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Chemistry

Humic substances in plant growth and water stress mitigation: a systematic and bibliometric review

Substâncias húmicas no crescimento vegetal e na mitigação do estresse hídrico: uma revisão sistemática e bibliométrica

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ABSTRACT

Humic substances (HS) have been extensively studied for their ability to stimulate plant growth, enhance nutrient uptake, and alleviate abiotic stresses. In this scenario, this study conducted a systematic and bibliometric analysis on the application of HS in promoting the growth of forest species and mitigating water stress in plants, based on data retrieved from the CAPES (*Brazilian Federal Agency for Support and Evaluation of Graduate Education*) and Scopus databases. From the CAPES database, 757 publications were initially identified, with 20 selected after applying inclusion and exclusion criteria—14 focused on forest species growth and 6 on water stress mitigation. In Scopus, 84 studies were found, of which 13 met the established criteria. The bibliometric analysis highlighted Brazil as a leading contributor to research on humic substances, with notable participation from influential researchers and international collaborations, particularly with Spain and Italy. The most frequently cited keywords were *humic substances, humic acid*, and *root growth*, while the *Revista Brasileira de Ciência do Solo (Brazilian Journal of Soil Science)* emerged as the most impactful journal in the field. The results point to a significant gap in the literature regarding the mechanisms of action of humic substances in forest species, reinforcing the need for further studies to elucidate their role in plant metabolism and expand their use in sustainable agriculture and forestry.

Keywords: Humic materials; Seedling production; Bibliometric indicators

RESUMO

As substâncias húmicas (SH) são amplamente estudadas devido à sua capacidade de estimular o crescimento vegetal, melhorar a absorção de nutrientes e atuar na mitigação de estresses abióticos. Este estudo teve por objetivo realizar uma análise sistemática e bibliométrica sobre o uso de substâncias húmicas no crescimento de espécies florestais e na mitigação do estresse hídrico de plantas em geral,

utilizando os bancos de dados da Capes e da Scopus. Foram identificados 757 trabalhos na Capes, limitados a 20 após a aplicação de critérios de inclusão e exclusão, sendo 14 relacionados ao crescimento de espécies florestais e 6 à mitigação do estresse hídrico. Na Scopus, dos 84 estudos encontrados, 13 foram selecionados, abordando os mesmos temas. A análise bibliométrica destacou o Brasil como um dos principais produtores de conhecimento sobre substâncias húmicas, com pesquisadores influentes e colaborações internacionais, especialmente com Espanha e Itália. As palavras-chave mais citadas foram substâncias húmicas, ácido húmico e crescimento radicular, e o periódico de maior impacto da Revista Brasileira de Ciência do Solo. Conclui-se que há uma lacuna na literatura sobre os mecanismos de ação das substâncias húmicas em espécies florestais, evidenciando a necessidade de mais pesquisas para aprofundar o entendimento de sua bioatividade no metabolismo vegetal.

Palavras-chave: Materiais húmicos; Produção de mudas; Indicadores bibliométricos

1 INTRODUCTION

Humic substances (HS) rank among the most extensively studied biostimulants due to their ability to enhance plant growth, improve nutrient availability and uptake, and stimulate the production of phytohormones that regulate root, stem, leaf, flower, and fruit development (Olivares et al., 2017; Jindo et al., 2020).

The molecular conformation of HS plays a pivotal role in plant vegetative growth, particularly in root hydraulic conductivity (Olaetxea et al., 2020). The root is the primary organ influenced by HS, exhibiting accelerated elongation and early cell differentiation at the root tip and primary zone. Depending on the HS fraction, these effects may manifest as enhanced differentiation in the central cylinder—improving water and nutrient transport—or in the cortex, leading to increased root diameter and resource storage (Pizzeghello et al., 2020).

HS have been also demonstrated efficacy in mitigating water deficit stress. Khorasani et al. (2023) reported improved growth parameters and yield in *Stevia rebaudiana* Bertoni, attributing these effects to HS-mediated nutrient uptake under water stress. Similarly, Khan et al. (2024) observed that humic acids enhanced drought tolerance in maize, increasing yield while improving nutrient retention and soil organic matter content.

The beneficial mechanisms of HS include the promotion of ion uptake via membrane protein biosynthesis and functionality, particularly proton pumps, which

amplify the electrochemical gradient across the plasma membrane to facilitate nutrient exchange (Azevedo et al., 2019). Additionally, HS enhance soil water retention by adsorbing water molecules (H_2O) onto their particles (Guo et al., 2023).

Humic substances (HS) represent a promising tool for the restoration of degraded ecosystems. By stimulating root system development, mitigating toxic metal effects, and enabling plants to explore larger soil volumes, HS facilitate forest recovery and soil phytoremediation (Pittarelo et al., 2018). Additionally, they enhance soil structure and buffering capacity, helping to maintain stable water regimes (Visnyakova; Ubugunov, 2023).

In arid and semi-arid regions, where soil organic matter content is typically low (Khorasani et al., 2023), vegetation restoration is further challenged by intense solar radiation, water stress, and diurnal temperature fluctuations (James et al., 2013). These difficulties underscore the importance of initiatives such as those led by the United Nations to address land degradation (UNCCD, 2015).

The application of HS in ecological restoration programs offers a viable strategy to improve seedling quality and root growth. Seedlings pre-treated with HS demonstrate greater tolerance to osmotic stress by regulating osmotic potential, sustaining net photosynthesis, maintaining K^+/Na^+ balance, and accumulating higher proline levels in leaves and sugars in roots (Benazzouk et al., 2018).

However, despite extensive research on HS in plant growth and abiotic stress mitigation, studies focusing on forest species' resilience to environmental stressors—such as water deficit—remain limited. For instance, Oliveira et al. (2021) examined only a narrow set of variables (e.g., *Betula pendula* Roth rooting), highlighting the need for broader investigations to establish more robust conclusions on HS efficacy in forest seedling production for restoration purposes.

From this perspective, this study presents a systematic and bibliometric review of published literature on HS applications in forest species growth and water stress mitigation, utilizing the CAPES Theses and Dissertations database and the Scopus platform.

2 MATERIALS AND METHODS

The research was conducted using databases including the Capes Theses and Dissertations Catalog and Scopus (Elsevier). In the Capes platform, searches were performed using the keyword “substâncias húmicas” (humic substances), while Scopus employed a combination of keywords: “humic substances*” AND “plant growth” OR “root growth” OR “hydrical stress”. The study targeted publications such as articles, dissertations, theses, conference proceedings, and book chapters available in English or Portuguese, with accessible abstracts and/or full texts. No publication date restrictions were applied. The Capes database contained works from 1987 to 2023, while Scopus records spanned 1997 to 2023.

