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Sustainability transitions and potential naturalization risk in the trade and cultivation of *Selaginella kraussiana* in tropical Indonesia

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Abstract. *Setyawan AD, Sutarno, Sugiyarto, Sunarto, Dianti. 2025. Sustainability transitions and potential naturalization risk in the trade and cultivation of* Selaginella kraussiana *in tropical Indonesia. Asian J Agric 9: 925-945.* *Selaginella kraussiana* has recently become popular as a tropical ornamental plant in Indonesia because of its attractive morphology, rapid vegetative growth, and suitability for humid shaded environments. However, information regarding the multidimensional sustainability of its cultivation and trade systems remains limited, particularly concerning ecological resilience, socio-economic performance, and potential naturalization risk associated with ornamental dissemination. This study evaluated the sustainability of *S. kraussiana* cultivation and trade systems in Central Java and Yogyakarta, Indonesia, using a RAPFISH-based multidimensional framework integrated with SWOT-TOWS analysis. Primary data were collected through semi-structured interviews, field observations, and environmental assessments involving 40 ornamental plant farmers and traders. Sustainability evaluation included ecological, economic, social, technological, and institutional dimensions. The ecological dimension achieved the highest sustainability index (83.93%), indicating highly sustainable cultivation conditions supported by humid microclimates and vegetative propagation systems. Economic sustainability was categorized as moderately sustainable (58.29%), whereas social sustainability remained low sustainable (36.70%). Technological and institutional dimensions showed unsustainable conditions (18.29%) due to limited innovation, weak institutional support, and low organizational integration. Monte Carlo validation confirmed strong RAPFISH ordination reliability with stress values below 0.25 and coefficients of determination (R^2) above 0.94. The study indicates that increasing ornamental trade and repeated movement of vegetative planting materials may elevate propagule pressure and warrant precautionary ecological monitoring under favorable humid tropical environments. These findings highlight the urgent need for integrating ecological precaution, technological adaptation, institutional strengthening, and biodiversity conservation into sustainable tropical ornamental horticulture systems while minimizing potential ecological risks associated with ornamental dissemination.

Keywords: Multidimensional sustainability, naturalization risk, ornamental horticulture, RAPFISH, *Selaginella kraussiana*

INTRODUCTION

The global ornamental plant industry has expanded rapidly during the last two decades, driven by urbanization, landscape development, indoor gardening trends, and the commercialization of exotic tropical plants. Ornamental horticulture has become an important component of the global bioeconomy because ornamental species contribute not only to commercial markets but also to urban greening, ecosystem services, and socio-cultural aesthetics (Çelik and Arısoy 2014; Francini et al. 2022). The popularity of tropical ornamental plants has increased further through digital marketing systems, online plant communities, and social media platforms, facilitating rapid dissemination of ornamental trends across regions (Mubarok et al. 2023). Consequently, many previously localized ornamental species are now distributed through increasingly interconnected trade networks.

In tropical countries such as Indonesia, ornamental horticulture represents an important livelihood strategy for rural and peri-urban communities. Small-scale ornamental plant cultivation provides supplementary household income, supports local markets, and contributes to regional economic diversification. Many ornamental species also contribute to microclimatic regulation, aesthetic enhancement, erosion control, and biodiversity enrichment within urban and rural landscapes (Francini et al. 2022). Compared with intensive agricultural systems, ornamental horticulture commonly relies on relatively small cultivation areas and flexible household-based production systems, making it economically accessible for small-scale farmers and traders. However, rapid commercialization may also generate sustainability challenges related to environmental dependency, market instability, technological limitations, and weak institutional regulation (Dehnen-Schmutz et al. 2007; van Kleunen et al. 2018).

One ornamental species that has recently gained popularity in tropical horticultural markets is *Selaginella kraussiana* (Kunze) A. Braun. This lycophyte species is characterized by creeping stems, dense branching morphology, rapid vegetative propagation, and tolerance to shaded humid environments. Originally native to parts of Africa, *S. kraussiana* has been widely introduced into tropical and subtropical regions as a groundcover ornamental plant, terrarium species, and decorative foliage component (Lawalree 1993; Setyawan 2011). Its compact growth form and bright green coloration make the species attractive for ornamental landscaping and indoor gardening applications. In Indonesia, *S. kraussiana* is increasingly cultivated in highland ornamental production centers and distributed through traditional and online trade systems. Cultivation commonly occurs under shaded nursery conditions with relatively low production costs and simple vegetative propagation techniques.

Despite its ornamental value, *S. kraussiana* also presents ecological and sustainability concerns. The species possesses rapid clonal growth, strong vegetative expansion, and high adaptability to humid microhabitats, characteristics frequently associated with naturalization potential in introduced environments (Reichard and White 2001; van Kleunen et al. 2018). In several countries, *S. kraussiana* has been reported as a naturalized or locally established species capable of altering understory vegetation structure and suppressing native ground flora (Nessia et al. 2014; Dang et al. 2019). The horticultural trade pathway is widely recognized as an important mechanism facilitating plant introductions and naturalization processes because ornamental species are intentionally propagated and distributed beyond their native ecological ranges (Dehnen-Schmutz et al. 2007). Consequently, sustainability evaluation of ornamental horticulture systems should consider not only economic viability but also ecological resilience, technological adaptation, institutional governance, and potential ecological concerns associated with ornamental plant dissemination.

Previous studies on *Selaginella* have largely focused on taxonomy, ecology, phylogeny, and pharmacological potential (Setyawan 2011; Fang et al. 2021), whereas research examining sustainability dimensions of ornamental trade systems remains limited. Similarly, multidimensional sustainability assessments integrating ecological, economic, social, technological, and institutional dimensions are still rarely applied to ornamental lycophyte cultivation systems in tropical countries. Most ornamental horticulture studies primarily emphasize market development and cultivation techniques without evaluating broader socio-ecological interactions and long-term sustainability implications. Information regarding leverage attributes influencing sustainability performance and strategic priorities for sustainable ornamental trade development also remains poorly documented in Indonesia.

Therefore, this study aimed to evaluate the multidimensional sustainability of *S. kraussiana* cultivation and trade systems in Central Java and Yogtakarta, Indonesia, using a RAPFISH-based sustainability framework integrated with SWOT-TOWS strategic analysis. Specifically, the study assessed ecological, economic, social, technological, and institutional sustainability dimensions; identified sensitive leverage attributes affecting sustainability performance; and examined broader implications related to ornamental horticulture development and potential ecological concerns related to ornamental dissemination in tropical environments. Although *S. kraussiana* is increasingly cultivated as a tropical ornamental plant in Indonesia, the sustainability and ecological implications of its trade systems remain poorly understood. This study hypothesized that ecological sustainability would remain relatively high under humid shaded environments, whereas technological and institutional sustainability would remain low because of limited innovation and weak organizational support. Increasing ornamental trade and movement of vegetative planting materials may also elevate propagule pressure and potentially increase localized naturalization risk under favorable tropical conditions. This study represents one of the first multidimensional sustainability assessments integrating ornamental horticulture systems and potential naturalization concerns in tropical lycophyte trade networks.

MATERIALS AND METHODS

Study area

The study was conducted in ornamental plant cultivation and trade centers in Central Java and Yogyakarta, Indonesia, including Baturraden, Sumbang, Gunung Pati, Boja, Kopeng (Getasan), Candimulyo, Banjarsari, Jebres, Tasikmadu, and Tawangmangu in Central Java. Then, Ngaglik, Umbulharjo, and Banguntapan in Yogyakarta. These locations were selected purposively because they represent important ornamental horticulture areas with different environmental conditions, cultivation intensities, and market orientations. The sites included lowland urban markets, peri-urban ornamental production systems, and humid highland cultivation centers, allowing comparative evaluation of ecological suitability and socio-economic characteristics associated with *S. kraussiana* cultivation.

Environmental conditions varied considerably in elevation, temperature, humidity, canopy cover, and cultivation infrastructure. Highland areas such as Tawangmangu and Kopeng were characterized by cool temperatures, persistent humidity, and dense vegetation cover favorable for *S. kraussiana* growth. In contrast, lowland urban areas such as Banjarsari and Umbulharjo exhibited warmer temperatures, lower humidity, and more fragmented cultivation environments. These environmental differences influenced cultivation performance, propagation success, and ornamental trade intensity across locations.

Geographical and environmental characteristics of all study locations are summarized in Table 1, whereas the spatial distribution of research sites is presented in Figure 1. The selected sites also represented important ornamental trade corridors connecting local nurseries, household growers, regional plant markets, and urban consumers. Although, Yogyakarta is administratively separate from Central Java Province, both regions were treated as a single study area because they form a geographically continuous area in the central part of Java, with Yogyakarta being almost entirely surrounded by Central Java.

Research design and respondent selection

This study employed a mixed qualitative-quantitative approach integrating field observations, semi-structured interviews, and multidimensional sustainability assessment using the RAPFISH framework. The research focused on ornamental plant farmers, traders, collectors, and small-scale horticultural actors directly involved in the cultivation and commercialization of *S. kraussiana* in Central Java and Yogyakarta.

Table 1. Environmental and geographical characteristics of study locations of *Selaginella kraussiana* in Central Java and Yogyakarta, Indonesia

Sites	Administrative region (District/city)	Elevation (m asl)	Mean environmental characteristics	Dominant ornamental plant activity	Observed cultivation suitability
Baturraden	Banyumas	640-750	Humid upland environment with high rainfall and dense vegetation cover	Cultivation and ornamental retail trade	High
Sumbang	Banyumas	200-450	Semi-humid agricultural landscape with mixed vegetation	Local ornamental plant trade	Moderate
Gunung Pati	Semarang City	200-350	Peri-urban hilly environment with mixed vegetation cover	Ornamental cultivation	Moderate
Boja	Kendal	250-300	Moist upland agricultural area with semi-shaded cultivation conditions	Ornamental plant farming	High
Kopeng (Getasan)	Semarang	1,400-1,500	Highland horticultural zone with cool climate and persistent moisture availability	Ornamental plant production and trade	Very high
Trenten (Candimulyo)	Magelang	450-650	Humid upland agricultural landscape with moderate canopy protection	Ornamental plant farming	High
Giyanti (Candimulyo)	Magelang	500-700	Humid upland agricultural landscape with moderate canopy protection	Ornamental plant farming and trade	High
Banjarsari	Surakarta City	90-110	Urban lowland area with relatively high temperature and limited canopy cover	Ornamental plant market	Moderate
Jebres	Surakarta City	90-100	Urban residential environment with fragmented green spaces	Small-scale ornamental trade	Moderate
Tasikmadu	Karanganyar	120-180	Transitional lowland-upland environment with moderate humidity	Household ornamental trade	Moderate
Tawangmangu	Karanganyar	800-1,500	Cool mountainous environment with relatively stable humidity and dense canopy vegetation	Major ornamental cultivation center/ trade	Very high
Ngaglik	Sleman	150-300	Urban-peri-urban environment with moderate environmental humidity	Ornamental retail trade	Moderate
Umbulharjo	Yogyakarta City	110-130	Urban environment with limited environmental humidity	Ornamental retail trade	Low
Banguntapan	Bantul	75-120	Warm lowland urban environment with relatively limited humidity	Small-scale ornamental trade	Low

