi* showed a downward trend in weight, suggesting that improper water management or suboptimal environmental conditions in river sand may have contributed to reduced biomass. In contrast, orchids cultivated in pine bark and peat soil showed consistent weight increases, indicating positive biomass accumulation. Notably, the weight gain in peat soil was particularly rapid, highlighting its potential as a superior growth medium for orchids.

Growth rate calculations based on weight changes further underscored these observations (Fig. 5b). In the river sand, both orchid species showed negative growth rates with a continuous decline, indicating that this substrate significantly inhibited growth. Conversely, the peat soil supported the highest growth rates, which showed a steady upward trend. These results confirm the growth-promoting effects of peat soil and emphasize its suitability for orchid cultivation.

3.5 Effect of substrate on physiological indicators of orchids

To ensure data accuracy and reliability, low-flux manual measurements were used as a control. Each watering event served as a reference point for calculating changes in orchid plant height, while leaf area growth was determined by measuring the dimensions (length and width) of the same leaf. The growth indices of orchids in the greenhouse were monitored and compared with those of orchids grown in a glasshouse. The results indicated that *C. goeringii* and *C. faberi* showed positive growth trends in plant height and leaf area across all three substrates (Fig. 6). The linear fitting of growth rates revealed that both species showed the highest growth rates for plant height when grown in peat soil. For leaf area growth, *C. goeringii* showed the fastest growth in peat soil, while *C. faberi* grew more rapidly in pine bark, followed by peat soil. Overall, the comprehensive analysis concluded that peat soil supported the highest growth rates for orchids.

In contrast to orchids grown on the Plantarray platform, those in river sand showed slower growth, although their growth rates remained positive. This discrepancy may be attributed to less precise irrigation in the greenhouse, potentially leading to uneven water and nutrient distributions. Additionally, manual measurements are prone to errors from factors such as measurement tools and operator variability, particularly when assessing complex plant structures or uneven growth patterns.

4 Discussion

4.1 Application of Plantarray in orchid research

This study explored the potential application of the Plantarray platform in orchid research by simulating conditions in greenhouse experiments with consistent

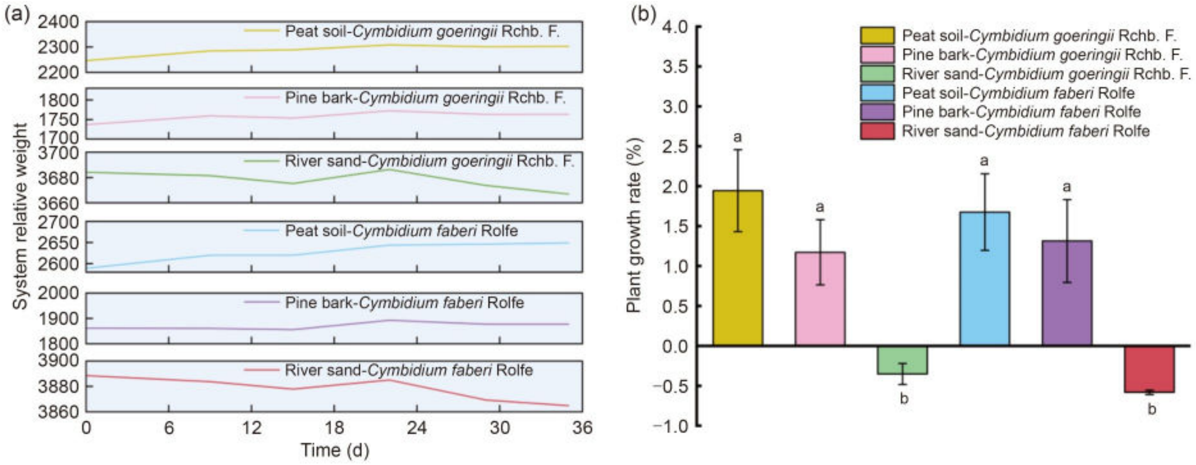

Fig. 5 Dynamics of system weight during the experiment and orchid growth rate. (a) The system weight changes reflect variations in plant biomass. (b) The orchid growth rate indicates how the plants develop under specific environmental conditions. The data are expressed as mean±standard error of the mean (SEM) (*n*=3); the different letters on the graph indicate significant differences (*P*<0.001).