Initially, all identified works were screened by reviewing titles and abstracts, with those unrelated to the topic being excluded. The remaining publications underwent full-text evaluation and were classified as included or excluded based on the criteria presented in Table 1. This two-stage selection process ensured the relevance of all analyzed materials to the research objectives.

For bibliometric analysis, the Scopus search results were exported in CSV format, containing comprehensive publication metadata including author information, titles, publication years, countries of origin, abstracts, keywords, journal details, and reference lists. These data were subsequently processed using VOSviewer software (version 1.6.16) to conduct detailed bibliometric analyses.

Table 1 – Inclusion and exclusion criteria for the selected studies

Inclusion Criteria	Exclusion Criteria
Experimental studies on the growth of forest species	Literature reviews, integrative, and systematic reviews
Experimental studies on water stress (plants in general)	Studies on the growth of plant species other than forest species
Works involving humic substances in association with other inputs and microorganisms	Studies involving only characterization without application to growth and/or water stress
Articles, dissertations, theses, conference proceedings, book chapters, and scientific notes.	-

Source: Authors (2024)

To ensure transparency and methodological quality in conducting the systematic review, the adapted PRISMA 2020 model was adopted, an updated guideline that directs the comprehensive reporting of systematic reviews and meta-analyses. This enhanced version replaces the PRISMA 2009 model, incorporating advances in the methodologies for study identification, selection, appraisal, and synthesis. The application of PRISMA 2020 aims to improve clarity and consistency in presenting the review processes, contributing to the replicability and reliability of the results (Page et al., 2021).

The VOSviewer analysis enabled the identification of key research trends, including the most productive countries, highly cited authors and references, prominent journals, and keyword co-occurrence patterns. Additional publication metrics, e.g. annual publication counts and geographical distributions, were obtained directly from Scopus's "Analyze search results" feature. The resulting bibliometric networks were visualized with cluster analysis, where distinct research themes were represented by specific color codes, providing clear visual representation of the research landscape.

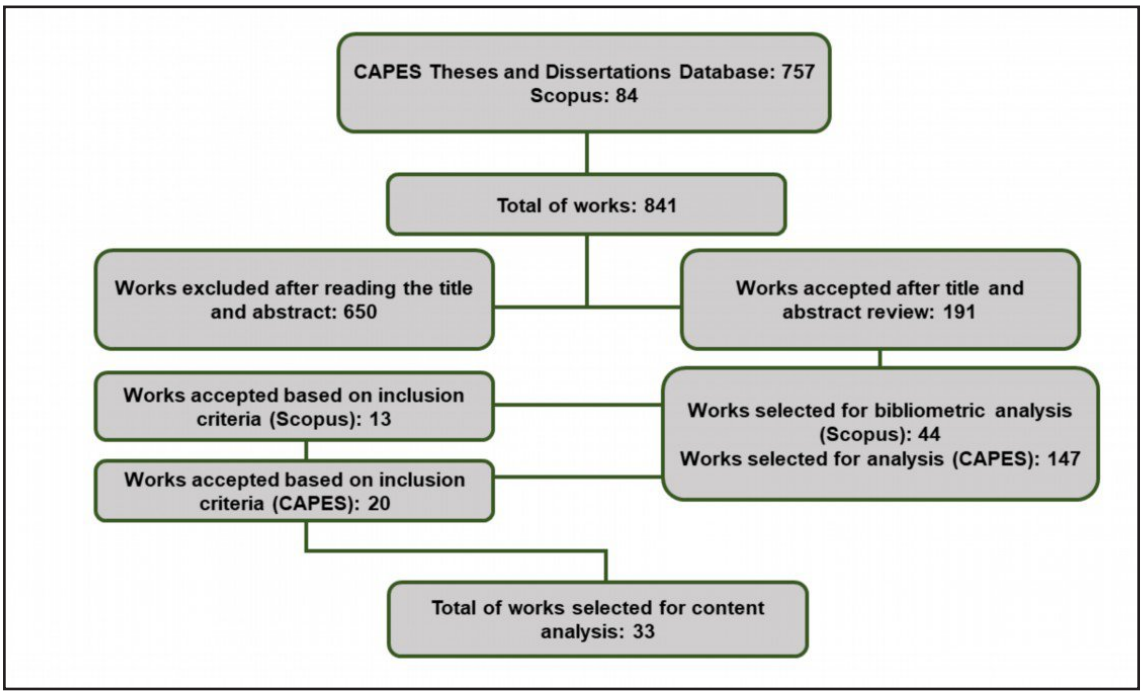
3 RESULTS AND DISCUSSION

The searches yielded a total of 841 studies (Figure 1). A total of 757 studies were initially identified in the CAPES thesis and dissertation database using the term "humic substances." After title/abstract screening and application of inclusion/exclusion criteria, this number was reduced to 20 studies: 8 master's theses and 6 doctoral dissertations on humic substances as growth promoters for forest species, plus 4 dissertations and 2 theses examining their role in mitigating water stress in general plant species. Notably, no studies specifically addressed water stress mitigation in forest species, thus highlighting the need to include of studies on general plants to demonstrate the effects of humic substances on water deficiency stress responses.

Eighty-four studies were initially identified in the Scopus database search using the keyword combination "humic substances*" AND "plant growth" OR "root

growth" OR "hydrical stress" (Figure 1). After applying rigorous screening criteria to titles and abstracts, thirteen studies met the inclusion requirements. The final selection comprised three articles investigating the effects of humic substances on vegetative growth in forest species and ten articles examining their role in water stress metabolism in general plant species. Notably, no studies specifically addressed water stress mitigation in forest species, warranting the inclusion of studies on general plant species to address this research gap.

Figure 1 – PRISMA 2020 flowchart adapted to present the article selection process according to the adopted inclusion and exclusion criteria



Source: Authors (2024)

The analysis of studies involving humic substances and forest species showed that various application methods were effective in promoting plant growth, including humic substances alone or in combination with microorganisms (Hinojosa, 2020), other organic molecules such as oxalic and citric acids (Morais, 2017), alternative nutrient sources like rock powder (Pereira, 2019), or in isolated fractions such as humic acids (Pinheiro, 2009). Notably, humic substances have

been shown promising results in enhancing plant growth under stress conditions caused by toxic metals, including iron (Fe), nickel (Ni), arsenic (As), and cadmium (Cd) (Barbirato, 2016; Pittarelo et al., 2018) (Table 2).