Note: "Observed cultivation suitability" categories were interpreted qualitatively based on repeated field observations of humidity availability, canopy cover, temperature conditions, and observed cultivation performance of *S. kraussiana* across study locations. These categories represent comparative field-based cultivation observations rather than direct quantitative environmental measurements

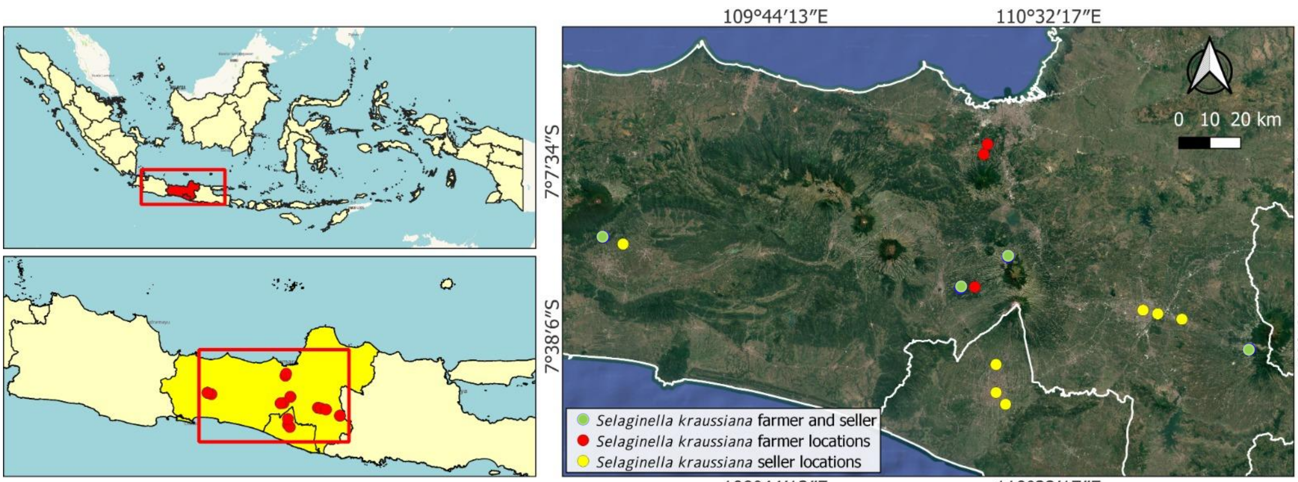

Figure 1. Geographic distribution of study sites in Central Java and Yogyakarta, Indonesia

Respondents were selected using purposive and snowball sampling techniques because informal business networks and household-based production systems dominate the ornamental plant trade system. Initial respondents were identified through ornamental plant markets, local nurseries, and cultivation centers, after which additional respondents were identified through trader and farmer recommendations. A total of 40 respondents participated in the study, consisting of ornamental plant cultivators, traders, and mixed farmer-trader actors with varying business scales and cultivation experience.

The number of respondents was considered adequate for this exploratory sustainability assessment because *S. kraussiana* is generally traded as a complementary ornamental species rather than as a primary commercial commodity in most ornamental plant markets and nurseries. Consequently, actors specifically involved in its cultivation and trade were relatively limited and scattered across informal horticultural networks. Respondent recruitment was continued until no substantially new information regarding cultivation practices, trade systems, sustainability constraints, and institutional conditions emerged from additional interviews. Selection criteria included active involvement in *S. kraussiana* cultivation or trade for at least one year, direct participation in ornamental plant distribution networks, and willingness to provide ecological, socio-economic, technological, and institutional information relevant to sustainability assessment.

Data collection procedures

Semi-structured interviews

Primary data were collected through semi-structured interviews conducted directly with ornamental plant farmers, traders, collectors, and nursery owners. Semi-structured interviews were selected because this approach allows systematic collection of comparable information while maintaining flexibility for exploring respondent experiences and local trade dynamics (Martin 1995; Creswell 2009). Interview topics included cultivation practices, propagation techniques, environmental requirements, production costs, market distribution, institutional support, technological adoption, and perceived sustainability challenges associated with *S. kraussiana* cultivation systems. Additional information regarding trade networks, market demand, and business continuity was also documented during interviews. Interviews were conducted in Indonesian and the local Javanese language, depending on the respondent's preference.

Cultivation observations and environmental assessment

Direct field observations were conducted at ornamental nurseries, household cultivation sites, urban ornamental markets, and shaded horticultural production areas. Observations focused on cultivation infrastructure, shading systems, irrigation management, propagation methods, growing media composition, and general environmental conditions associated with *S. kraussiana* cultivation. Microclimatic characteristics such as canopy cover, relative moisture conditions, temperature characteristics, and growing media conditions were evaluated qualitatively through repeated field observations across study locations rather than direct instrumental measurements. Morphological characteristics, vegetative propagation structures, and representative cultivation systems of *S. kraussiana* were also documented photographically to support ecological interpretation and comparative cultivation assessment (Figure 2).

Socio-economic and institutional data collection

Socio-economic information collected from respondents included production scale, sales volume, market orientation, business status, labor involvement, household participation, and access to ornamental plant distribution networks. Institutional variables included participation in farmer groups, access to government extension services, technical guidance, cultivation training, and market information systems. Additional information related to technological adaptation, environmentally friendly cultivation practices, and ornamental trade constraints was incorporated into the RAPFISH sustainability assessment framework. Secondary information supporting the study was obtained from regional horticultural reports, ornamental trade publications, and relevant scientific literature related to ornamental horticulture sustainability and biological invasion pathways (Dehnen-Schmutz et al. 2007; Hinsley et al. 2018; van Kleunen et al. 2018).

RAPFISH sustainability assessment framework

Multidimensional sustainability assessment was conducted using the RAPFISH ordination approach adapted for tropical ornamental horticulture systems (Pitcher and Preikshot 2001; Kavanagh and Pitcher 2004). The framework integrated ecological, economic, social, technological, and institutional dimensions influencing *S. kraussiana* cultivation and trade systems in Central Java and Yogyakarta, Indonesia. Sustainability dimensions and attributes were selected based on field observations, semi-structured interviews, ornamental horticulture characteristics, and previous sustainability studies related to smallholder agricultural systems (Fauzi and Anna 2005; Makate 2020; Zhang et al. 2024). RAPFISH ordination analysis was conducted using Microsoft Excel-based procedures adapted from Pitcher and Preikshot (2001), Kavanagh and Pitcher (2004) and Sabrina et al. (2024).

Each sustainability attribute was evaluated using an ordinal four-point scoring system representing poor (score 1), low (score 2), moderate (score 3), and good sustainability conditions (score 4). Scoring was based on integrated interpretation of interview responses, field observations, cultivation assessments, and socio-economic conditions recorded during the survey period. To reduce subjectivity, scoring was conducted independently by three researchers familiar with ornamental horticulture systems and RAPFISH assessment. Final scores were determined through consensus-based discussion after independent evaluation, whereas discrepancies were resolved through re-examination of field observations, interview records, and cultivation evidence.

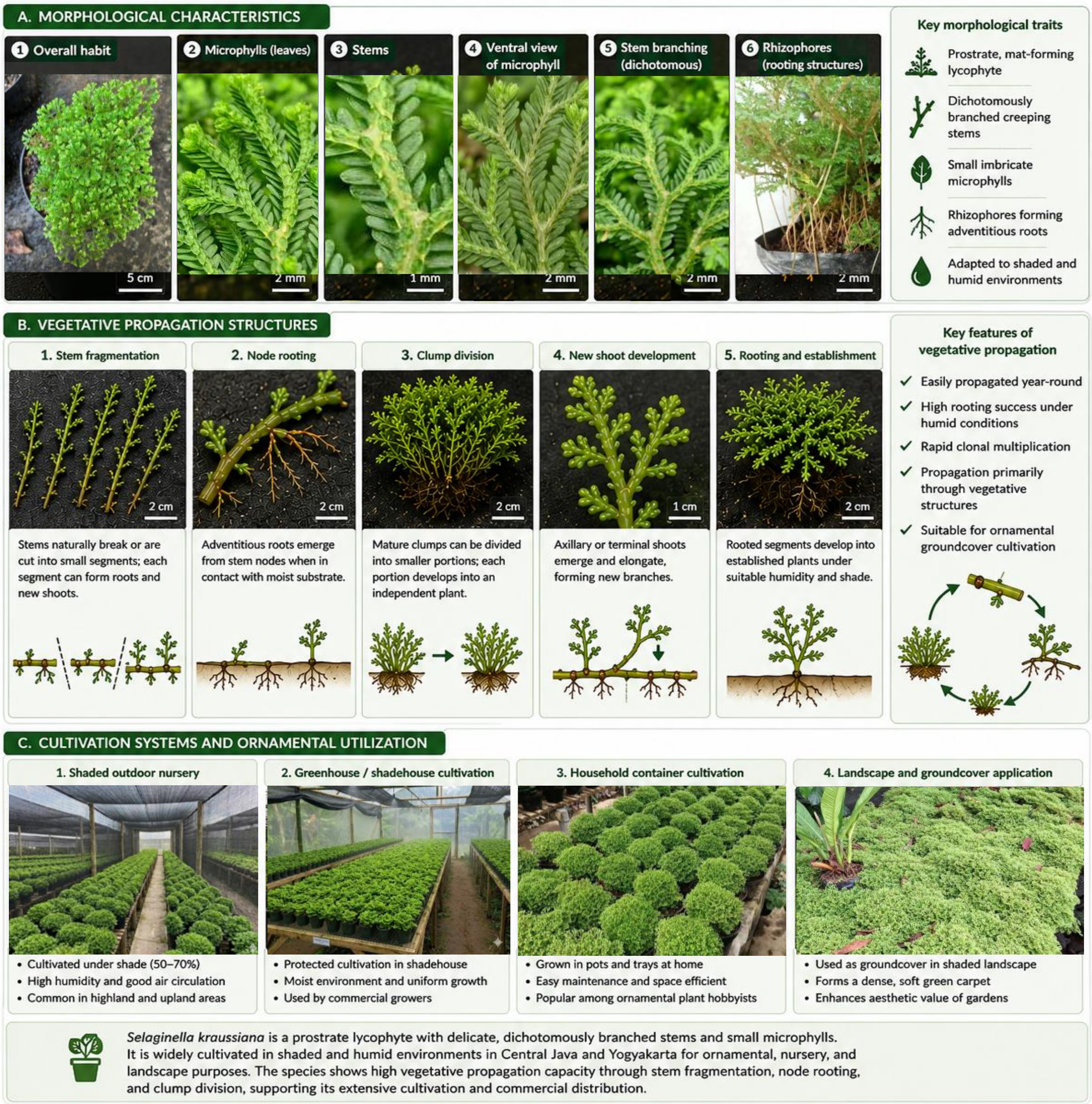

Figure 2. Morphological characteristics, vegetative propagation, cultivation systems, and ornamental utilization structures of *Selaginella kraussiana*

Higher scores indicated stronger sustainability performance, lower ecological disturbance, greater adaptive capacity, and better socio-economic or institutional support conditions. Several sustainability attributes represented semi-quantitative indicators evaluated through field observations, interviews, and cultivation assessments. Attributes such as biodiversity conservation, policy consistency, conflict resolution, and research access were assessed using indicators related to institutional involvement, organizational participation, environmental management, and respondent-reported governance conditions. Triangulation among interviews, field observations, multi-evaluator scoring, and Monte Carlo validation was applied to reduce uncertainty and subjective bias.