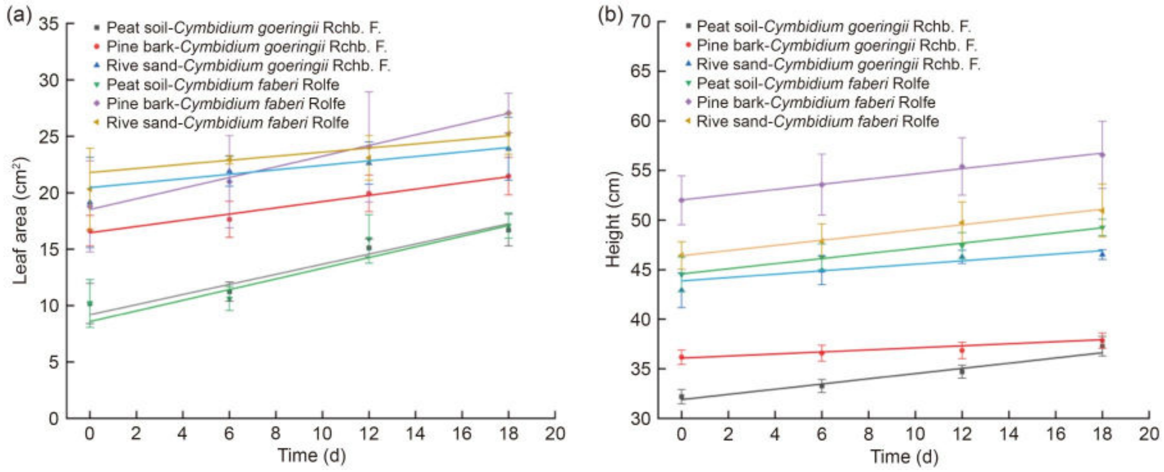

Fig. 6 Changes of leaf area (a) and plant height (b) of orchids measured manually after each watering. These parameters are critical for evaluating orchid growth vigor and development stage.

watering schedules. Growth conditions of *C. goeringii* and *C. faberi* were assessed across three substrates, river sand, pine bark, and peat soil, through manual measurements of plant height, leaf length, leaf area, and stomatal conductance (Lawson and Milliken, 2023; Bălăiţă et al., 2024). However, under shaded greenhouse conditions, near-zero stomatal conductance was observed, likely due to the cold, humid environment or measurement limitations, leading to its exclusion from final analysis. Instead, growth rates and plant height were evaluated based on leaf area changes, though this approach remains prone to measurement errors and environmental variability.

The Plantarray platform offers a high-throughput, precise, and non-invasive method for acquiring phenotypic data, enabling comprehensive monitoring of environmental conditions and plant growth while minimizing errors. Its real-time capture of multiple parameters provides critical insights into growth dynamics and physiological responses, making it a valuable tool for studying orchid development and genetics. Despite these advantages, the platform has yet to be applied in orchid research, highlighting the need for further studies to assess its feasibility and benefits in this field.

4.2 Effects of substrates on orchid growth and physiological characteristics

Under identical conditions, *C. goeringii* and *C. faberi* cultivated in river sand showed negative or low growth rates with minimal biomass accumulation, attributed to the excessive drainage of the substrate and poor nutrient retention. While cost-effective, river sand is unsuitable for orchid cultivation. Pine bark, known for its aeration, drainage, and natural nutrients, theoretically supports root growth and development (Mirzakhaninafchi et al., 2022). However, orchids in pine bark showed only moderate growth rates, likely due to the limited nutrient content and high drainage, hindering fertilizer absorption. Combining pine bark with other materials could enhance its water retention and improve orchid growth. Peat soil, renowned for its superior water and nutrient retention, proved most effective when mixed with perlite. The orchids in this substrate showed higher biomass accumulation and growth rates than those in other substrates. Additionally, peat soil and perlite are more affordable and accessible than pine bark (Pieruschka et al., 2010; Collado et al., 2024). Thus, the peat soil-perlite mixture emerged as the optimal substrate for promoting orchid growth among the tested groups.

