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Review Article

Advances and limitations in *Caladium* breeding: A bibliometric perspective

Avanços e limitações no melhoramento genético de *Caladium*: Uma perspectiva bibliométrica

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Abstract
Caladium is a predominantly ornamental and medicinal genus with high commercial value. Several studies on *Caladium* breeding have addressed inheritance, micropropagation, and morphological, cytological, molecular, and genomic characterization. However, few studies have examined the temporal and spatial evolution of research themes, authors, locations, and trends. Therefore, this study aimed to analyze advances, limitations, and emerging trends in *Caladium* breeding through bibliometric analysis. A systematic search was performed in the *Scopus* and *Web of Science* databases, covering publications from 1992 to 2025. A total of 141 documents were identified, of which 98 remained after duplicate records were removed. Data were analyzed using the Bibliometrix package in R, within the RStudio environment, through the *Biblioshiny* graphical interface. The results revealed fluctuations in publication patterns, with the United States and China standing out in scientific output. An evolution from classical breeding approaches toward a stronger focus on inheritance, somaclonal variation, and molecular genetics has been observed over the past two decades. The absence of a precise explanation for the biological mechanisms underlying somaclonal variation, combined with the scarcity of studies on epigenetics and post-production morphophysiological responses, represents a significant gap in *Caladium* breeding. Future research should promote integrated studies among the subareas of cytogenetics, molecular biology, and classical breeding to accelerate the release of new cultivars for the ornamental market.
Keywords: Araceae, Genetic diversity, Scientific mapping, Somaclonal variation.

Resumo
Caladium é um gênero majoritariamente ornamental e medicinal com elevado valor comercial. Estudos voltados ao melhoramento genético em *Caladium* vêm sendo realizados, incluindo o estudo da herança, micropropagação, caracterização morfológica, citológica, molecular e genômica, contudo, existem poucos estudos sobre a evolução no tempo e no espaço dos principais temas, autores, locais e tendências das pesquisas. Assim, objetivou-se neste trabalho analisar os avanços, limitações e tendências emergentes no melhoramento de *Caladium* utilizando análise bibliométrica. Foi realizada uma busca sistemática nas bases de dados *Scopus* e *Web of Science*, abrangendo publicações de 1992 a 2025. Foram identificados 141 documentos, dos quais 98 permaneceram após a remoção dos duplicados. Os dados foram analisados utilizando o pacote Bibliometrix no R, no ambiente RStudio, pela interface gráfica *Biblioshiny*. Os resultados revelaram uma flutuação no padrão de publicação de artigos, onde os EUA e a China destacam-se na produção cientifica. Observou-se uma evolução do melhoramento clássico para um foco robusto ligado herança, variação somaclonal e genética molecular nas últimas duas décadas. A ausência de uma explicação precisa sobre os mecanismos biológicos da variação somaclonal, aliado a falta de estudos relacionados a epigenética e as respostas morfofisiológicas pós-produção, representam uma lacuna no melhoramento de *Caladium*. Pesquisas futuras devem massificar estudos integrados entre as subáreas de citogenética, biologia molecular e melhoramento clássico, para acelerar o lançamento de novas cultivares para mercado ornamental.
Palavras-Chave: Araceae, Diversidade genética, Mapeamento científico, Variação somaclonal.

Introduction

Caladium stands out as one of the genera with high commercial value within the Araceae, owing to its ornamental potential, characterized by the diversity of leaf coloration and shape, and can be cultivated both in pots and in open-field gardens (Deng, 2018; Zhou et al., 2023). In addition, it exhibits considerable medicinal potential, including applications in the treatment of hypertension and infections (Ijeoma et al., 2019; Paula Filho et al., 2024).

In recent years, studies on *Caladium* breeding have been conducted, aiming to understand the mechanisms underlying leaf number, coloration, size, and shape, as well as tolerance to abiotic factors (Deng, 2018; Yu et al., 2022; Xiang et al., 2024). However, explaining the high genetic diversity observed in this genus remains a challenge for most breeders, particularly regarding the mechanisms involved in somaclonal variation (Hu et al., 2024).

Several breeding techniques, including studies on inheritance, micropropagation, and morphological, cytological, molecular, and genomic characterization, have been applied to advance *Caladium* breeding (Chen et al., 2021; Heedchim et al., 2022; Hu et al., 2024). However, the temporal and spatial evolution of the main research themes, authors, locations, and research trends remains poorly studied, highlighting the need for studies evaluating these aspects.