No differential weighting scheme was applied, and all sustainability attributes were weighted equally to maintain analytical consistency and comparability across sustainability dimensions, particularly because no validated weighting coefficients are currently available for tropical ornamental horticulture sustainability systems. The study primarily applied exploratory multidimensional sustainability appraisal rather than inferential statistical comparison among locations; therefore, observed spatial differences were interpreted descriptively to identify general sustainability patterns across contrasting cultivation environments. Operational scoring criteria are presented in Table 2, whereas sustainability dimensions and attributes are summarized in Table 3.

Table 2. Operational scoring criteria used in RAPFISH sustainability assessment of *Selaginella kraussiana* cultivation systems

Sustainability attribute	Score 1 (poor)	Score 2 (low)	Score 3 (moderate)	Score 4 (good)
Ecological				
Water availability/humidity	Severe shortage	Seasonal limitation	Adequate humidity	Stable humidity
Cultivation pattern/shading	Unsuitable open system	Limited shading	Moderately shaded	Optimal shaded system
Growing media suitability	Poor media	Limited suitability	Suitable media	Highly suitable media
Organic fertilizer use	No application	Limited use	Moderate use	Consistent use
Temperature suitability	Unsuitable	Occasionally limiting	Generally suitable	Highly suitable
Pest and disease management	No management	Limited management	Moderate management	Effective management
Biodiversity conservation	Habitat degradation	Limited concern	Moderate protection	Biodiversity-supportive
Organic matter content	Very low	Limited	Moderate	High
Wind protection	No protection	Limited protection	Moderate protection	Effective protection
Waste management	No management	Limited reuse	Partial reuse	Eco-friendly management
Economic				
Sales volume/market demand	Very unstable	Seasonal demand	Stable local demand	Broad stable demand
Business profitability	Financial loss	Low profitability	Moderate profitability	High profitability
Price stability	Highly unstable	Moderately unstable	Relatively stable	Stable
Market access	Very limited	Local access	Regional access	Broad market access
Production costs	Very high	Moderately high	Manageable	Efficient low-cost
Business scale/ownership	Insecure status	Short-term use	Relatively stable	Secure ownership
Household income contribution	Very limited	Minor contribution	Moderate contribution	Major contribution
Value-added potential	No added value	Limited value	Moderate value-added	High value-added
Financial capital availability	No access	Limited access	Moderate support	Adequate capital
Market diversification	Single market	Limited buyers	Multiple buyers	Diversified markets
Credit access	No access	Limited access	Moderate access	Easy access
Social				
Employment opportunities	None	Temporary jobs	Moderate employment	Stable employment
Community participation	No involvement	Limited participation	Moderate participation	Strong participation
Relationships among cultivators	No collaboration	Weak interaction	Moderate cooperation	Strong network
Benefit distribution	Unequal	Limited equity	Moderate equity	Broad equity
Knowledge sharing	No exchange	Limited sharing	Moderate exchange	Active sharing
Gender involvement	One-gender dominance	Limited participation	Moderate balance	Balanced participation
Youth involvement	No involvement	Limited involvement	Moderate involvement	Strong involvement
Social acceptance	Poor acceptance	Limited acceptance	Moderate acceptance	Strong acceptance
Access to social services	No access	Limited access	Moderate access	Good access
Community conflict	Frequent conflict	Occasional conflict	Minor conflict	No significant conflict
Technological				
Eco-friendly technology use	No technology	Limited use	Partial adoption	Consistent adoption
Cultivation technology availability	No technology	Limited tools	Moderate availability	Adequate technology
Access to innovations	No access	Limited access	Moderate adoption	Active adoption
Growing technology use	Traditional methods	Limited use	Moderate adaptation	Efficient technology
Irrigation technology	No irrigation	Inefficient irrigation	Moderate use	Efficient irrigation
Postharvest handling	No handling	Limited handling	Moderate handling	Effective handling
Infrastructure maintenance	Poor infrastructure	Limited maintenance	Moderate maintenance	Well-maintained
Information technology access	No access	Limited use	Moderate use	Extensive use
Digital marketing use	No digital use	Limited promotion	Moderate marketing	Intensive marketing
Research and development access	No support	Limited support	Moderate collaboration	Strong support
Technology adoption capacity	Unable to adopt	Limited adaptability	Moderate adaptability	High adaptability
Institutional				
Government guidance/extension	No support	Rare support	Occasional support	Regular guidance
Participation in organizations	No involvement	Passive membership	Moderate participation	Active participation
Institutional marketing support	No support	Limited facilitation	Moderate support	Strong support
Institutional collaboration	No collaboration	Weak linkage	Moderate collaboration	Strong collaboration
Regulatory support	No support	Limited regulation	Moderate facilitation	Strong regulation
Policy information access	No access	Limited information	Moderate access	Continuous access
Policy consistency	Highly unstable	Occasionally inconsistent	Moderately stable	Stable policies
Monitoring and evaluation	No monitoring	Limited monitoring	Moderate evaluation	Regular evaluation
Information system access	No access	Limited availability	Moderate access	Integrated access
Conflict resolution mechanisms	No mechanism	Weak management	Moderate support	Effective mechanism

Note: Sustainability attributes were adapted from the RAPFISH multidimensional sustainability framework and expanded according to ecological, socio-economic, technological, and institutional characteristics of tropical ornamental horticulture systems

Table 3. Sustainability dimensions and RAPFISH attributes used in the assessment of *Selaginella kraussiana* cultivation and trade

Sustainability dimension/ Attribute	Description and sustainability relevance
Ecological	
Water availability/humidity	Humidity and water continuity for growth
Cultivation pattern/shading	Suitability of shaded cultivation systems
Growing media suitability	Suitability of moisture-retaining media
Use of organic fertilizer	Environmentally sustainable nutrient input
Growing temperature suitability	Temperature suitability for plant growth
Pest and disease management	Effectiveness of pest control practices
Biodiversity conservation	Reduction of ecological disturbance
Soil/media organic matter content	Organic matter supporting moisture retention
Wind exposure protection	Protection from desiccation stress
Waste management in cultivation	Reuse and management of cultivation waste
Economic	
Sales volume/market demand	Stability of ornamental plant demand
Profitability of the ornamental business	Financial feasibility of cultivation and trade
Price stability	Stability of ornamental plant prices
Access to markets	Access to local and regional markets
Production costs	Financial inputs for cultivation activities
Business scale/land ownership status	Business security and continuity
Income contribution to the household	Contribution to household income
Value added of *S. kraussiana*	Ornamental and commercial value enhancement
Availability of financial capital	Access to operational financial resources
Market diversification	Diversity of trade channels and buyers
Access to credit	Availability of financial loan support
Social	
Employment opportunities	Contribution to local job creation
Community participation in cultivation activities	Community involvement in cultivation
Social relationships among cultivators	Cooperation among horticultural actors
Distribution of economic benefits	Equity of economic benefit distribution
Knowledge sharing among cultivators	Exchange of cultivation and market knowledge
Gender involvement in cultivation	Participation across gender groups
Youth involvement in ornamental horticulture	Participation of younger generations
Social acceptance of cultivation activities	Community acceptance of ornamental business
Access to social services	Availability of social support services
Conflict with communities	Potential social conflict occurrence
Technological	
Use of environmentally friendly technology	Adoption of low-impact technologies
Availability of appropriate cultivation technology	Availability of suitable cultivation tools
Access to cultivation innovations	Access to technological improvements
Use of media/growing technology	Application of propagation technologies
Irrigation technology application	Irrigation supporting humidity stability
Postharvest handling technology	Maintenance of ornamental product quality
Technology maintenance and infrastructure	Maintenance of cultivation facilities
Access to information technology	Use of digital communication systems
Digital marketing technology use	Use of online marketing platforms
Access to research and development	Access to technical and research support
Capacity to adopt new technology	Ability to implement innovations
Institutional	
Access to government guidance/extension	Availability of extension and supervision
Participation in farmer organizations	Involvement in horticultural organizations
Institutional support for marketing	Institutional facilitation for commercialization
Collaboration with other institutions	Cooperation with external stakeholders
Regulatory support for the ornamental trade	Policy support for ornamental trade
Access to formal policy information	Access to institutional information
Policy consistency for ornamental trade	Stability of institutional policies
Monitoring and evaluation of cultivation systems	Institutional sustainability supervision
Access to information systems	Availability of trade information systems
Conflict resolution mechanisms	Institutional dispute resolution support

Note: Sustainability attributes were adapted from the RAPFISH multidimensional sustainability framework and modified according to ecological, socio-economic, technological, and institutional characteristics of tropical ornamental horticulture systems

The ecological dimension evaluated environmental suitability and ecological impacts associated with *S. kraussiana* cultivation systems, including water availability, cultivation pattern, planting waste management, source of planting material, and natural habitat disturbance. Economic sustainability included variables related to ornamental trade feasibility and market continuity, such as sales volume, production costs, market diversification, net profit, and price stability. Social sustainability examined socio-cultural and organizational aspects, including land or business status, relationships among business actors, access to training, perceived business continuity, and family involvement. Technological sustainability evaluated cultivation technologies and adaptive production systems, whereas institutional sustainability assessed governance and organizational support through variables such as access to government guidance, participation in farmer or trader groups, access to market information, and institutional collaboration among stakeholders.

All sustainability attribute scores were analyzed using MDS ordination to generate sustainability index values ranging from 0 to 100. Sustainability categories followed Fauzi and Anna (2005): unsustainable (0-25), low sustainable (25-50), moderately sustainable (50-75), and highly sustainable (75-100). Leverage analysis based on Root Mean Square (RMS) changes was applied to identify sensitive attributes influencing sustainability performance within each dimension. Monte Carlo simulation (100 iterations) was additionally conducted to evaluate RAPFISH ordination stability and uncertainty. Ordination reliability and goodness-of-fit were assessed using stress values and coefficients of determination (R^2), where stress values below 0.25 and R^2 values approaching 1.00 indicated acceptable ordination performance and strong analytical reliability (Kavanagh and Pitcher 2004).

Multidimensional sustainability analysis and data visualization

All sustainability attribute scores were analyzed using RAPFISH Multidimensional Scaling (MDS) ordination to generate sustainability index values for ecological, economic, social, technological, and institutional dimensions. Ordination outputs were visualized using RAPFISH sustainability plots and integrated spider diagrams to compare sustainability performance among dimensions. Sustainability results were further interpreted descriptively to explain multidimensional interactions and sustainability patterns associated with *S. kraussiana* cultivation and trade systems.