4.3 Interpretation and application of the phenotypic data of orchid species

The weight data obtained through the Plantarray platform serve as a direct indicator of orchid growth status. A sharp decline in weight may signal the onset of senescence or mortality, while fluctuations in weight can reveal trends in biomass accumulation. Rapidly growing plants typically show significant weight increases due to efficient carbon fixation from photosynthesis, whereas slow-growing plants show minimal changes (Zhang et al., 2018). Additionally, water availability strongly influences plant weight: abundant moisture promotes biomass accumulation, while drought conditions lead to reduced fresh weight. Thus, weight data not only reflect growth status but also provide insights into environmental conditions, particularly soil moisture levels. The soil moisture content is a critical reference for determining optimal watering schedules (Driesen et al., 2021). Complementing this, environmental parameters such as light intensity, temperature, and humidity are essential indicators of orchid growth and serve as guides for adjusting environmental conditions to optimize development.

Transpiration, a key component of the SPAC, is a critical metric for assessing the water loss of a plant and its ability to regulate water use efficiency (Ngui et al., 2024; Ke et al., 2025). TRs are affected by external environmental factors, growth stages, and nutritional status. During the periods of rapid growth, heightened metabolic activity increases transpiration, while dormancy leads to reduced rates. Nutrient deficiencies, particularly in nitrogen, phosphorus, and potassium, can also suppress transpiration (Yang et al., 2024). These parameters are instrumental in selecting optimal growth substrates and serve as reliable indicators in research on orchid breeding, gene expression analysis, and stress response mechanisms (Allohverdi et al., 2021). For instance, under drought stress and subsequent rehydration, changes in morphology, stomatal conductance, and biomass accumulation can be monitored to investigate water physiology and recovery mechanisms (Zhang et al., 2024). The Plantarray platform thus offers a powerful tool for studying orchid responses to environmental challenges and informing sustainable cultivation practices.

4.4 Research limitations and future research directions

This study investigated mainly the effects of different substrates on orchid biomass and growth rates, but did not delve into the distribution of above-ground and below-ground biomass. In addition to above-ground parameters such as plant height and leaf area, the impact of different substrates on below-ground biomass and root development should be acknowledged, as they are equally critical in evaluating overall plant growth. The root architecture plays a fundamental role in water uptake, nutrient absorption, and overall plant health. Substrates can alter root distribution, density, and architecture, which in turn affects how effectively a plant can access essential resources from the soil. Although root development data were not included in this study, it is important to recognize that substrates may cause significant differences in root morphology and function. Discussing the potential effects of substrates on root architecture and water uptake would provide a more comprehensive understanding of a substrate impact on plant performance. Future research could incorporate additional biochemical indicators, such as chlorophyll content and enzyme activity, to provide a more comprehensive understanding of orchid physiology. Integrating physiological indicators with environmental parameters would enhance the comprehensiveness and accuracy of experimental outcomes (Kim et al., 2021). Additionally, the application of machine learning algorithms or statistical models could be explored to analyze the relationships among environmental factors, substrate characteristics, and orchid growth. Such models could optimize substrate selection and predict suitable substrate combinations under specific growth conditions.

The formula of leaf area was originally developed for *Cymbidium* species, and in this study was applied to estimate the leaf areas of *C. goeringii* and *C. faberi*. While the algorithm showed reasonable accuracy for these species, the applicability of this formula to different *Cymbidium* species may be subject to variations in growth habit and leaf morphology. Future studies could consider adjusting the formula parameters to improve its accuracy for these species or developing specific formulas for different *Cymbidium* species. Further validation of the algorithm across other *Cymbidium* species with various growth forms would help establish the generalizability of the formula for estimating leaf area.