Bibliometric review has emerged as an important analytical approach, as it considers a large volume of relevant data from the scientific literature across research fields, allowing the assessment of the current state, developments, evolution, and emerging areas within a given topic (Öztürk et al., 2024).

In this regard, the present study aimed to analyze advances, limitations, and emerging trends in *Caladium* breeding through a bibliometric approach.

Methodology

A bibliometric analysis was conducted to map and quantify scientific publications related to *Caladium* breeding, aiming to identify research trends, gaps, and the evolution of the field, with the main methodological steps summarized in Fig. 1.

The Web of Science (WoS) and Scopus databases were used due to their broad coverage and relevance in indexing high-impact journals. The search was conducted in January 2026 using relevant keywords combined with the Boolean operators “AND” and “OR” to retrieve literature on the topic, restricted to English-language publications and covering publications from 1992 to 2025.

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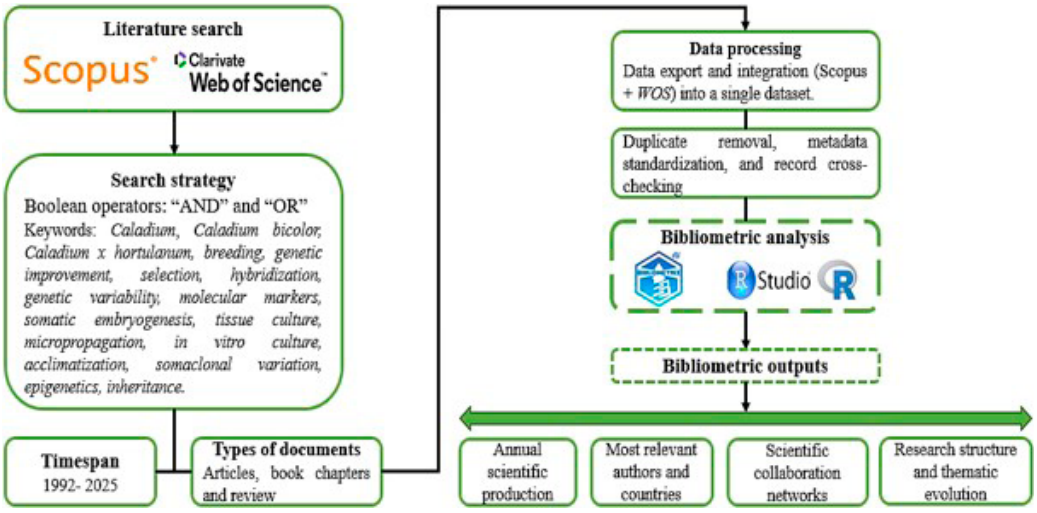


Fig. 1. Flowchart of the methodological process used for the search, selection, data processing, and bibliometric analysis of the literature on *Caladium* breeding.

The Scopus search followed the strategy (TITLE-ABS-KEY((*Caladium* OR "*Caladium bicolor*" OR "*Caladium x hortulanum*")) AND TITLE-ABS-KEY((*breeding* OR "*genetic improvement*" OR *selection* OR *hybridization* OR "*genetic variability*" OR "*molecular markers*" OR "*somatic embryogenesis*" OR "*tissue culture*" OR *micropropagation* OR "*in vitro culture*" OR *acclimatization* OR "*somaclonal variation*" OR *epigenetics* OR *inheritance*))) AND PUBYEAR > 1991 AND PUBYEAR < 2026 AND (LIMIT-TO(DOCTYPE, "ar") OR LIMIT-TO(DOCTYPE, "ch") OR LIMIT-TO(DOCTYPE, "re")). The *Web of Science* search followed the strategy (*Caladium* OR "*Caladium bicolor*" OR "*Caladium x hortulanum*") AND (*breeding* OR "*genetic improvement*" OR *selection* OR *hybridization* OR "*genetic variability*" OR "*molecular markers*" OR "*somatic embryogenesis*" OR "*tissue culture*" OR *micropropagation* OR "*in vitro culture*" OR *acclimatization* OR "*somaclonal variation*" OR *epigenetics* OR *inheritance*) in the Topic field, covering publications from 1992 to 2025. Articles, book chapters, and review articles were considered.

The files were exported and combined into a single dataset, after which duplicate records were removed. Following this integration, the dataset was manually checked and standardized to correct inconsistencies in bibliographic metadata arising from differences between the two databases. This procedure included cross-referencing document titles and bibliographic identifiers, as well as correcting and standardizing variations in author names, journal titles, citation information, and other bibliographic fields. The analyses were performed using R software (version 4.5.1) with the Bibliometrix package in the RStudio environment, which includes the Bibliophagy graphical interface (R Core Team, 2025).