Among the 17 studies identified from the CAPES thesis and dissertation database and articles indexed in Scopus, two focus on native species from the Caatinga ecosystem (*Chloroleucon dumosum* (Benth)) G.P. Lewis and *Calophyllum brasiliense* Cambess), two on mangrove species (*Rhizophora mangle* L.), one on restinga (*Schinus terebinthifolius* Raddi), and one on the Atlantic Forest species (*Schizolobium parahyba* (Vell.) Blake). The remaining studies address species exotic to Brazil (Table 2).

Overall, a central finding of this review is that humic substances not only promote plant growth but also enhance tolerance to toxic metal exposure (Pittarello et al., 2018). They stimulate the development of both primary and lateral roots, thereby expanding the root system's surface area for water and nutrient uptake.

With regard to the application of humic substances as mitigators of water stress, 16 studies were identified—six from the Capes Theses and Dissertations Catalog (comprising four dissertations and two theses) and approximately 10 published journal articles indexed in Scopus. Of these, 10 were conducted in Brazil, including studies on soybean (*Glycine max*) (Silva et al., 2022; Silva, 2022; Campos, 2020; Prado et al., 2016; Prado, 2014), rice (*Oryza sativa*) (Castro et al., 2022; García et al., 2016), beans (P*haseolus vulgaris*) (Melo, 2014), tomato (*Solanum lycopersicum*) (Gomes, 2019), and corn (*Zea mays*) (Silva, 2023). The remaining six studies focused on water stress management in soybean (Matuszak-Slamani et al., 2022), corn (Hernández et al., 2021), foxtail millet (*Setaria italica*) (Shen et al., 2020), pepper (*Capsicum spp*.) (Qin & Leskovar, 2018), and wheat (*Triticum aestivum*) (Shahryari et al., 2012; Mirzamasumzadeh, 2011), and were conducted in Poland, Mexico, China, the United States, and Iran, respectively.

Table 2 – Studies on the use of humic substances as growth promoters in forest species (1987–2023)

Works published by platform	
CAPES Theses and Dissertations Database	**Reference**
Biostimulators in Olive Trees, from Nursery to Field: Clonal Garden, Seedling Production, and Essential Oil	(Ritter, 2022)
Combined application of humic substances and co-inoculation of rhizobia and *Azospirillum brasilense* in legumes and grasses	(Hinojosa, 2020)
Humic substances and rock powder in the growth and nodulation of *Chloroleucon dumosum* (Benth) G.P. Lewis	(Pereira, 2019)
Initial growth of *Calophyllum brasiliense* cambes (Guanandi) treated with humic substances and plant growth-promoting bacteria	(Souza, 2019)
Humic Substances in the Morphophysiology and Growth of *Schizolobium parahyba* var. *parahyba* (Vell.) Blake	(Aguiar, 2019)
Microorganisms and Humic Substances in the Rooting of Olive Cultivar Cuttings	(Ritter, 2019)
Interaction of sewage sludge and biomass ash in the early development of eucalyptus	(Leite, 2012)
Nutrition and Growth of Eucalyptus: Effect of Sources and Concentrations of Humic Acids and Their Interaction with Oxalic and Citric Acids	(Morais, 2017)
Action of Humic Substances on *Rhizophora mangle* L. Seedlings Under Fe and Ni Stress	(Barbirato, 2016)
Effect of foliar fertilization and soil conditioners on the rooting, growth, and hardening of clonal *Pinus* spp. seedlings	(Santos, 2015)
Humic substances as a biostimulant aimed at the restoration of degraded coastal ecosystems	(Tesch, 2015)
Mitigation of Iron Toxicity in Aroeira (*Schinus terebinthifolius Raddi*) Seedlings Treated with Humic Substances	(Santos, 2014)
Growth and nutrition of an eucalyptus clone in response to the application of humic acids.	(Pinheiro, 2009)
Humification of Organic Waste during Vermicomposting and Its Effect on Soil Chemical Attributes and the Initial Growth of Black Acacia (*Acacia mearnsii*)	(Antunes, 2009)
Scopus	
Humic substances stimulate initial growth and reduce arsenic stress in *Corymbia citriodora* seedlings.	(Santos et al., 2023)
Effects of Different Concentrations of Humic Substances on Root Anatomy and Cd Accumulation in *Avicennia germinans* (Black Mangrove) Seedlings	(Pittarello et al., 2018)
Alteration in the expression of the ATP B1/19 linkage cassette, glutamine synthetase, and alcohol dehydrogenase during root elongation in *Betula pendula* Roth and *Alnus glutinosa* L. Gaertn in response to humic substances from leachate and leonardite	(Tahiri et al., 2016)

Source: Authors (2024)

Although no studies were identified concerning forest species under water stress, a substantial body of research on non-forest species demonstrates the effectiveness of humic substances in mitigating oxidative stress associated with drought conditions. Most published studies report positive outcomes, regardless of the source of humification, whether from vermicompost (Garcia et al., 2016), lignite (Qin et al., 2018), or as liquid organomineral fertilizer (Prado, 2014) (Table 3).

This review also highlights the positive influence of humic substances on plant-associated microbial communities, particularly in water-stressed conditions. These substances significantly increase the abundance of endophytic bacterial communities in both leaves and roots, with Proteobacteria being the most prevalent phylum, followed by Firmicutes and Bacteroidetes. Similar effects are observed in fungal communities, with water-stressed leaves showing increased abundance of *Erysiphaceae*, and roots showing greater prevalence of *Chaetomiaceae* (Silva, 2022). Moreover, studies suggest that plant–microbe interactions mediated by humic substances contribute to the regulation of abscisic acid (ABA) levels, thereby supporting plant growth under water-deficit conditions (Salomon et al., 2014).