Sensitive leverage attributes influencing sustainability performance within each dimension were identified using Root Mean Square (RMS) values generated through RAPFISH ordination analysis. Attributes with higher RMS values were interpreted as having a stronger influence on sustainability outcomes and, therefore, represented priority variables for sustainability improvement and management intervention. Results of the sustainability assessment were subsequently visualized and interpreted descriptively to facilitate comparative evaluation among sustainability dimensions.

SWOT-TOWS strategic analysis

SWOT-TOWS analysis was conducted to identify strategic factors influencing the sustainability of *S. kraussiana* cultivation and trade systems. Internal factors consisted of strengths and weaknesses associated with cultivation practices, environmental suitability, production systems, and market characteristics, whereas external factors included opportunities and threats related to ornamental plant demand, climate variability, institutional support, technological development, and potential naturalization risk associated with ornamental dissemination. SWOT factors identified through interviews and field observations were subsequently integrated into a TOWS framework to formulate sustainability-oriented management strategies (Gürel and Tat 2017). Strategic recommendations emphasized ecological resilience, market diversification, technological adaptation, institutional strengthening, and environmentally responsible ornamental horticulture development.

RESULTS AND DISCUSSION

Respondent characteristics and ornamental trade systems

Demographic profile of respondents

A total of 40 respondents participated in this study, consisting of ornamental plant farmers, traders, and mixed farmer-trader actors involved in the cultivation and commercialization of *S. kraussiana* in Central Java and Yogyakarta. Respondents were distributed across several ornamental production and trade centers, including Tawangmangu, Baturraden, Kopeng, Candimulyo, Surakarta, and Yogyakarta. Most respondents were middle-aged household-scale ornamental plant actors operating through informal trade networks and small to medium-scale nursery systems. Cultivation knowledge was acquired primarily through practical experience, family-based learning, and interaction among ornamental plant traders rather than through formal horticultural education. Many respondents had long-term experience in ornamental horticulture and commonly integrated *S. kraussiana* cultivation with broader ornamental plant businesses involving ferns, aroids, mosses, and tropical foliage plants. Detailed demographic and socio-economic characteristics of respondents are presented in Table 4.

Trade networks, cultivation scales, and distribution systems

Trade systems associated with *S. kraussiana* in Central Java and Yogtakarta were characterized predominantly by informal, small-scale, and locally interconnected ornamental horticulture networks. Highland regions such as Tawangmangu, Kopeng, and Baturraden functioned primarily as cultivation centers because humid environmental conditions supported stable vegetative growth and continuous propagation, whereas urban lowland areas, including Surakarta and Yogyakarta, were dominated by ornamental traders relying on interregional supply chains. Most cultivation systems operated at household or small nursery scales using shaded outdoor production areas, polybag systems, hanging pots, and terrarium-oriented ornamental arrangements, with propagation depending largely on vegetative clump division and stem fragmentation.

Table 4. Demographic and socio-economic characteristics of respondents involved in *Selaginella kraussiana* cultivation and trade in Central Java and Yogyakarta, Indonesia

Variable	Category	No. of respondents	Percentage (%)
Gender	Male	27	67.5
	Female	13	32.5
Age group (years)	20-30	5	12.5
	31-40	11	27.5
	41-50	14	35.0
	>50	10	25.0
Education level	Elementary school	6	15.0
	Junior high school	9	22.5
	Senior high school	18	45.0
	Diploma/S1 degree	7	17.5
Main occupation	Ornamental plant farmer	14	35.0
	Ornamental plant trader	11	27.5
	Farmer and trader	9	22.5
	Other occupations	6	15.0
Experience in the ornamental plant business	<5 years	8	20.0
	5-10 years	15	37.5
	>10 years	17	42.5
Cultivation scale	Small (<100 pots/trays)	18	45.0
	Medium (100-300 pots/trays)	15	37.5
	Large (>300 pots/trays)	7	17.5
Land/business status	Own property	24	60.0
	Rented property	10	25.0
	Shared/family-managed	6	15.0
Marketing system	Direct local sales	21	52.5
	Regional distribution	13	32.5
	Online marketing	6	15.0
Participation in farmer/ trader groups	Active member	11	27.5
	Non-member	29	72.5

Note: Respondents consisted of ornamental plant farmers, traders, and mixed farmer-trader actors involved directly in the cultivation, propagation, and commercialization of *Selaginella kraussiana* across Central Java and Yogyakarta regions

The ornamental trade chain showed relatively localized yet interconnected distribution patterns across Central Java and nearby provinces. Highland production centers supplied ornamental products to urban retail markets in Surakarta, Yogyakarta, Semarang, Purwokerto, and surrounding peri-urban areas. Distributed products included potted ornamental plants, vegetative propagules, hanging ornamental arrangements, and ground-cover planting materials for landscaping purposes. Product circulation generally involved small-scale growers, local collectors, urban traders, and household consumers through decentralized marketing systems such as ornamental markets, roadside stalls, and direct transactions. Digital marketing utilization remained limited, although several respondents had begun using social media and online ornamental plant communities to expand market access. The overall trade chain and regional distribution network of *S. kraussiana* cultivation systems are illustrated in Figure 3.

Ecological characteristics and cultivation environments

Morphological characteristics and vegetative propagation

Field observations showed that *S. kraussiana* possesses morphological characteristics favorable for ornamental horticulture, including creeping growth, dense branching, fine foliage texture, and rapid vegetative regeneration. The species commonly formed compact ground-cover mats through horizontal stem expansion and adventitious root formation. Respondents considered the species relatively easy to cultivate because fragmented stems and separated clumps regenerated rapidly without specialized propagation facilities. Propagation was conducted mainly through clump division, stem fragmentation, and transplantation of rooted segments into organic growing media. Morphological characteristics and propagation structures observed during field surveys are presented in Figure 2.

Microclimatic requirements and habitat preferences

Successful cultivation of *S. kraussiana* was strongly associated with stable microclimatic conditions, particularly in humid upland production centers such as Tawangmangu and Kopeng. Most respondents cultivated the species under partial shade using moisture-retaining growing media composed of compost, rice husks, humus soil, and livestock manure. The species performed best under indirect light exposure and relatively stable temperature conditions, whereas urban cultivation sites with fragmented canopy cover generally showed lower cultivation success during dry periods. Environmental conditions associated with successful cultivation systems are illustrated in Figure 4, while comparative cultivation characteristics across study locations are summarized in Table 5.

Environmental limitations affecting cultivation sustainability

Environmental fluctuation represented the primary ecological limitation affecting the cultivation sustainability of *S. kraussiana*. Respondents frequently reported reduced vegetative growth, lower colony compactness, and increased plant mortality during prolonged dry periods, particularly in warmer lowland environments. Excessive sunlight exposure also reduced ornamental quality by causing foliage discoloration and colony fragmentation, resulting in strong dependence on shaded cultivation systems. Additional constraints included limited cultivation space in urban areas and higher maintenance requirements under unstable environmental conditions. In contrast, humid upland production centers generally maintained more stable cultivation performance and lower maintenance costs. Minor pest disturbances involving slugs and snails were occasionally observed but were considered manageable through routine maintenance.

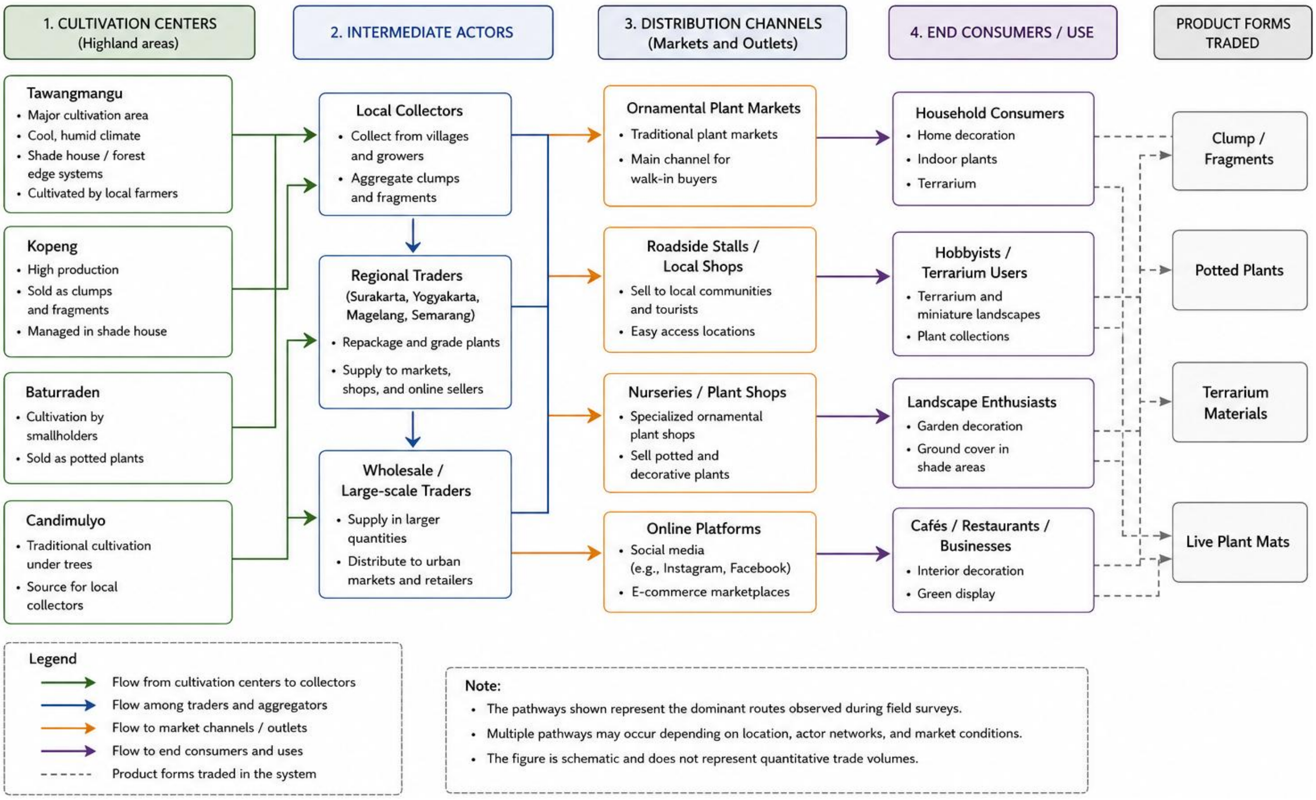

Figure 3. Observed cultivation, trade, and distribution pathways of *Selaginella kraussiana* in Central Java and Yogyakarta, Indonesia

Figure 4. Environmental conditions associated with the successful cultivation of *Selaginella kraussiana*

Table 5. Cultivation characteristics, propagation systems, and trade scales of *Selaginella kraussiana* in Central Java and Yogyakarta, Indonesia