The bibliometric review consisted of evaluating annual publication trends, the most relevant authors and countries, the frequency of scientific collaborations, a three-field plot including authors, keywords, and sources, a word cloud to visualize the relative frequency of terms, as well as topic trend analysis and thematic evolution.

Results

Based on the search results, a total of 141 documents published between 1992 and 2025 were identified, of which 43 were removed due to duplication, resulting in 98 documents related to *Caladium* breeding (Fig. 2). These were published by 159 authors across 51 journals, with an average of 10 citations per document (Fig. 2).



Fig. 2. General information on *Caladium* breeding from 1992 to 2025.

Based on the databases used, it was possible to determine that articles focusing on *Caladium* breeding gained prominence with the publication of articles in 1992. Following this, the topic gained prominence again in 1999, and since then, the number of articles published on this genus has increased. From this period up to 2025, fluctuations in the pattern of scientific publications were observed. The peak in publication output occurred in 2022, with eight articles published (Fig. 3).

Among the various authors publishing on *Caladium* breeding, Deng Z stands out for consistent productivity, as his recent work has focused primarily on the release and characterization of new cultivars, with 46 published articles, being the leading contributor to breeding studies in this genus, followed by Harbaugh BK, with more than 26 published articles (Fig. 4).

Research on *Caladium* breeding has been conducted in many parts of the world, either independently or through collaboration

among different countries. The United States of America and China had the highest numbers of publications and exhibited the strongest international collaboration networks, with 44 and 15 Single Country Publications (SCP) and 4 and 2 Multiple Country Publications (MCP), respectively (Fig. 5).

The three-field plot correlates the main authors, keywords, and sources, in which the thickness of the lines represents the number of connections (Fig. 6). Deng and Harbaugh emerge as the most prolific authors, with the highest number of publications on *Caladium* breeding, particularly *C. bicolor* and *C.* x *hortulanum*. Their work focuses predominantly on the development of ornamental cultivars and genetic characterization, involving somaclonal variation, and biotechnological approaches. These emphases are reflected in the most frequent keywords, including "*Caladium*", "*Caladium bicolor*", "somaclonal variation", "ornamental breeding", "nuclear DNA content", and "inheritance".

Among the main publication sources, *HortScience* is the most frequently used journal for scientific dissemination on *Caladium*, followed by *Journal of the American Society for Horticultural Science* (Fig. 6).

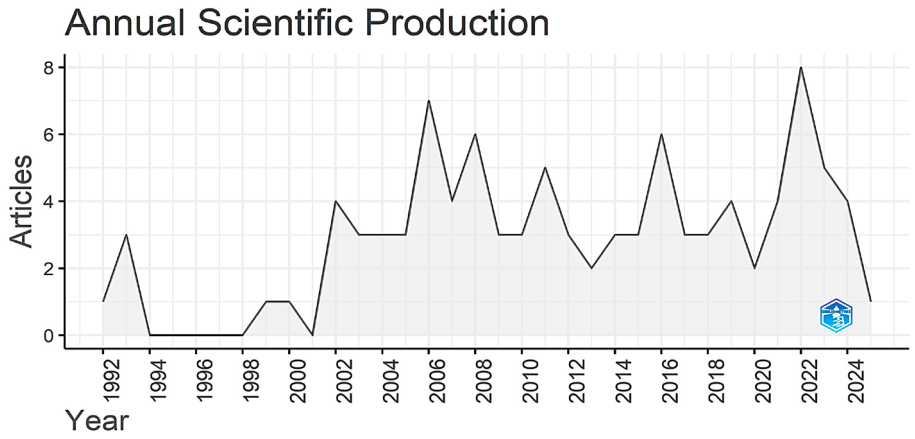


Fig. 3. Bibliometric results related to the annual scientific production on *Caladium* breeding from 1992 to 2025.