Table 3 – Studies on the use of humic substances as water stress mitigators in plant species (1987–2023)

(Continue)

Works published by platform	
CAPES Theses and Dissertations Database	**Reference**
Strategies for the application of humic substances in ecophysiology and water stress mitigation in corn plants	(Silva, 2023)
Effect of humic acid application on soybean growth and the endophytic microbiome under water stress conditions	(Silva, 2022)
Influence of humic substances and different water availability in the soil on soybean	(Campos, 2020)
Bio stimulants and their effects on production components, gas exchanges, and water use efficiency in tomato plants under water stress	(Gomes, 2019)
Liquid organomineral fertilizer containing humic substances in soybean cultivated under water stress	(Prado, 2014)
Evaluation of drought tolerance in common bean inoculated with rhizobia and endophytic diazotrophic bacteria in the presence of humic acids	(Melo, 2014)

Table 3 – Studies on the use of humic substances as water stress mitigators in plant species (1987–2023) (Conclusion)

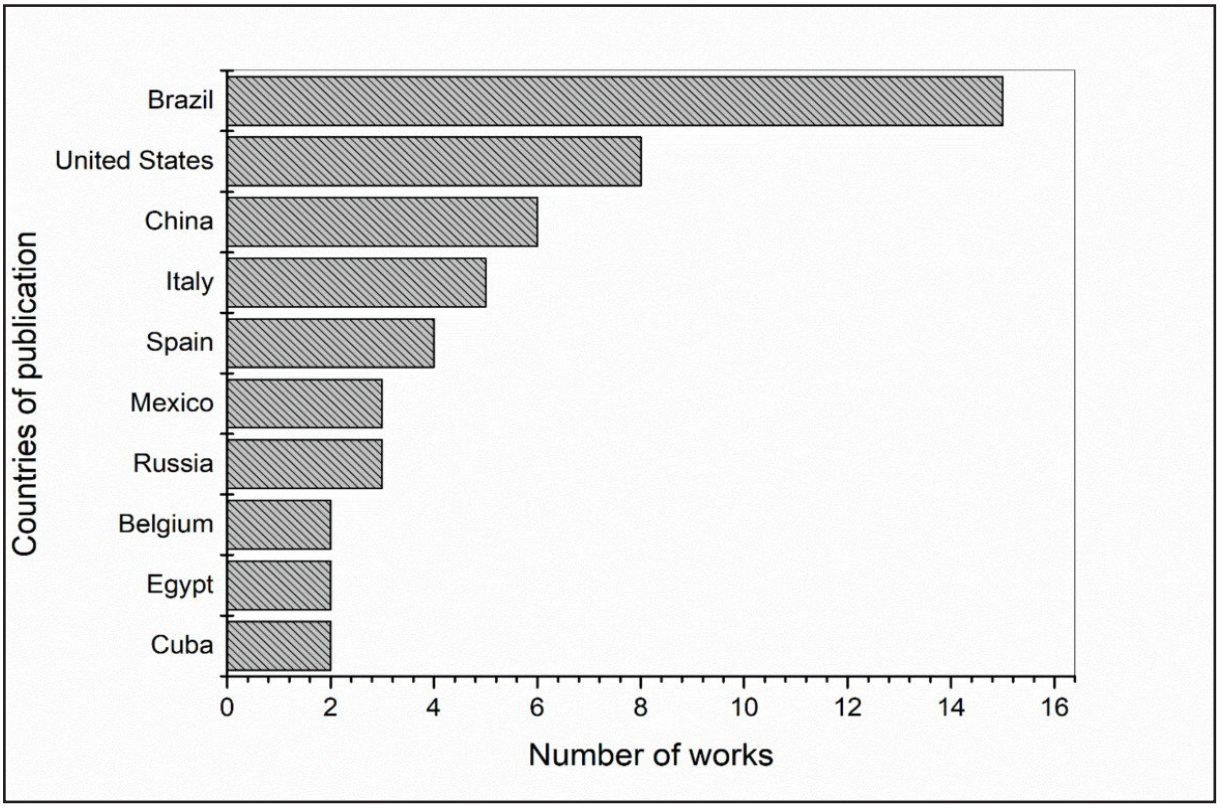
Works published by platform	
CAPES Theses and Dissertations Database	**Reference**
Scopus	
Humic acids affect the photosynthetic quantum efficiency in rice under water stress	(Castro et al., 2022)
Effect of humic acids on soybean seedling growth under water stress induced by polyethylene glycol-6000	(Matuszak-Slamani et al., 2022)
Effects of humic acids on plant growth and protection against water stress in selected native populations of corn from Mexico	(Hernández et al., 2021)
Effect of the application of vermicompost and humic acid compost on the soybean microbiome under water restriction conditions	(Silva et al., 2022)
An investigation into the beneficial effects and molecular mechanisms of humic acid on fox tail millet under drought conditions	(Shen et al., 2020)
Humic substances derived from lignite modulate pepper growth and soil biota under water deficit stress	(Qin; Leskovar, 2018)
Humic acids from vermicompost modulate ROS accumulation in rice plants.	(Garcia et al., 2016)
Humic substances in soybeans grown under water stress	(Prado et al., 2016)
In vitro effect of the humic fertilizer on nitrate reductase activity under polyethylene glycol-mediated water stress in wheat	(Shahryari et al., 2012)
Application of potassium humate in wheat seed production under post-anthesis drought conditions	(Mirzamasumzadeh, 2011)

Source: Authors (2024)

Figure 2 depicts the contribution of each country to the scientific literature on the subject. Between 1997 and 2023, Brazil led with 15 publications indexed in the Scopus database, followed by China (8), the United States (6), Italy (5), and Spain (4). Mexico and Russia both contribute with three publications, while Cuba and Egypt published two each.

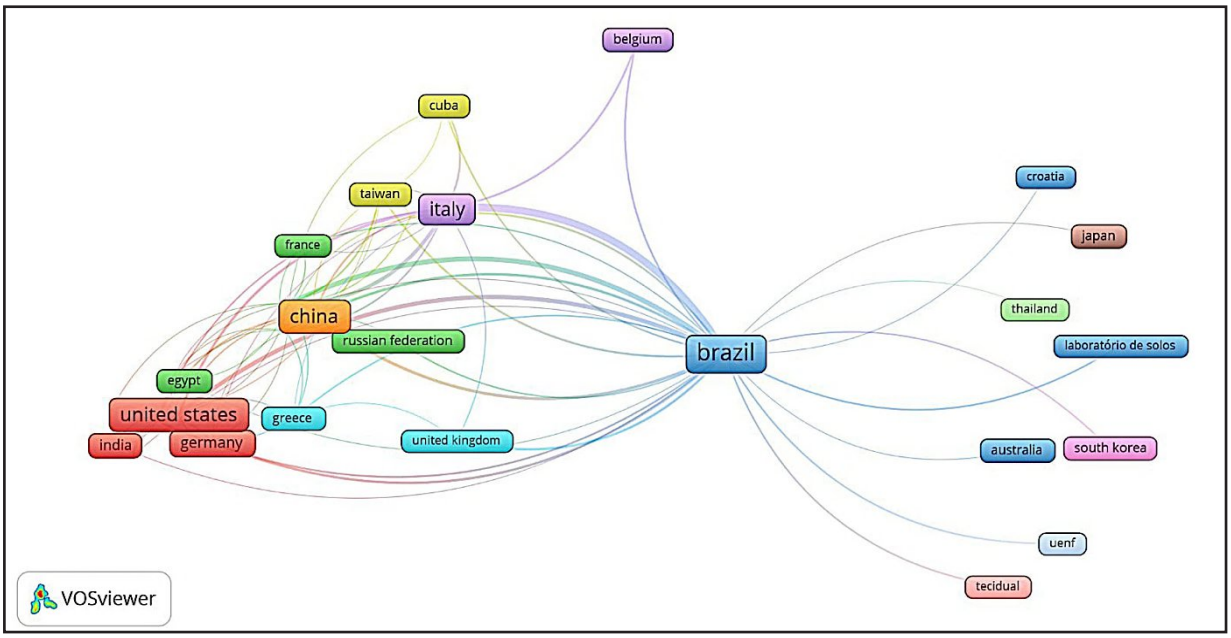
These findings align with the data presented in Table 2, which show that most studies on the use of humic substances as mitigators of water stress were conducted in Brazil. Among the Brazilian articles, two focused on soybean and two on rice. This pattern reinforces Brazil's prominence in applied research on humic substances.