Sites	Dominant cultivation system	Main propagation method	Growing media composition	Environmental condition	Average trade scale	Main market orientation
Baturraden	Semi-shaded household cultivation	Clump division	Soil, manure, compost	Humid upland	Medium	Local-regional
Sumbang	Household ornamental cultivation	Clump division, fragmentation	Soil, compost, organic matter	Semi-humid agricultural	Small-medium	Local trade
Gunung Pati	Household garden cultivation	Clump separation	Compost, garden soil	Peri-urban hilly	Small-medium	Urban consumers
Boja	Semi-shaded nursery	Stem fragmentation	Organic soil mixture	Moist upland	Medium	Regional distribution
Kopeng (Getasan)	Highland nursery and greenhouse	Vegetative fragmentation	Compost, humus soil	Cool humid highland	Large	Regional-interprovincial
Trenten (Candimulyo)	Agro-horticultural cultivation	Stem fragmentation	Soil, rice husks, manure	Humid upland	Medium	Local trade
Giyanti (Candimulyo)	Semi-shaded farming system	Clump division, fragmentation	Soil, compost	Humid upland	Medium	Regional distribution
Banjarsari	Urban retail cultivation	Purchased propagules	Organic potting media	Warm urban lowland	Medium	Urban retail
Jebres	Container-based trade	Vegetative propagation	Commercial media	Urban residential	Small-medium	Household buyers
Tasikmadu	Small shaded cultivation	Vegetative cuttings	Soil, rice husks	Transitional lowland-upland	Small	Roadside stalls
Tawangmangu	Shaded outdoor nursery	Clump division, fragmentation	Soil, compost, leaf litter	Cool mountainous	Large	Interregional markets
Ngaglik	Peri-urban cultivation	Clump division	Compost media	Moderate-humidity peri-urban	Medium	Urban landscaping
Umbulharjo	Urban retail cultivation	Purchased propagules	Commercial potting media	Dry urban environment	Small	Urban consumers
Banguntapan	Small retail cultivation	Purchased fragments	Soil, compost	Warm lowland urban	Small	Local consumers

Note: Trade scale categories were classified based on observed cultivation intensity and product distribution capacity. Small = Limited household-scale production, Medium = Stable local and regional distribution and Large = High production intensity supplying broader interregional ornamental markets

RAPFISH sustainability assessment

Multidimensional RAPFISH analysis revealed contrasting sustainability performance among ecological, economic, social, technological, and institutional dimensions of *S. kraussiana* cultivation and trade systems in Central Java and Yogtakarta. Sustainability indices ranged from highly sustainable ecological conditions to unsustainable technological and institutional dimensions, indicating substantial imbalance among components influencing long-term ornamental horticulture sustainability. Detailed sustainability indices and leverage attributes are summarized in Table 6.

Ecological sustainability

The ecological dimension achieved the highest sustainability index (83.93%), categorized as highly sustainable. Water availability/humidity and cultivation pattern/shading represented the most sensitive ecological leverage attributes, with RMS values of 2.61 and 2.27, respectively. These findings indicate that the ecological sustainability of *S. kraussiana* cultivation systems strongly depends on relative stable humidity conditions and appropriate shaded cultivation environments. Nevertheless, ecological sustainability remained vulnerable to climatic variability, particularly prolonged drought and excessive sunlight exposure in lowland cultivation environments (Figure 5.A).

Economic sustainability

The economic dimension achieved a sustainability index of 58.29%, categorized as moderately sustainable. Sales volume/market demand represented the most sensitive economic leverage attribute (RMS 1.83), followed by profitability of ornamental business (1.62) and price stability (1.38). Economic sustainability was influenced primarily by ornamental market continuity, consumer demand, and dependence on interregional supply networks from humid upland production centers (Figure 5.B).

Social sustainability

The social dimension produced a sustainability index of 36.70%, categorized as low sustainable. Employment opportunities represented the most sensitive social leverage attribute (RMS 1.78), followed by community participation in cultivation activities (1.56) and social relationships among cultivators (1.41). Social sustainability remained constrained by weak organizational interaction, limited formal training participation, and low institutional engagement among ornamental horticulture actors (Figure 5.C).

Technological sustainability

Technological sustainability exhibited the lowest performance among all assessed dimensions, with a sustainability index of 18.29%, categorized as unsustainable. Use of environmentally friendly technology represented the most sensitive technological leverage attribute (RMS 2.24), followed by access to cultivation innovations (1.68) and availability of appropriate cultivation technology (1.55). Technological limitations included low adoption of climate-adaptive cultivation systems, limited digital marketing integration, and minimal production innovation (Figure 5.D).

Table 6. Sustainability indices and leverage attributes across ecological, economic, social, technological, and institutional dimensions of *Selaginella kraussiana* cultivation and trade systems

Sustainability dimension	Sustainability index (%)	Sustainability category	Most sensitive leverage attributes	RMS value	Relative influence
Ecological	83.93	Highly sustainable	Water availability/humidity	2.61	Very high
			Cultivation pattern/shading	2.27	Very high
			Growing media suitability	1.95	High
			Use of organic fertilizer	1.72	High
			Growing temperature suitability	1.48	Moderate
			Pest and disease management	1.31	Moderate
			Biodiversity conservation	1.08	Moderate
			Soil/media organic matter content	0.85	Low
			Wind exposure protection	0.63	Low
			Waste management in cultivation	0.41	Very low
Economic	58.29	Moderately sustainable	Sales volume/market demand	1.83	High
			Profitability of the ornamental business	1.62	High
			Price stability	1.38	Moderate
			Access to markets	1.24	Moderate
			Production costs	1.11	Moderate
			Business scale/land ownership status	1.01	Moderate
			Income contribution to the household	0.86	Low
			Value added of *S. kraussiana*	0.72	Low
			Availability of financial capital	0.55	Low
			Market diversification	0.44	Very low
			Access to credit	0.32	Very low
Social	36.70	Low sustainable	Employment opportunities	1.78	High
			Community participation in cultivation activities	1.56	High
			Social relationships among cultivators	1.41	Moderate
			Distribution of economic benefits	1.27	Moderate
			Knowledge sharing among cultivators	1.12	Moderate
			Gender involvement in cultivation	0.98	Low
			Youth involvement in ornamental horticulture	0.85	Low
			Social acceptance of cultivation activities	0.72	Low
			Access to social services	0.61	Low
			Conflict within communities	0.44	Very low
Technological	18.29	Unsustainable	Use of environmentally friendly technology	2.24	Very high
			Access to cultivation innovations	1.68	High
			Availability of appropriate cultivation technology	1.55	High
			Use of media / growing technology	1.45	Moderate
			Irrigation technology application	1.32	Moderate
			Postharvest handling technology	1.18	Moderate
			Technology maintenance and infrastructure	0.95	Low
			Access to information technology	0.72	Low
			Digital marketing technology use	0.61	Low
			Access to research and development	0.44	Very low
			Capacity to adopt new technology	0.38	Very low
Institutional	18.68	Unsustainable	Access to government guidance/extension	2.31	Very high
			Participation in farmer organizations	1.87	High
			Institutional support for marketing	1.64	High
			Collaboration with other institutions	1.38	Moderate
			Regulatory support for the ornamental trade	1.22	Moderate
			Access to training and policy information	1.05	Moderate
			Policy consistency for cultivation and trade	0.89	Low
			Monitoring and evaluation of cultivation systems	0.89	Low
			Access to information systems	0.71	Low
			Conflict resolution mechanisms	0.46	Very low

Note: Sustainability categories followed RAPFISH classification criteria: 0-25 = Unsustainable; 25-50 = Low sustainable; 50-75 = Moderately sustainable; 75-100 = Highly sustainable. RMS (Root Mean Square) values indicate the relative sensitivity of leverage attributes affecting sustainability performance within each dimension

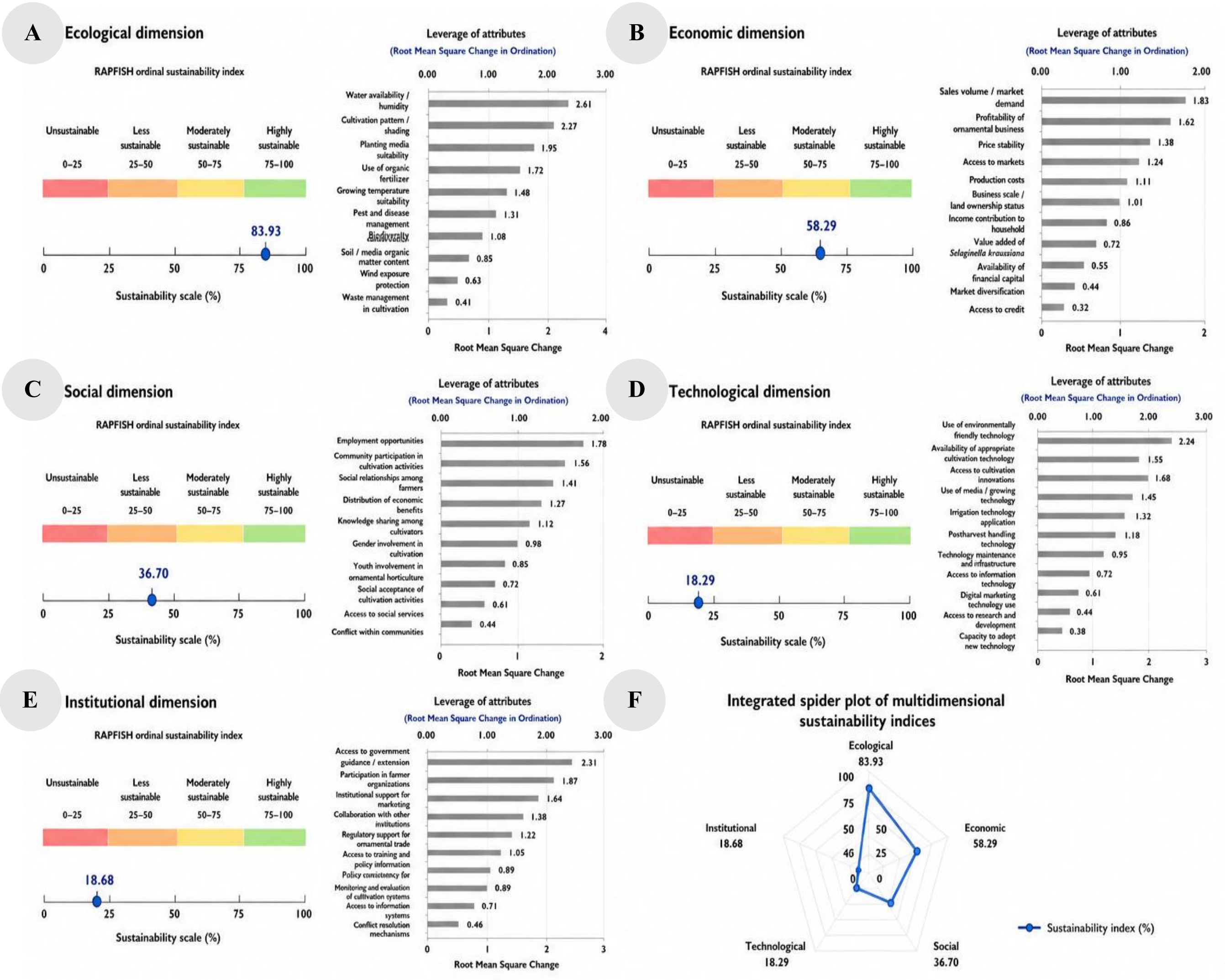

Figure 5. RAPFISH ordination and leverage analysis across sustainability dimensions of *Selaginella kraussiana* cultivation and trade systems. Notes: A. Ecological dimension, B. Economic dimension, C. Social dimension, D. Technological dimension, E. Institutional dimension, F. Integrated spider plot. Sustainability scale ranged from 0-100 (%), with higher values indicating better sustainability performance

Institutional sustainability

The institutional dimension also produced a sustainability index of 18.68%, categorized as unsustainable. Access to government guidance/extension represented the most sensitive institutional leverage attribute (RMS 2.31), followed by participation in farmer organizations (1.87) and institutional support for marketing (1.64). Institutional sustainability remained limited because of weak organizational collaboration, restricted access to technical guidance and market information, and minimal coordination among farmers, traders, universities, and government agencies (Figure 5.E).