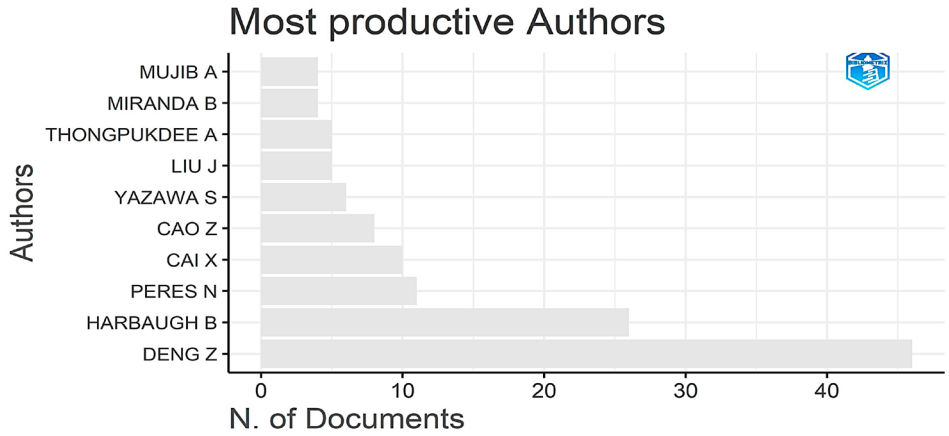


Fig. 4. Most relevant authors in scientific publications on *Caladium* breeding from 1992 to 2025. *N. of documents* represents the total number of publications associated with each author.

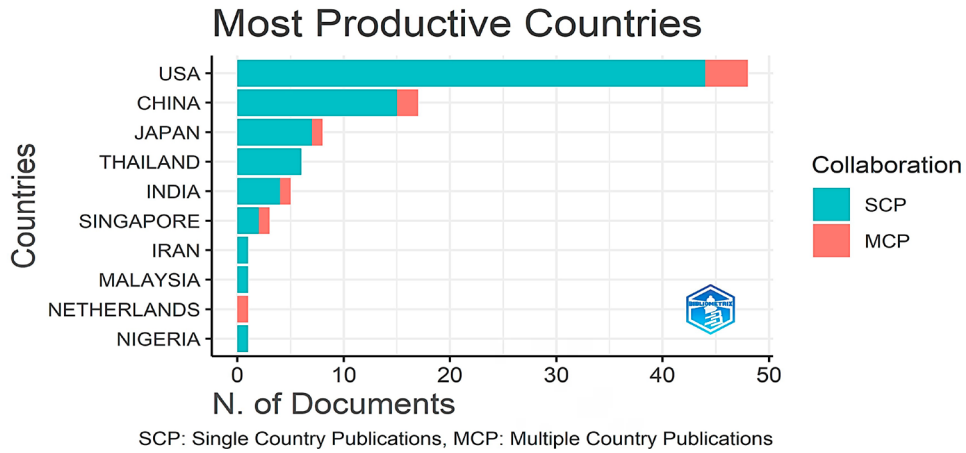


Fig. 5. Most relevant countries based on their scientific output and collaboration patterns in *Caladium* breeding between 1992 and 2025. *N. of documents* represents the total number of publications associated with each country.