Figure 2 – Distribution of the number of studies on the topic published over the last 13 years



Source: Adapted from the SCOPUS database (2024)

Figure 3 – Network clustering of the countries with the highest number of publications on the topic



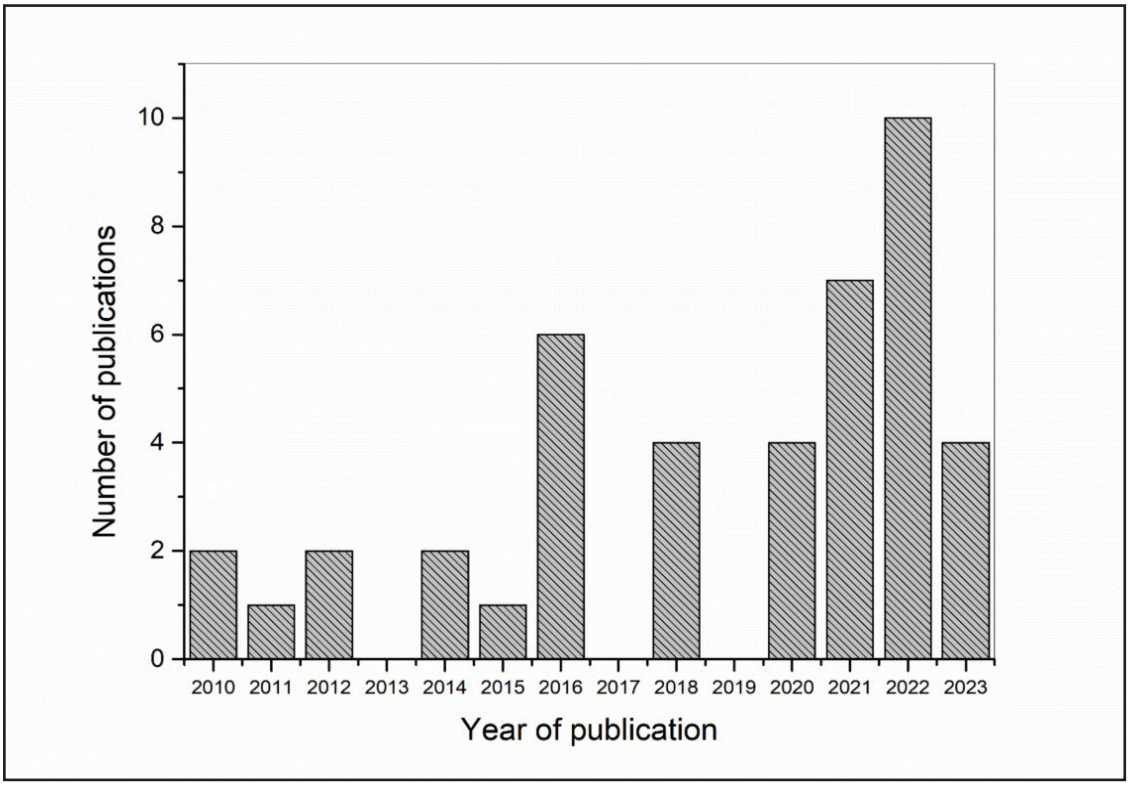
Source: Authors (2024)

Figure 3 visually confirms the publication volume by country, with the size of each colored rectangle corresponding to the number of articles. Brazil stands out clearly, and similar color tones among countries may suggest thematic convergence in their research outputs.

The bibliometric analysis identified 22 countries represented in the network graph, exceeding the total shown in the earlier ranking because the statistical software analyzes the full dataset, whereas the previous graph was generated using a specific filter within the Scopus online database. Despite this methodological difference, the relative positions of most countries remain consistent, as reflected by the size of their respective rectangles.

Brazil's centrality in the network underscores its role in international collaborations. Notably, studies authored by A.C. Garcia were developed in partnership with M. Olaetxea from the University of Navarra in Madrid, Spain, as confirmed by the co-authorship patterns observed in the literature.

Figure 4 – Distribution of the number of studies on the topic published from 2010 to 2023



Source: Authors (2024)

Figure 4 illustrates the distribution of published studies over time. The first publication appeared in 1997, followed by a gap until 2009, suggesting that research on humic substances in agriculture was still emerging. From 2010 onward, publication activity increased. Between 2010 and 2015, the number of publications fluctuated between one and two per year, except in 2013, which saw no publications. A notable rise occurred in 2016, with six articles published. No publications were recorded in 2017 and 2019, while 2018 marked a peak with eight studies. A steady upward trend resumed in 2020 (4 publications), 2021 (7), and 2022 (10). However, this figure declined to four in 2023. This drop may be attributed to the post-pandemic impact, as many researchers and institutions were compelled to suspend research activities during the COVID-19 pandemic (2020–2022).