Integrated sustainability performance and strategic implications

Multidimensional sustainability patterns

Integrated RAPFISH analysis demonstrated substantial imbalance among sustainability dimensions within *S. kraussiana* cultivation and trade systems. The ecological dimension showed the strongest sustainability performance, whereas technological and institutional dimensions remained critically weak. Economic sustainability occupied an intermediate position categorized as moderately sustainable, while the social dimension remained low sustainable. These patterns indicate that current ornamental horticulture systems are ecologically feasible but remain vulnerable from technological and institutional perspectives.

The integrated spider plot clearly illustrated asymmetric sustainability distribution among dimensions (Figure 5.F). Ecological sustainability exceeded other dimensions because cultivation systems relied on relatively low-input practices and vegetative propagation. In contrast, technological and institutional dimensions formed the smallest sectors within the multidimensional sustainability profile, reflecting limited innovation, weak institutional coordination, and low access to formal support systems. The mean integrated sustainability index reached 43.26%, indicating that the overall sustainability of *S. kraussiana* cultivation systems remained within the low sustainable category.

These findings further suggest that long-term sustainability cannot rely solely on favorable ecological conditions. Although humid tropical environments currently support stable cultivation performance, sustainability vulnerability may increase substantially under climate variability, market instability, and weak institutional governance. Consequently, future ornamental horticulture development requires integrated socio-ecological management strategies.

Monte Carlo validation and model reliability

Monte Carlo analysis confirmed that RAPFISH ordination results possessed relatively high analytical stability and acceptable reliability across all sustainability dimensions. Differences between multidimensional scaling (MDS) outputs and Monte Carlo simulations were generally small, ranging from 0.47 to 1.63, indicating relatively low uncertainty within sustainability scoring and ordination processes. The ecological dimension showed the highest sustainability consistency because environmental suitability and cultivation practices among humid upland production centers were relatively homogeneous.

Stress values for all dimensions ranged between 0.16 and 0.21, remaining below the acceptable threshold of 0.25 recommended for RAPFISH multidimensional ordination analysis (Kavanagh and Pitcher 2004). Coefficients of determination (R^2) ranged from 0.94 to 0.97, indicating strong ordination performance and high explanatory power of sustainability attributes within the multidimensional assessment framework. The relatively high model reliability indicates that the selected attributes adequately represented multidimensional sustainability characteristics of *S. kraussiana* cultivation systems. Detailed sustainability indices, stress values, Monte Carlo outputs, and coefficients of determination are presented in Table 7.

Sensitive sustainability attributes

Heatmap analysis of leverage sensitivity revealed that several attributes exerted disproportionately strong influence on overall sustainability performance (Figure 6). Water availability and cultivation pattern represented the most influential ecological variables, confirming the strong dependency of *S. kraussiana* on humid microclimatic conditions. Within the economic dimension, sales volume and production costs showed the highest sensitivity values, indicating that economic sustainability is highly dependent on stable ornamental market demand and efficient cultivation management.

Land or business status, relationships among business actors, and access to training emerged as critical social sustainability attributes. Meanwhile, environmentally friendly technology and access to government guidance were identified as dominant leverage attributes within technological and institutional dimensions, respectively. The concentration of sensitive attributes within organizational and technological sectors further explains the low sustainability performance observed in these dimensions. Leverage analysis demonstrated that sustainability improvement should prioritize institutional strengthening, technological adaptation, and environmentally controlled cultivation systems while maintaining ecological compatibility and market continuity.

SWOT-TOWS strategic analysis

Internal and external strategic factors

SWOT analysis demonstrated that *S. kraussiana* cultivation systems possess several internal strengths supporting ornamental horticulture development in tropical environments. Major strengths included adaptation to humid shaded environments, easy vegetative propagation, relatively low production costs, and relatively stable ornamental demand in urban and peri-urban markets. Highland production centers such as Tawangmangu and Kopeng provided environmentally favorable conditions supporting continuous vegetative growth and relatively efficient cultivation management. The attractive morphology and compact colony structure of *S. kraussiana* further increased its commercial value as a decorative ground-cover and terrarium plant.

Table 7. Integrated sustainability indices, stress values, Monte Carlo validation, and coefficients of determination (R^2) for RAPFISH analysis of *Selaginella kraussiana* cultivation and trade systems

Sustainability dimension	Sustainability index (%)	Sustainability category	Monte Carlo value (%)	Difference between MDS and Monte Carlo	Stress value	Coefficient of determination (R^2)
Ecological	83.93	Highly sustainable	82.30	1.63	0.17	0.97
Economic	58.29	Moderately sustainable	57.82	0.47	0.19	0.95
Social	36.70	Low sustainable	37.20	0.50	0.21	0.94
Technological	18.29	Unsustainable	20.07	1.78	0.16	0.97
Institutional	18.68	Unsustainable	19.85	1.17	0.18	0.96
Average sustainability index	43.26	—	—	—	0.18	0.96

Note: Stress values below 0.25 and R^2 values approaching 1.00 indicate acceptable ordination performance and reliable RAPFISH model configuration. Small differences between MDS and Monte Carlo results indicate stable multidimensional sustainability estimation

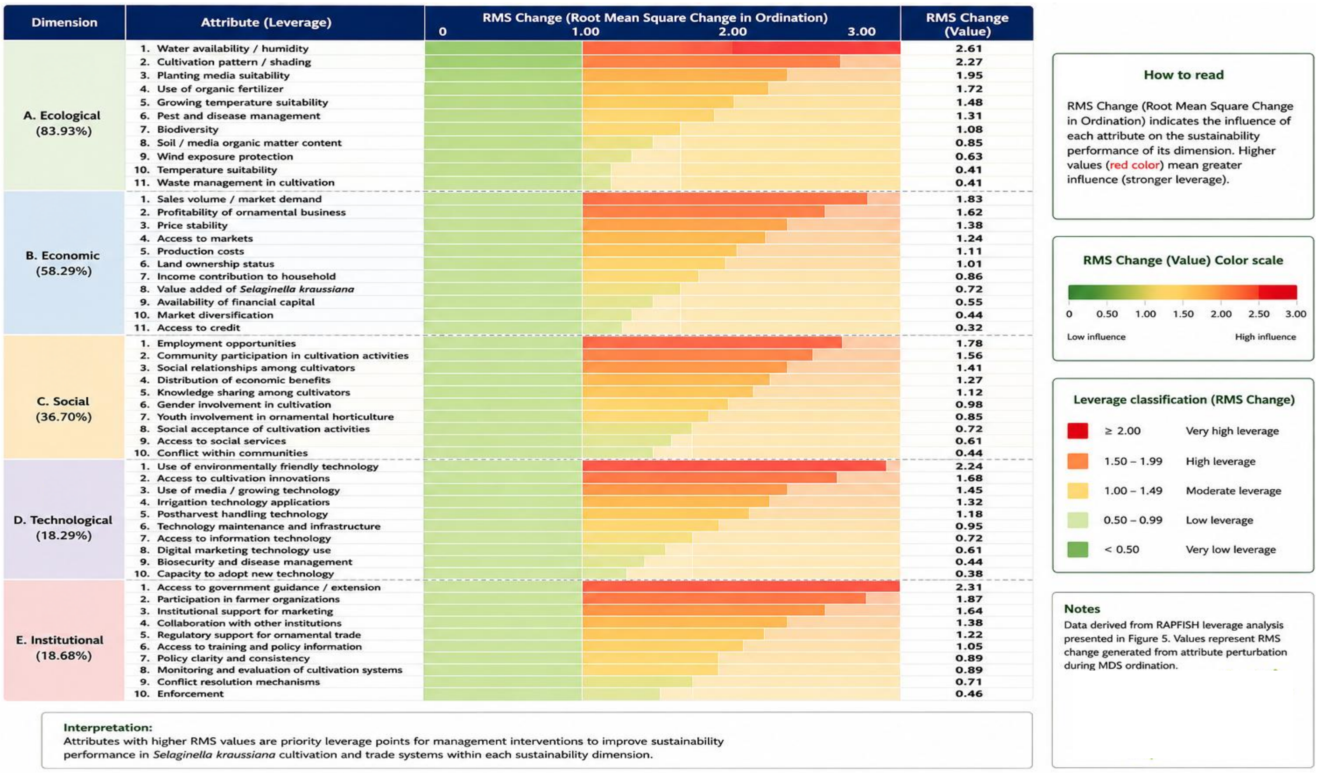

Figure 6. Heatmap of leverage attribute sensitivity across sustainability dimensions of *Selaginella kraussiana* cultivation and trade systems (RAPFISH leverage analysis)

However, several internal weaknesses were also identified. Cultivation systems remained highly dependent on stable humidity and canopy protection, making production vulnerable to drought and elevated temperatures. Technological innovation, digital marketing integration, and institutional collaboration among farmers, traders, and government agencies remained limited. Most ornamental trade systems also operated at small household scales without coordinated production management or formal business organization.

External opportunities were associated with increasing public interest in tropical ornamental plants, urban landscaping, indoor gardening, and expansion of online ornamental trade systems. Growing interest in environmentally friendly horticulture may also provide broader market opportunities for humidity-adapted tropical species such as *S. kraussiana*. Nevertheless, external threats included climate variability, fluctuating ornamental market trends, increasing competition with other ornamental ground-cover plants, and potential ecological concerns related to plant establishment outside cultivation systems. Internal and external strategic factors identified during field observations and respondent interviews were subsequently integrated into a SWOT-TOWS framework to formulate sustainability-oriented management strategies (Table 8).

Sustainability transition priorities

The TOWS framework indicated that sustainability improvement should prioritize integrated ecological, technological, and institutional interventions. Strategies combining strengths and opportunities emphasized expansion of low-disturbance ornamental cultivation systems, development of digital marketing networks, and strengthening of tropical ornamental branding. Strategies addressing weaknesses and opportunities focused on improving cultivation training, climate-adaptive nursery management, and institutional collaboration among ornamental horticulture actors.