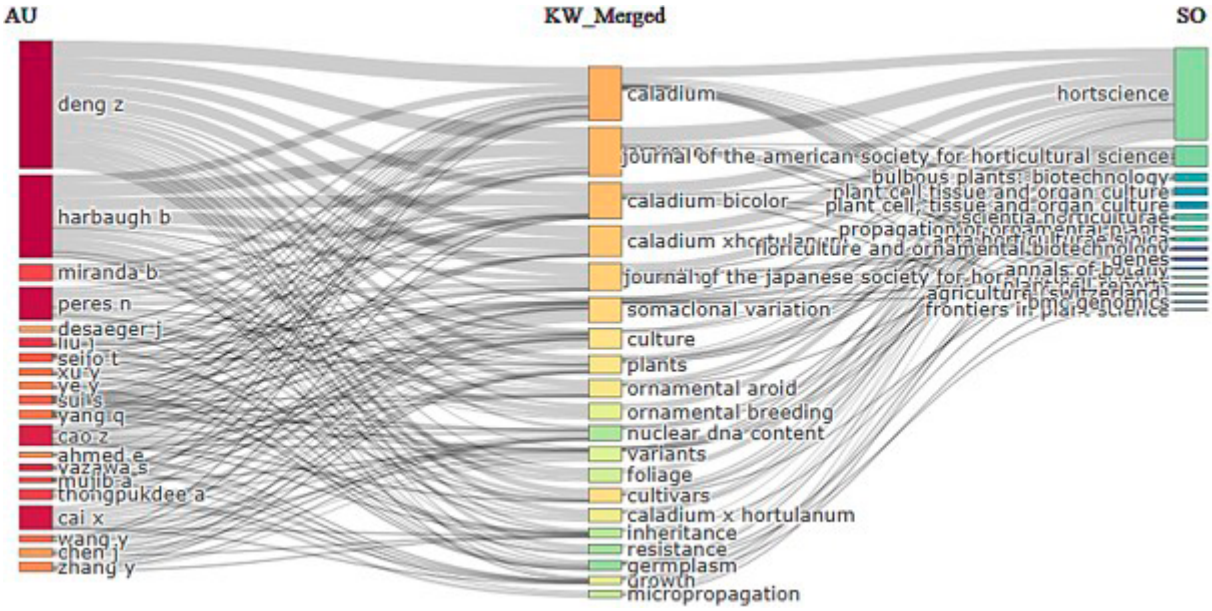


Fig. 6. Three-field plot showing the relationship among authors (left), keywords (center), and sources (right) in *Caladium* breeding studies from 1992 to 2025.

In the keyword co-occurrence network (Fig. 7), the thickness of the connections indicates the frequency of co-occurrence in scientific publications, while the size of the nodes is proportional to the frequency of each keyword in *Caladium* breeding studies. The central red cluster highlights the genus *Caladium*, which integrates several breeding-related research areas, including studies on cultivars, plants, and molecular markers.

The blue cluster highlights the family Araceae and is primarily associated with taxonomy and the development of new *Caladium* cultivars, as indicated by terms such as "ornamental breeding", "*Caladium* x *hortulanum*", and "*Caladium bicolor*". The green and purple clusters in the keyword network highlight research on breeding and somaclonal variation, respectively (Fig 7). Within the breeding cluster, terms such as "ornamental aroid", "new cultivar", "leaf characteristics", and "resistance" indicate that researchers have increasingly focused on developing new ornamental cultivars based on leaf characteristics and enhanced resistance to biotic and abiotic factors. In contrast, other studies have focused on somaclonal variation as a source of genetic variability within the genus, using biotechnological and cytogenetic approaches, such as tissue culture, DNA content analysis, and chromosome number determination (Fig. 7).

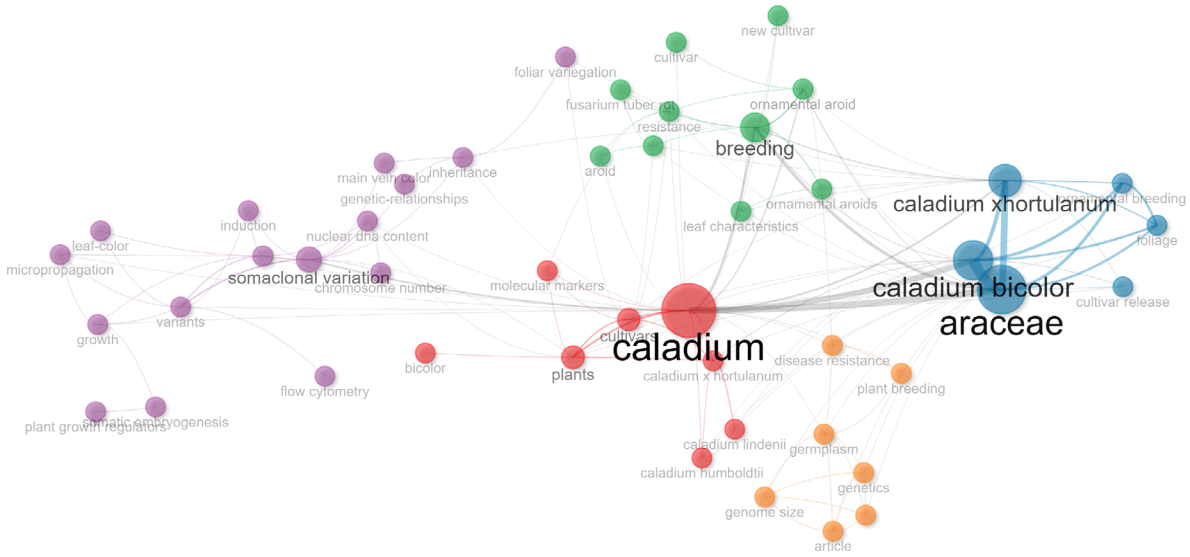


Fig. 7. Keyword co-occurrence network analysis in *Caladium* breeding studies from 1992 to 2025.

The analysis of thematic evolution over time showed that motor themes were associated with the study of inheritance, the development of ornamental cultivars with enhanced resistance, and somaclonal variation. The study of germplasm and genetic material emerged as niche themes, whereas basic themes were primarily centered on the Araceae family. Among the themes positioned within the emerging or declining themes quadrant were micropropagation, somatic embryogenesis, and conventional plant breeding (Fig. 8A and 8B).