Table 4 – Most-cited authors from the portfolio of 44 articles in Scopus on humic substances in the growth of forest species and the mitigation of water stress in plants in general

Authors	Number of citations	Authors	Number of citations
Canellas, Luciano Pasqualoto	2.245	Garcia, Andrés Calderin	215
Façanha, Arnoldo Rocha	1.277	Castro, Rosane Nora	204
Picollo, Alessandro	813	Zonta, E.	191
Dobbss, L. B	435	Santos, Leandro Azevedo	182
Zandonadi, Daniel Basílio	355	Hita, David	162
Baigorri, Roberto	313	Tavares, orlando Carlos Huertas	160
Mora, V.	312	Zamarreño, Angel M	108
Berbara, Ricardo Luiz Louro	280	Nardi, Serenella	100
Fuentes, Marta	260	Silva, Carlos Alberto	40

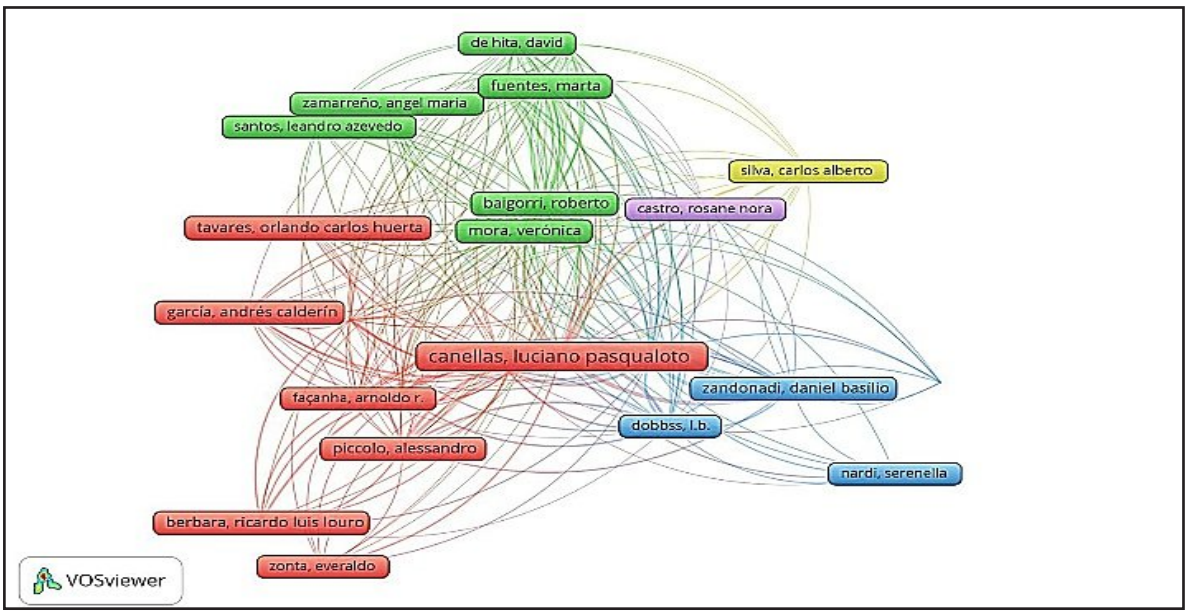
Source: Authors (2024)

From the portfolio of 44 Scopus-indexed articles, a total of 596 authors were identified. Applying a minimum threshold of 40 citations per author, 18 emerged as

the most frequently cited. Among them, L.P. Canellas had the highest citation count (2,245), followed by A.R. Façanha (1,277), and A. Picollo (813). The remaining authors had citation counts ranging from 40 to 435, which is notable considering the specificity of the research area within the broader field of humic substances (Table 4).

Figure 5 presents the network clustering of the most-cited authors globally. Three distinct clusters were formed, representing collaborative groupings among researchers specializing in the use of humic substances as plant growth promoters and water stress mitigators.

Figure 5 – Network clustering of the most cited authors on the topic



Source: Authors (2024)

The red cluster of Figure 5 comprises seven authors, with Luciano Pasqualoto Canellas standing out at its center. His position likely reflects his influence in the field and his status as the most cited author on the topic. Canellas's centrality in the network, including connections to authors in other clusters, indicates that his work is widely cited across different research groups. Additionally, the size of his frame in the visualization corresponds to his high citation count, further confirming his prominence in the field.

The green cluster includes approximately six authors, while the blue cluster consists of three highly cited authors. Two additional clusters—purple and yellow—each contain a single author. This isolation may suggest that these individuals produce bibliographic content that differs significantly from that of other groups, leading to their separation in the network (Figure 5).

Among the 18 most influential authors identified, the majority—11 in total (Canellas, Tavares, Garcia, Façanha, Berbara, Zonta, Santos, Zandonadi, Dobbss, Castro, and Silva)—are Brazilian. Five authors (Hita, Fuentes, Zamarreño, Baigori, and Mora) are affiliated with Spanish institutions, while two (Piccolo and Nardi) are from Italy. These findings underscore Brazil's leading role in global research on humic substances and highlight the substantial contributions of Brazilian researchers to advances in both agriculture and environmental sciences (Figure 5).

A total of 7,436 references were cited across the 44 articles in the Scopus portfolio (Table 5). A co-citation analysis of these references identified 18 sources as the most frequently cited by authors within the same dataset. Among these, Stevenson (1994) emerged as the most influential reference, cited 11 times, followed by Chen (1990) with 10 citations and Vaughan (1985) with 9. The remaining references received between 4 and 7 citations, as detailed in Table 5.