The scope of substrates evaluated in this study was relatively limited. Future research could leverage the Plantarray platform to conduct comparative analyses of a broader range of substrates, considering their diverse physical and chemical properties, such as aeration and nutrient content (Ma et al., 2024). Establishing a standardized evaluation system for these characteristics would enhance the scientific rigor of substrate assessment. Furthermore, research on substrate improvement should be prioritized. For instance, the effects of biochar and other soil amendments on water retention and nutrient release could be investigated. Studies on how substrate improvement technologies impact orchid growth could contribute to the development of high-performance cultivation substrates, supporting sustainable and efficient orchid production (Halperin et al., 2017; Fang et al., 2023).

5 Conclusions and outlook

5.1 Main findings of this research

This research aimed to scientifically determine the optimal frequency and volume of watering for orchids through detailed observation and analysis. By monitoring changes in orchid weight and substrate moisture content, precise irrigation guidelines were established. Three commonly used substrates were compared to evaluate their suitability for orchid cultivation. Observations of biomass and growth rate changes in *C. goeringii* and *C. faberi* under identical conditions revealed that a peat-perlite mixed substrate significantly enhanced biomass accumulation and growth rates. Given its cost-effectiveness, material availability, and superior performance, this mixed substrate is strongly recommended as the preferred choice for orchid cultivation.

5.2 Potential applications of the Plantarray platform in the cultivation and breeding of orchids

The Phenotype platform has revolutionized orchid growth research with its comprehensive, efficient, and precise data collection and analysis capabilities, emerging as an indispensable tool in orchid studies. This platform deepens the understanding of orchid growth mechanisms and offers potential for integration with other omics approaches, driving innovation in breeding and cultivation. The high-throughput, precise, and non-invasive plant phenotypic data acquisition technology provided by the Phenotype platform represents a milestone in orchid research. By quickly collecting vast amounts of plant phenotype data across multiple dimensions, including growth rate, morphological characteristics, and physiological responses, it provides clear directions and strong support for early-stage breeding selection, significantly accelerating the breeding process. Especially in the identification of phenotypes under adverse stress conditions, the Phenotype platform enables dynamic and quantitative analysis of plant phenotypic changes under stress factors such as drought, salinity, and nitrogen deficiency. This capability is crucial for identifying orchid cultivars with enhanced adaptability to specific environmental challenges. In breeding programs, the application of the Phenotype platform is indispensable, offering deeper insight into orchid growth mechanism and adaptability, thereby providing a solid scientific foundation for breeding efforts. Furthermore, integrating phenotype data from the platform with other omics data, such as genomics, transcriptomics, proteomics, and metabolomics, can offer a more comprehensive perspective on the regulatory networks and functional gene expression involved in orchid growth and development. This integration is expected to further advance orchid breeding technologies, fostering continued innovation and progress in the field.

Data availability statement

All the data supporting the findings of this study are available within the paper and its supplementary information files.

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Author contributions

Jia YAO and Xubo KE wrote the manuscript, conceived and designed the study. Jia YAO, Xubo KE, Xinyue GU, Zhihan JIANG, and Zhengzheng YING performed the experiments and data analysis. Chenze LU, Chongbo SUN, and Pei XU reviewed and edited the manuscript. All authors have read and approved the final manuscript, and therefore, have full access to all the data in the study and take responsibility for the integrity and security of the data.

Compliance with ethics guidelines

Jia YAO, Xubo KE, Xinyue GU, Zhihan JIANG, Zhengzheng YING, Chenze LU, Chongbo SUN, and Pei XU declare that they have no conflicts of interest.

This article does not contain any studies with human or animal subjects performed by any of the authors.

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Supplementary information

Figs. S1 and S2