Based on the keyword trend analysis, topics such as phylogeny, somaclonal variation, inheritance, and variants have been among the most frequently studied during the last 10 years, reflecting efforts to understand phylogenetic relationships, genetic inheritance, and the mechanisms underlying genetic variation (Fig. 8B). However, substantial research interest in growth and tissue culture techniques can also be observed over several years (Fig. 8B).

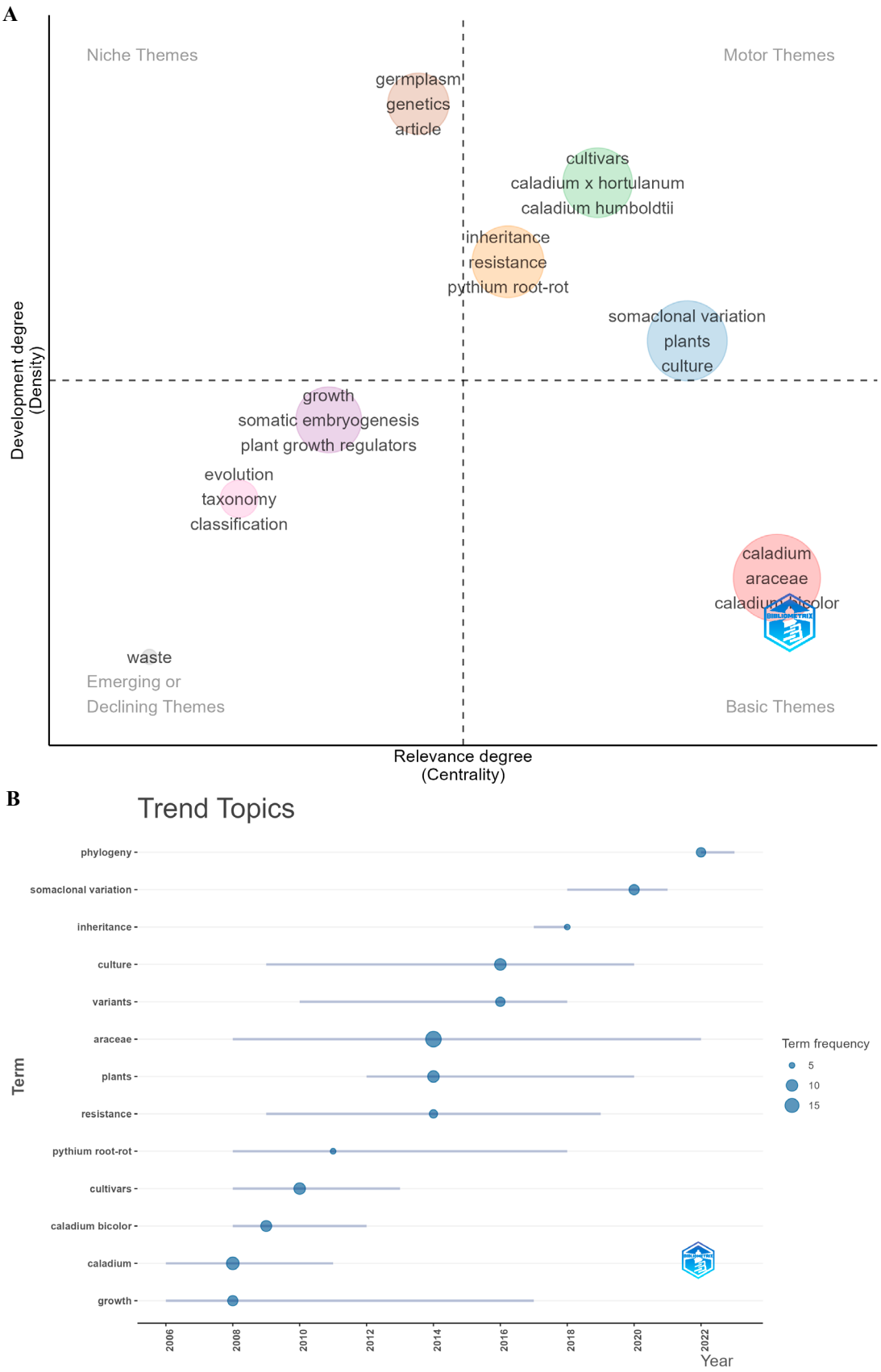


Fig. 8. Thematic evolution in *Caladium* breeding from 1992 to 2025. (A) Thematic categorization based on motor themes, basic themes, niche themes, and emerging or declining themes; (B) Topic trends in *Caladium* breeding.