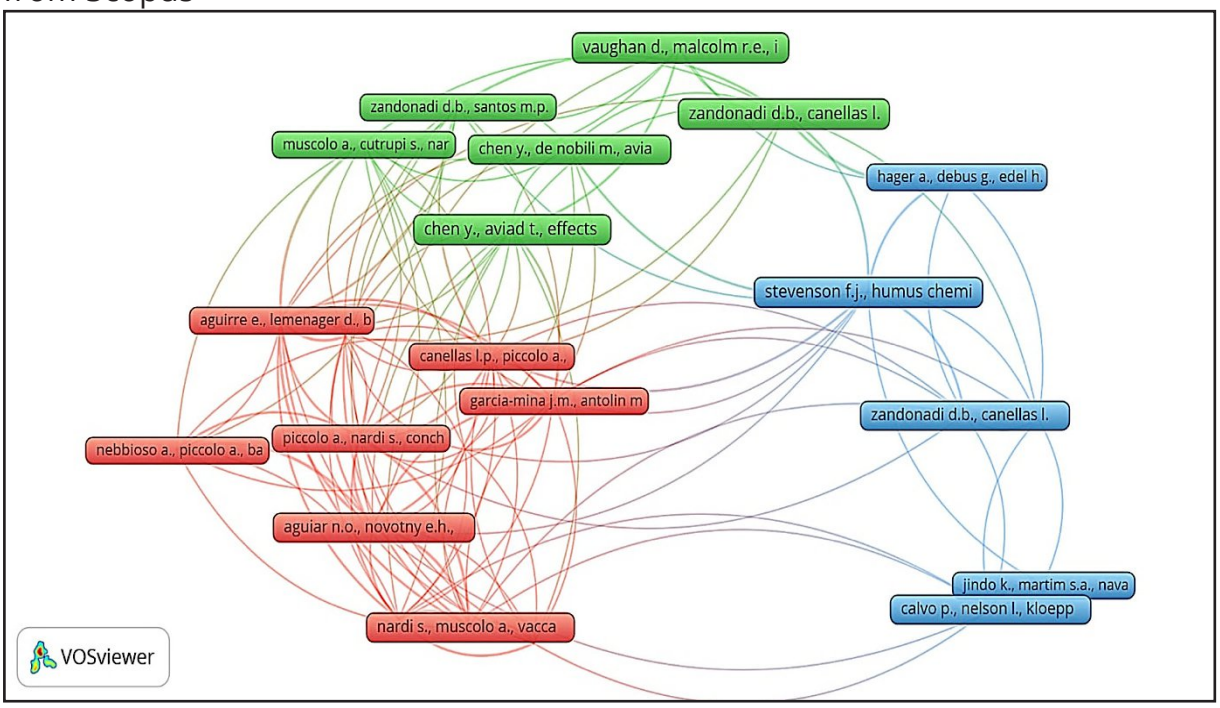
Table 5 – Most cited references by the authors of the 44 works from the Scopus portfolio

Quote from the article	Number of citations	Citation from the article	Number of citations
Stevenson (1994)	11	Muscolo et al. (1998)	5
Chen; A. (1990)	10	Piccolo et al. (1992)	5
Vaughan; M. (1985)	9	Nebbioso; Piccolo (2011)	5
Zandonadi et al. (2007)	7	Garcia-Mina et al. (2004)	5
Calvo et al. (2014)	7	Hager et al. (1991)	5
Zandonadi et al. (2007b)	7	Aguirre et al. (2009)	5
Chen et al. (2004)	6	Zandonadi et al. (2010)	4
Aguiar et al. (2013)	6	Canellas et al. (2015)	4
Nardi et al. (2007)	6	Jindo et al. (2012)	4

Source: Authors (2024)

The results discussed previously are further supported by Figure 6, which illustrates the formation of three clusters, representing groups of the most frequently cited references. These clusters are visually distinguished by color, and their composition reflects thematic similarities among the cited works.

Figure 6 – Co-citation analysis based on the references of the 44 studies selected from Scopus



Source: Authors (2024)

An analysis of the articles within each cluster revealed that the red cluster encompasses seven studies focused on the characterization of humic substances and their fractions derived from various sources of organic matter. These studies include the use of spectroscopy, elemental analysis, and investigations into nutrient and heavy metal complexation. The green cluster comprises six articles centered on the role of humic substances in plant morphophysiological processes and soil quality enhancement. Specific topics include root elongation, lateral root development, and the elucidation of underlying mechanisms, such as the involvement of nitric oxide in root growth and plasma membrane dynamics,

and the interaction between indoleacetic acid and humic acids in stimulating growth via H^+-ATPase activation in the plasmalemma. The blue cluster includes five broader studies on the use of biostimulants and organic waste rich in humic acids as plant growth promoters (Figure 6).

Overall, these findings provide a clear overview of the core literature related to humic substances as plant growth stimulants. They serve as a foundation for further research and underscore the pioneering contributions of these works to the field of soil science and humic substance studies.

A total of 96 journals were cited in the Scopus portfolio, representing both the publication sources of the 44 analyzed articles and the references cited within them. Among these, 13 journals were identified as the most influential based on two criteria: (1) having at least two citations within the portfolio and (2) achieving a minimum of 13 global citations in the relevant field. The Revista Brasileira de Ciência do Solo emerged as the most cited journal within the portfolio, with eight citations, followed by Plant and Soil, Agronomy, and Chemical and Biological Technologies in Agriculture, each with four citations. The remaining journals received between two and three citations (Table 6).

In terms of global citation impact, *Plant and Soil* was the most influential journal, with 1,378 citations, followed by *Planta* with 365 citations, and *Revista Brasileira de Ciência do Solo* with 193 citations. The remaining journals recorded citation counts ranging from 13 to 175.

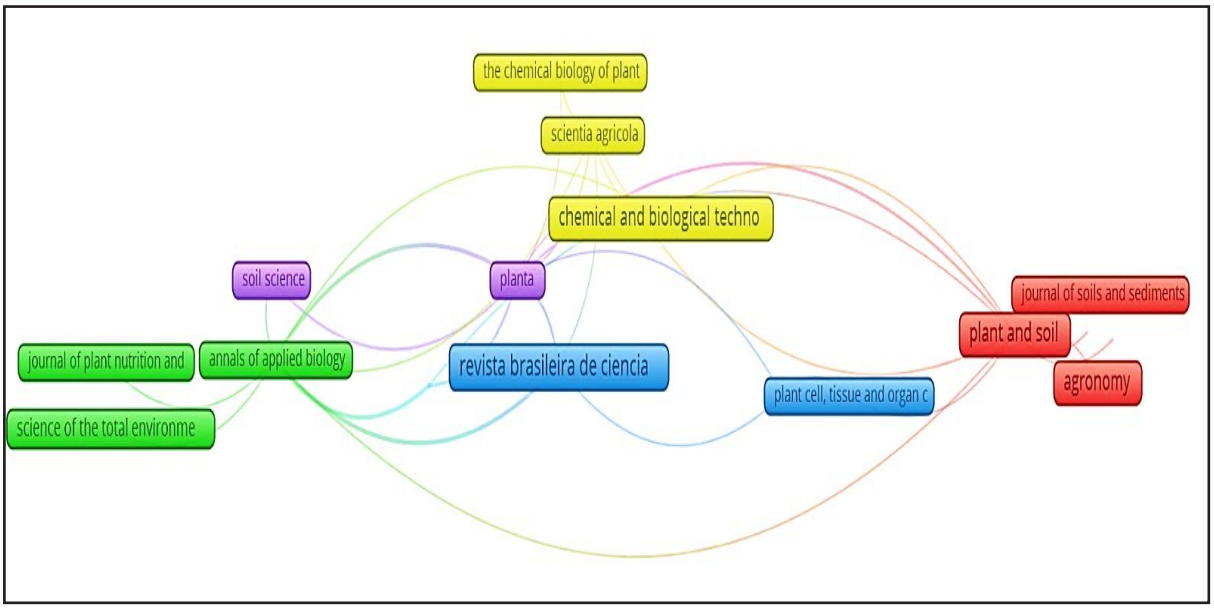
Five clusters were identified after network analysis, representing the grouping of journals that most frequently publish on the topic addressed in this study. The green cluster comprises three journals and is positioned at a distance from the red cluster, which also includes three journals. This spatial separation in the network suggests that these journals are rarely co-cited, likely due to differences in the focus and content of the studies they publish (Figure 7).