Defensive strategies targeting threats highlighted the importance of environmental monitoring, humidity management, and responsible ornamental distribution practices to reduce ecological vulnerability and potential establishment outside cultivation systems. Institutional strengthening also emerged as a major sustainability priority because current ornamental trade systems remain weakly connected to formal horticultural development programs and technical support networks.

SWOT-TOWS analysis further demonstrated that future sustainability transitions in *S. kraussiana* cultivation systems require balanced integration among ecological resilience, technological adaptation, market diversification, and institutional governance rather than production expansion alone. Although humid tropical environments currently support relatively stable cultivation performance, long-term sustainability may remain vulnerable under increasing climate variability, market instability, and weak institutional coordination. Sustainability improvement should prioritize climate-adaptive cultivation, responsible ornamental trade systems, technological innovation, and precautionary ecological monitoring.

Table 8. SWOT-TOWS matrix for sustainability strategy development in *Selaginella kraussiana* cultivation systems

SWOT components	Main findings
Strengths (S)	Observed tolerance to humid tropical environments; easy vegetative propagation; low-input cultivation systems; attractive ornamental morphology; relatively stable consumer demand; compatibility with shaded ornamental landscapes
Weaknesses (W)	High dependency on humidity and shade availability; sensitivity to drought and heat stress; limited technological innovation; weak institutional organization; low digital marketing utilization; small-scale production capacity
Opportunities (O)	Increasing demand for tropical ornamental plants; expansion of urban landscaping and indoor gardening markets; development of digital commerce platforms; growing interest in environmentally friendly horticulture; interregional ornamental trade potential
Threats (T)	Climate variability and prolonged dry seasons; competition with fast-growing ornamental ground-cover species; unstable ornamental plant market trends; limited institutional monitoring; and potential ecological concerns related to establishment outside cultivation systems
SO strategies	Expand environmentally sustainable ornamental cultivation systems; strengthen tropical ornamental branding; increase regional market diversification; develop eco-friendly ornamental horticulture promotion through digital platforms
WO strategies	Improve cultivation training and technical guidance; increase adoption of climate-adaptive cultivation technologies; strengthen farmer and trader collaboration networks; develop environmentally controlled cultivation infrastructure
ST strategies	Maintain humidity-stable cultivation systems; improve ecological monitoring and cultivation management; strengthen product quality under fluctuating climatic conditions; promote responsible ornamental plant distribution practices
WT strategies	Enhance institutional support and extension services; improve sustainability awareness among farmers and traders; strengthen ecological monitoring and environmental regulation; increase access to market information and technological innovation

Note: SWOT-TOWS analysis was used to identify strategic priorities for improving the long-term sustainability of *Selaginella kraussiana* cultivation and trade systems through integration of ecological, socio-economic, technological, and institutional considerations

Discussion

Sustainability paradox and potential naturalization risk in ornamental lycophyte cultivation systems

The present study revealed a sustainability paradox within *S. kraussiana* cultivation systems in Central Java and Yogtakarta. RAPFISH analysis demonstrated relatively high ecological sustainability supported by low-input cultivation practices, limited harvesting from natural habitats, and suitability to humid tropical environments. Similar ecological advantages have been reported in ornamental horticulture systems where household-scale propagation contributes indirectly to ex situ conservation and reduces pressure on wild plant populations (Heywood 2011; Francini et al. 2022). The predominance of vegetative propagation further indicates that commercialization of *S. kraussiana* currently depends mainly on cultivated planting materials rather than direct collection from natural ecosystems.

However, the same ecological characteristics supporting cultivation success may also increase potential naturalization risk. *S. kraussiana* possesses rapid clonal growth, adventitious rooting capacity, dense mat formation, and strong regeneration from stem fragmentation, traits commonly associated with naturalization potential in introduced environments (Reichard and White 2001; van Kleunen et al. 2018). Similar traits have been linked to increased establishment potential in ornamental species distributed through horticultural trade pathways (Humair et al. 2015). Previous studies from New Zealand, Europe, and Australia reported that *S. kraussiana* may establish dense understory colonies capable of suppressing native vegetation and altering forest floor composition (McClymont et al. 2013; Nessia et al. 2014; Dang et al. 2019).

The horticultural trade pathway is widely recognized as an important mechanism facilitating plant introductions because ornamental species are intentionally propagated and distributed beyond their native geographical ranges (Dehnen-Schmutz et al. 2007; Hulme et al. 2018). In the present study, *S. kraussiana* showed favorable cultivation performance in cool upland environments with dense canopy cover, conditions resembling many tropical forest understories and riparian habitats in Indonesia. Increasing commercialization and redistribution of planting materials may therefore increase propagule pressure and opportunities for localized establishment outside cultivation systems.

Despite these concerns, cultivation systems observed in this study remained relatively localized and environmentally dependent. Field observations indicated that *S. kraussiana* was rarely found growing spontaneously outside managed nursery environments, and extensive naturalized populations surrounding cultivation sites were generally not detected. This suggests that current ecological risk in the study area remains primarily potential rather than fully established under existing ornamental trade conditions. Successful establishment outside cultivation systems likely requires stable moisture, suitable growing media, and protected canopy cover, conditions that may not always be consistently available in surrounding landscapes.

These findings indicate that the sustainability assessment of ornamental lycophyte cultivation systems should not rely solely on economic feasibility or cultivation performance. Ecological sustainability at the production level does not necessarily guarantee ecological safety at the landscape scale. Sustainable ornamental horticulture development should therefore integrate ecological precaution, environmental monitoring, responsible disposal of vegetative waste, and institutional oversight alongside technological and economic development.

Ecological resilience and microclimatic dependency of Selaginella kraussiana

The present study demonstrated that the cultivation performance of *S. kraussiana* is strongly influenced by microclimatic stability, particularly water availability, canopy protection, and temperature moderation. Water availability and cultivation pattern emerged as the most sensitive ecological leverage attributes in RAPFISH analysis, indicating that the sustainability of ornamental lycophyte cultivation systems depends heavily on favorable environmental conditions. Similar ecological dependency has been reported in tropical understory ferns and lycophytes requiring stable shaded habitats for physiological performance and vegetative growth (Setyawan 2011; Watkins and Cardelús 2012). Successful cultivation systems were concentrated mainly in upland regions such as Tawangmangu and Kopeng, where cool temperatures and stable humidity supported continuous colony expansion.

The species also demonstrated relatively strong vegetative resilience under suitable conditions. Creeping stems, adventitious roots, and clonal fragmentation enabled efficient propagation after transplantation or physical disturbance, similar to other *Selaginella* species in tropical environments (Fang et al. 2021). These traits provide advantages for ornamental horticulture because propagation can be maintained with relatively low technological input and production costs.

In contrast, cultivation performance declined in warmer urban lowland environments such as Surakarta and Yogyakarta. Reduced humidity, prolonged dry conditions, and excessive sunlight exposure frequently caused leaf desiccation, lower colony density, and slower vegetative spread. Similar environmental sensitivity has been reported in humidity-dependent ornamental fern systems affected by evaporative stress (Francini et al. 2022). These findings indicate that the ecological resilience of *S. kraussiana* is conditional rather than universal, with cultivation stability strongly dependent on suitable environmental thresholds.

Climate variability may therefore become an important sustainability constraint for *S. kraussiana* cultivation systems in tropical regions. Increasing temperatures, fluctuating rainfall, and declining humidity associated with climate change could reduce cultivation suitability, particularly in lowland environments (De Mastro et al. 2025). Long-term sustainability may therefore require climate-adaptive management strategies such as improved shading systems, moisture-retaining growing media, low-cost irrigation, and environmentally controlled nursery infrastructure.

The ornamental trade system documented in this study was dominated by informal, household-based, and locally interconnected business networks. Most respondents operated through small nurseries, roadside stalls, or home-based cultivation systems without formal supply arrangements. Similar informal trade structures have been widely reported in tropical ornamental horticulture systems in Southeast Asia (van Touch et al. 2024). These systems provide relatively low market-entry barriers and supplementary income opportunities for small-scale producers.

The study also demonstrated spatial differentiation between upland cultivation centers and urban distribution markets. Highland regions such as Tawangmangu, Kopeng, and Baturraden functioned mainly as production hubs because environmental conditions supported stable propagation and ornamental quality, whereas urban regions such as Surakarta and Yogyakarta acted primarily as consumer-oriented distribution centers. Similar geographical specialization has been reported in tropical ornamental plant industries supplying urban landscaping and household gardening markets (Çelik and Arısoy 2014; Mubarok et al. 2023).

Despite moderate economic sustainability, the trade system remained vulnerable to fluctuating ornamental trends and changing consumer preferences. Market demand was strongly influenced by social media exposure and ornamental fashion cycles, consistent with global ornamental horticulture patterns (Altman et al. 2022). Many respondents therefore diversified cultivation portfolios with additional ornamental plants such as ferns, aroids, and moss-associated species to reduce dependence on a single commodity.

Social sustainability remained constrained by weak organizational structures and limited participation of younger generations. Cultivation knowledge was transmitted mainly through practical experience and informal social learning rather than formal institutional training. Limited participation in ornamental horticulture organizations also reduced opportunities for coordinated marketing, technological innovation, and collective sustainability management. Socio-economic sustainability of *S. kraussiana* cultivation systems, therefore, continues to depend more on localized trade flexibility than on institutionalized horticultural development structures.

Technological and institutional limitations in small-scale ornamental horticulture

Technological and institutional dimensions exhibited the lowest sustainability performance in the present study, indicating that *S. kraussiana* cultivation systems remain constrained by limited innovation capacity and weak organizational support. Most respondents relied on manual cultivation techniques involving clump division, conventional watering systems, and naturally shaded nursery environments. Although these low-input systems reduced production costs and chemical dependency, they also limited production efficiency, environmental control, and long-term adaptive capacity. Similar technological limitations have been reported in smallholder horticultural systems in tropical developing countries where financial constraints restrict access to climate-adaptive infrastructure and cultivation technologies (Indurthi et al. 2024; De Mastro et al. 2025).

Environmental dependency further increased technological vulnerability because most respondents lacked humidity regulation systems, automated irrigation, environmental monitoring devices, or protected cultivation infrastructure. Similar limitations have been documented in tropical fern and bryophyte-associated horticultural systems where microclimatic instability directly reduces ornamental quality and vegetative performance (Francini et al. 2022). Digital technology adoption also remained limited, with only a small proportion of respondents utilizing online marketing platforms despite the rapid expansion of digital ornamental markets (Mubarok et al. 2023).

Institutional sustainability was similarly weak because most respondents operated independently without formal collaboration with government agencies, universities, or horticultural organizations. Limited participation in farmer groups and ornamental plant associations reduced opportunities for technical training, innovation transfer, and coordinated sustainability management. Weak institutional coordination may also reduce environmental monitoring capacity associated with ornamental plant distribution and potential ecological risk. Consequently, strengthening technical assistance, institutional collaboration, and climate-adaptive cultivation technologies should become major priorities for improving the sustainability of small-scale ornamental horticulture systems in tropical environments.