Discussion

Over the past 30 years, the number of publications related to *Caladium* breeding has been irregular, with a peak in 2022, with eight articles published, however, the overall growth rate remains very low (Fig. 2 and Fig. 3). Fluctuations in scientific publication may be associated with changes in scientific interest as well as shifts in research funding, as suggested by Dagli et al. (2024). In addition, global crises such as the COVID-19 pandemic may have contributed to a decline in scientific output, as observed in 2020 in this study.

The downward fluctuation observed in 2025 (Fig. 3) reflects a pattern consistent with the publication history of the genus, which is characterized by irregular publication cycles. Nevertheless, interest in *Caladium* remains active through emerging research fronts, such as biotechnology and pharmacology, which may open new avenues for breeding traits related to medicinal uses, as reported by Agoi (2025) and Lalmuanpuia (2025), who described its potential in wound healing and in the treatment of nicotine dependence and withdrawal.

The United States and China are the countries with the highest number of collaboration and scientific output (Fig. 5). Although some species, such as *Caladium bicolor*, are native to Brazil (Madison, 1981), the country is not among the top ten contributors in publications on this genus, indicating an academic and scientific gap and suggesting the underutilization of native genetic resources. Therefore, there is a need to initiate and/or resume research on *Caladium* in Brazil.

Among the main publication sources, *HortScience*, with an impact factor of 1.9 and an SJR of 0.391 (Q2) over the past five years, stands out as the most frequently used journal (Fig. 6). This may be primarily related to its scope and accessibility, as it is an open-access scientific journal that emphasizes the publication of precise, clear, reproducible, and unbiased studies in applied horticultural research. According to Zerfu (2023), publishing in high-impact journals provides researchers with the opportunity to disseminate original research questions and findings to a broader audience.

The terms *Caladium*, Araceae, breeding, and somaclonal variation characterize the most frequently used keyword network over time in studies on breeding (Fig. 7). These terms reflect the historical development of research, with an initial emphasis on the taxonomy of the Araceae family and on the morphological and genetic characterization of accessions, progressing toward the development and release of new cultivars. Based on this initial characterization, a technical evolution in the study of *Caladium* diversity can be observed, including the evaluation of somaclonal variation in leaf color in plants regenerated *in vitro* (Zhu at al., 1993).

Subsequently, PCR-based molecular markers were introduced as tools for assessing genetic diversity, followed by the adoption of techniques such as amplified fragment length polymorphism (AFLP) analysis (Loh et al., 2000), which demonstrated the ability of these markers to distinguish intra- and interspecific groups based on their distinct banding patterns. This approach provided a foundation for subsequent studies in *Caladium*, including Deng (2014) and Ye et al. (2023).

The explanation of genetic variability in *Caladium* remains a major challenge to this day. This limitation may be associated with the relatively limited integration of cytogenetic, molecular, and breeding studies, as illustrated by the keyword network (Fig. 7), as well as with the insufficient integration of reproductive biology into breeding studies, particularly regarding characteristics that affect the efficiency of controlled hybridization. According to Parrish and Deng (2022), *Caladium* is one of the most important species in the ornamental market, therefore, the continuous investigation of breeding mechanisms is essential to better understand its evolutionary processes.

Genetic variability is a key component of any breeding program, as it enables the selection of individuals with desirable traits and the identification of superior hybrid combinations (Luo et al., 2025). Genetic variability has been more effectively elucidated through the integration of morphoagronomic and molecular characterization in other ornamental species, such as *Paphiopedilum* (Tang et al., 2025), demonstrating that the integration of conventional and molecular approaches may represent a promising strategy for a better understanding of genetic variability in *Caladium*.

One of the main sources of genetic variability is related to somaclonal variation. This represents one of the motor themes (Fig. 8A) and one of the most studied topics in recent years (Fig. 8B). Plants derived from cell, tissue, or organ cultures that differ from the original plant are defined as somaclonal variants (Parrish et al., 2023).

According to the results reported by Ahmed et al. (2004), the presence of auxins such as NAA, IBA, IAA, 2,4,5-T, and 2,4-D increases the occurrence of somaclonal variants in *Caladium*. However, Parrish et al. (2023), reported that somaclonal variants also occur in the absence of auxins, indicating that auxins have limited influence on this process. This contrast in findings suggests that somaclonal variation is a multifactorial process, in which auxins may contribute to genomic alterations but are not the primary cause of somaclonal variation in *Caladium*.

Morphological, cytological, cytogenetic, molecular, and genomic studies (Chen et al., 2021; Parrish et al., 2023; Hu et al., 2024) have reported changes in morphology, nuclear DNA content, as well as chromosome number and size in *Caladium*. According to Cao and Deng (2020), these mutations may be associated with the B and V gene loci, which are responsible for leaf spotting and the coloration of the main leaf vein, respectively. In spot formation, the B allele is dominant over the b allele for the absence of spots, whereas for main vein color, the dominance hierarchy is red allele (V^r) > white allele (V^w) > green allele (V^g) 2 (Deng and Harbaugh, 2006).

Techniques such as direct somatic embryogenesis aimed at assessing stability have shown that plants regenerated through this method exhibit DNA ploidy levels similar to those of the parental plants (Syeed et al., 2022). However, despite the efforts undertaken, the mechanisms underlying somaclonal variation in *Caladium* have not yet been precisely elucidated, and investigating nuclear genome size may provide an alternative approach to gaining further insight into the mechanisms underlying genetic variation, particularly given that, to date, only the chloroplast genome has been characterized. Ye et al. (2022) identified 131 annotated genes in the chloroplast genome, including 86 protein-coding genes (PCGs), 37 transfer RNA genes (tRNAs), and eight ribosomal RNA genes (rRNAs). In addition to variants, phylogeny and inheritance have been among the most extensively studied topics in recent years (Fig. 8B). This interest may be associated with the increasing demand for ornamental plants, as well as the relative ease of conducting such studies, given that *Caladium* exhibits variegated leaves and traits such as leaf shape and primary vein color are controlled by genes that act independently (Deng and Harbaugh, 2006). In studies on inheritance, results from Cao et al. (2016) showed that a single locus with two alleles controls the presence or absence of rugose leaves in *Caladium* populations, supporting the inference presented here.

In recent years, several advances have been achieved through the combined study of inheritance and other biotechnological tools, including the search for material tolerant to biotic factors, such as resistance to root rot caused by *Pythium* and leaf blight caused by *Xanthomonas* (Deng et al., 2008), as well as to abiotic factors, including responses to different light sources during acclimatization (Dehestani-Ardakani et al., 2025). These advances have led to the release of several cultivars with broad diversity, enhanced ornamental value, and increased resistance to biotic and abiotic stresses, including those reported by Deng et al. (2026).

The limited number of integrated studies across the subareas of cytogenetics, molecular biology, and classical breeding can be considered a gap, resulting in the lack of a precise explanation of the biological mechanisms underlying somaclonal variation in *Caladium*. The scarcity of studies addressing *Caladium* epigenetics also represents a gap, since in plants, epigenetic changes, including variations in histone modification and DNA methylation, are associated with changes in gene expression (Sena et al., 2024). In addition, there is a need for studies on post-production morphophysiological responses, including during transport, as for an ornamental species with high commercial value, understanding post-production physiological responses is essential to maintain quality (Joy et al., 2025).

Thus, future research should focus on the *Caladium* genome, including understanding the presence or absence of genetic modifications during DNA packaging by histones and how this mechanism may influence the formation of somaclonal variants. Expanding integrated studies across different breeding subareas, as well as post-production responses, is essential for the production and commercialization of ornamental plants with high genetic and commercial standards.

Conclusions

The bibliometric analysis reveals that *Caladium* breeding has transitioned from a merely taxonomic and morphological approach to a

robust focus on inheritance, somaclonal variation, and molecular genetics over the past two decades, and that the United States and China stand out in scientific production.

The absence of a precise explanation for the biological mechanisms underlying somaclonal variation, combined with the scarcity of studies on epigenetics and post-production morphophysiological responses, represents a significant gap in *Caladium* breeding.

Future research should promote integrated studies among the subareas of cytogenetics, molecular biology, and classical breeding to accelerate the release of new cultivars for the ornamental market.

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Author Contribution

AFB: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Writing – Original Draft. **MMR:** Supervision, Investigation, Validation, Writing – Review & Editing. **LLM:** Writing – Review & Editing. **VAL:** Writing – Review & Editing. **MGS:** Writing – Review & Editing. **ERR:** Supervision, Formal Analysis, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All the research data is contained in the manuscript.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT (OpenAI) in order to assist in the English language translation. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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