Ornamental plant trade and propagule pressure dynamics

The present study indicates that increasing commercialization of *S. kraussiana* may elevate propagule pressure through repeated transportation and redistribution of planting materials among cultivation centers, ornamental markets, and urban consumers. Propagule pressure is widely recognized as an important predictor of invasion success because repeated introduction events increase opportunities for establishment and spread (Pyšek et al. 2020). The decentralized and weakly regulated ornamental trade system documented in this study may further increase this vulnerability because most cultivation and distribution activities occur without formal environmental monitoring or institutional oversight.

In the present study, upland cultivation centers continuously supplied ornamental products to urban markets and household consumers through interconnected informal trade networks. Such circulation may increase opportunities for accidental escape of vegetative fragments into surrounding semi-natural environments, particularly in moisture-stable landscapes resembling the preferred habitat conditions of *S. kraussiana*. Similar pathways have been documented in ornamental horticulture systems where redistribution of non-native ornamental plants facilitates gradual naturalization beyond cultivation areas (Dehnen-Schmutz et al. 2007; Hulme et al. 2018).

Nevertheless, current cultivation systems remain relatively localized and environmentally dependent. This dependency may partially limit the establishment outside cultivation systems in dry or highly exposed environments. However, continued expansion of ornamental horticulture networks, urban landscaping activities, and climate-driven environmental changes could gradually increase opportunities for localized establishment in suitable habitats. Consequently, sustainable ornamental horticulture development should incorporate precautionary ecological management, including responsible disposal of vegetative waste, public awareness regarding potential naturalization risk, and institutional guidance for environmentally responsible ornamental plant distribution systems.

Sustainability transition pathways and implications for biodiversity conservation

The multidimensional sustainability assessment indicates that long-term sustainability of *S. kraussiana* cultivation systems depends on transitions toward more integrated socio-ecological horticultural management. Although ecological sustainability remained relatively high, technological and institutional dimensions exhibited substantial weaknesses that may reduce adaptive capacity under climate variability, market instability, and expanding ornamental trade networks. Similar transition challenges have been reported in tropical horticultural systems where ecological suitability alone is insufficient without technological adaptation and institutional support (Francini et al. 2022; De Mastro et al. 2025).

One major transition priority involves strengthening climate-adaptive cultivation systems capable of maintaining stable environmental conditions under variable climatic regimes. Improved shading systems, moisture-retaining growing media, low-cost irrigation technologies, and environmentally controlled nursery infrastructure may improve cultivation resilience while maintaining relatively low ecological impacts. Expansion of digital marketing systems and broader regional market integration may also improve economic resilience and reduce dependence on localized trade systems. However, technological adaptation should remain compatible with environmentally responsible horticultural practices to minimize ecological disturbance associated with intensive ornamental production.

Institutional strengthening also represents an important sustainability priority. Limited collaboration among farmers, traders, universities, and government agencies reduced opportunities for technical training, innovation transfer, environmental monitoring, and coordinated sustainability management. Strengthening farmer associations, extension services, and sustainability-oriented governance systems could improve adaptive capacity and support more environmentally responsible ornamental horticulture development. Institutional coordination is also important for improving information exchange related to cultivation management, market stability, and environmental risks.

The findings further highlight implications for biodiversity conservation. Although current cultivation systems rely mainly on cultivated planting stocks rather than direct extraction from natural habitats, the biological characteristics of *S. kraussiana* indicate potential ecological risks associated with expanding ornamental trade systems. Rapid vegetative spread and adaptability to humid environments may increase opportunities for localized establishment outside cultivation systems under suitable environmental conditions. Sustainable ornamental horticulture should therefore integrate ecological precaution, environmental monitoring, responsible disposal of vegetative waste, and institutional oversight to minimize unintended environmental impacts associated with non-native ornamental plant distribution.

Figure 7 summarizes the precautionary conceptual pathway linking ornamental trade expansion, vegetative fragment movement, propagule pressure, environmental filtering, and potential naturalization risk in *S. kraussiana* cultivation systems. The framework highlights that repeated movement of vegetative propagules under favorable humid and shaded tropical environments may increase ecological concern associated with ornamental dissemination, thereby emphasizing the importance of precautionary monitoring and responsible horticultural management.

These findings highlight the importance of integrating ecological precaution, technological adaptation, institutional strengthening, and biodiversity conservation within sustainable tropical ornamental horticulture systems. Although *S. kraussiana* demonstrated high adaptability to humid tropical cultivation environments, its extensive vegetative propagation capacity and increasing ornamental trade distribution may increase potential naturalization risk under suitable environmental conditions. The combination of ornamental commercialization, repeated vegetative dissemination, and humid shaded microhabitats could facilitate localized establishment outside cultivation systems, particularly in environmentally favorable areas. However, no direct invasion assessment, escaped population survey, or ecological impact quantification was conducted in this study. Therefore, precautionary monitoring and environmentally responsible ornamental trade management are recommended to minimize potential long-term ecological risks associated with ornamental plant dissemination.

Study limitations and future research directions

Several limitations should be considered when interpreting the findings of this study. First, this research was designed as an exploratory RAPFISH-based sustainability appraisal focusing on ornamental trade networks and cultivation systems in Central Java and Yogyakarta and therefore may not fully represent ornamental horticulture systems across Indonesia. Second, sustainability assessment relied primarily on cross-sectional interviews, repeated field observations, and semi-quantitative ordinal scoring within a limited study period. Although triangulation, multi-evaluator scoring, and Monte Carlo validation were applied, several attributes still involved interpretative assessment that may contain subjective variability. In addition, environmental variables such as humidity stability, temperature conditions, and growing media characteristics were evaluated qualitatively rather than through direct instrumental measurements.

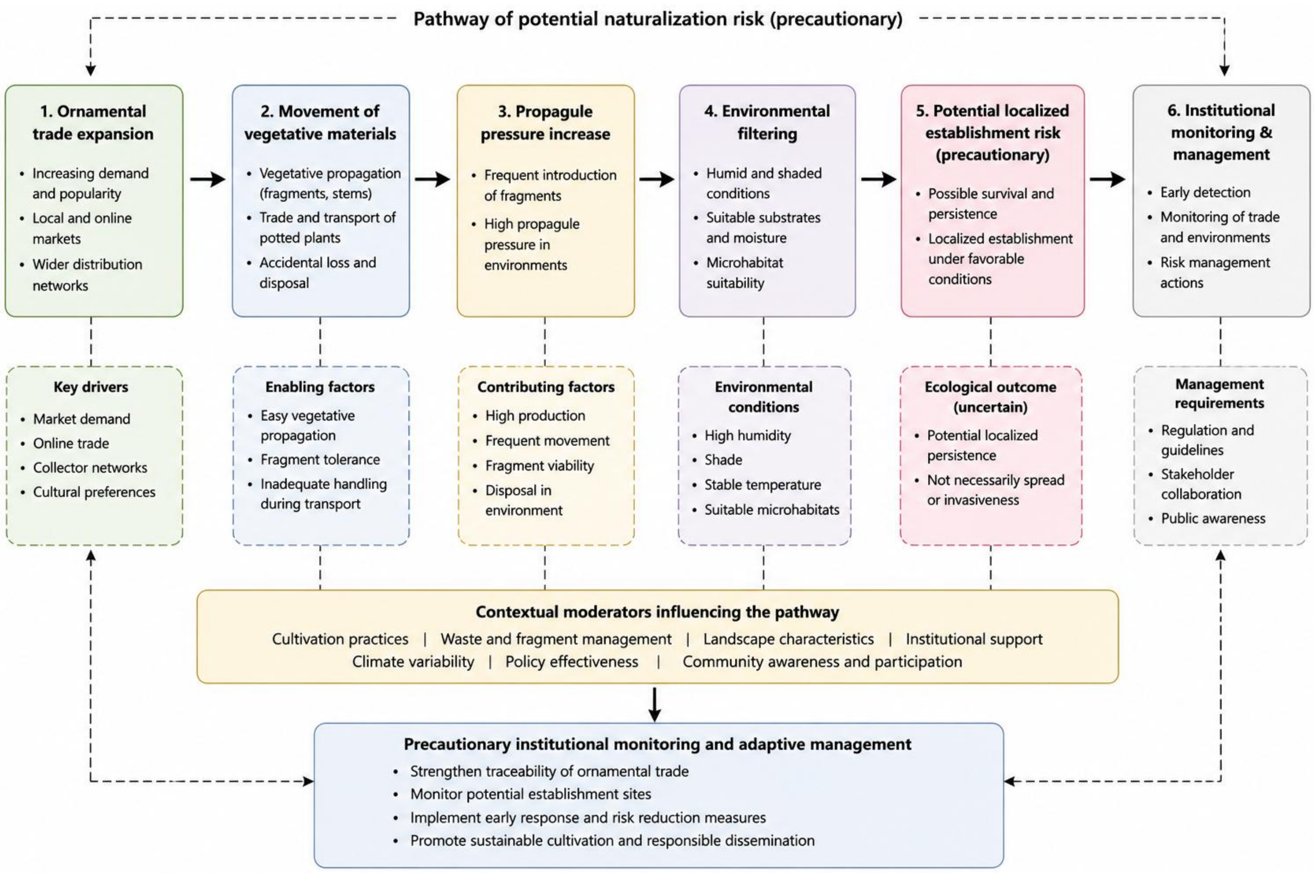

Figure 7. Conceptual pathway linking ornamental trade expansion, propagule pressure, environmental filtering, and potential naturalization risk of *Selaginella kraussiana* in tropical horticulture systems

The study also did not include direct invasion assessment, escaped-population surveys, ecological impact quantification, or spatial mapping of populations established outside cultivation systems. Consequently, interpretations regarding potential naturalization risk should be considered precautionary rather than confirmatory. Future research should incorporate long-term ecological monitoring, quantitative environmental measurements, ecological niche modeling, and experimental evaluation of environmental tolerance under different climatic conditions. Comparative studies involving additional ornamental lycophyte and fern species may further improve understanding of sustainability transitions and ecological risks associated with tropical ornamental horticulture systems.

In conclusion, this study demonstrated substantial imbalance among multidimensional sustainability components within *S. kraussiana* cultivation and trade systems in Central Java and Yogtakarta. RAPFISH analysis showed that the ecological dimension was highly sustainable (83.93%), supported by humid shaded environments and efficient vegetative propagation, whereas the economic dimension was moderately sustainable (58.29%). In contrast, the social dimension remained low sustainable (36.70%), while technological (18.29%) and institutional (18.68%) dimensions were classified as unsustainable because of limited innovation, weak extension services, and insufficient institutional coordination. Monte Carlo validation confirmed strong RAPFISH reliability, with stress values below 0.25 and coefficients of determination (R^2) ranging from 0.94 to 0.97. The study also revealed a sustainability paradox in which ecological conditions supporting successful ornamental cultivation may simultaneously increase propagule pressure and potential localized establishment outside cultivation systems under favorable humid conditions. Although no direct invasion assessment was conducted, these findings highlight the importance of precautionary ecological monitoring associated with ornamental plant dissemination. Future studies should incorporate quantitative environmental measurements, escaped-population surveys, and long-term ecological monitoring to better evaluate naturalization dynamics and ecological risks.

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