Table 6 –Ranking of journals that contribute the most to the topic from 1997 to 2023

Periodical	Number of citations in the portfolio	Total number of citations
Revista Brasileira de Ciências do solo	8	193
Plant and Soil	4	1.378
Agronomy	4	93
Chemical and biological technology	4	76
Science of the Total Environment	3	34
Annals of Applied biology	2	175
Planta	2	365
Soil Science	2	97
Journal of Soils and Sediments	2	83
The Chemical biology of plant	2	13
Scientia Agricola	2	55
Plant Cell, Tissue Annd organ Culture	2	20
Journal of Plant Nutrition and Soil Scienc	2	33

Source: Authors (2024)

Figure 7 – Network of journals that contribute the most to the topic of humic substances in forest species growth and the mitigation of water stress in plants in general from 1997 to 2023



Source: Authors (2024)

The yellow cluster also includes three journals, while the purple and blue clusters both consist of two journals. Notably, *Revista Brasileira de Ciência do Solo*, located in the blue cluster, occupies a central position within the network, indicating strong connectivity with journals from all other clusters. This centrality suggests that it is cited by the majority of articles on the subject across the analyzed journals (Figure 7). These findings once again underscore Brazil's prominent role in advancing humic substance science and highlight the journal's influence in disseminating knowledge on their benefits to plant metabolism.

From the occurrence analysis, a total of 1,608 keywords related to the topic were identified, comprising 492 author keywords and 1,285 indexed keywords. Among these, the 22 most frequently cited keywords were selected based on their prevalence in relevant literature. The keyword humic substances had the highest frequency, appearing 137 times, followed by humic acid with 47 citations, and root growth in third with 29 citations (Table 7). These results were anticipated, as these terms are commonly used in studies and were among the core search terms employed during the bibliographic survey for this research. The remaining keywords appeared between 9 and 29 times.

Table 7 – Occurrence of the most cited keywords on the topic

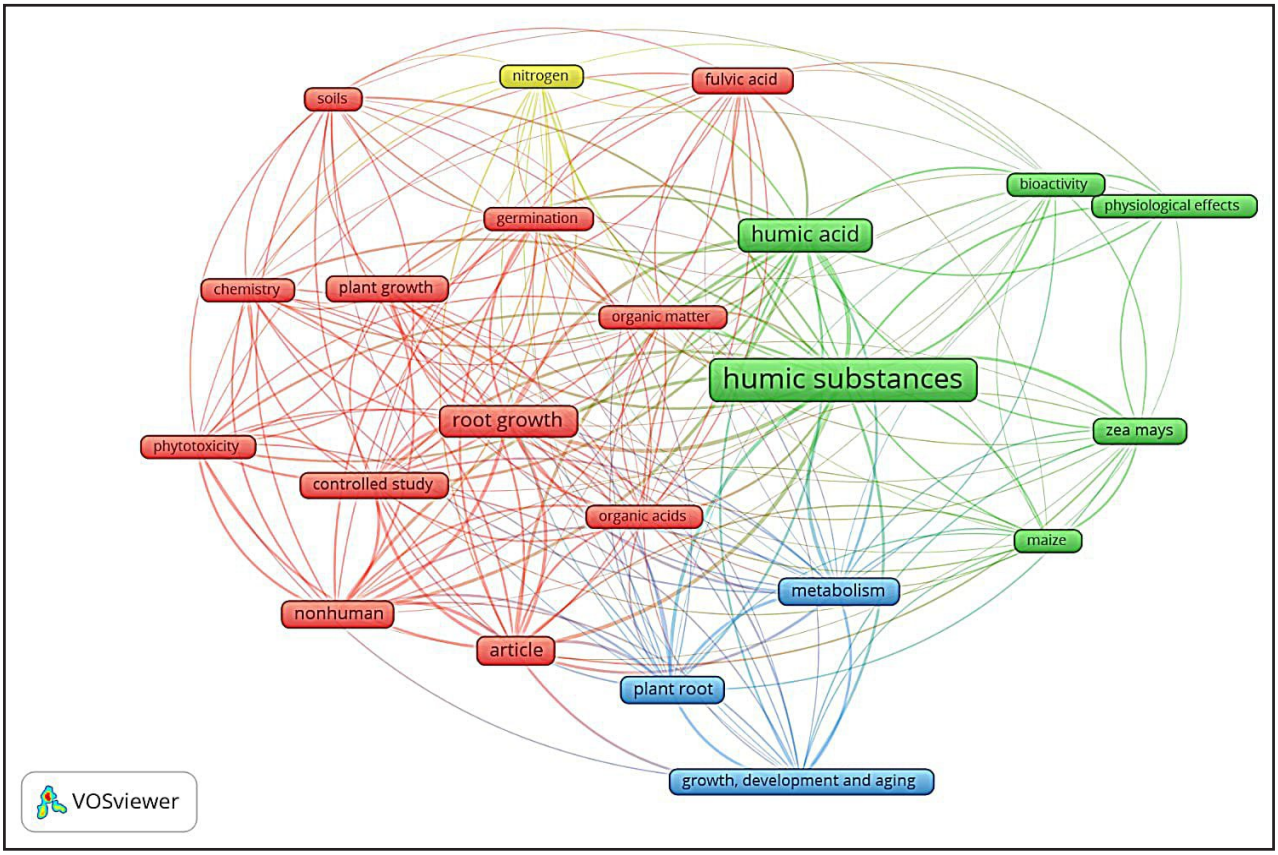
Keyword	Occurrence	Keyword	Occurrence
Humic substances	137	Chemistry	10
Humic acid	47	Fulvic acid	13
Root growth	37	Bioactivity	12
Article	29	Phitotoxicity	12
Metabolism	25	Germination	11
Plant root	23	Soils	11
Nonhuman	23	Physiological efeccts	10
Controlled study	17	Organic mater	10
Plant growth	16	Maize	10
Zea mays	16	Organic acids	10
Growth, development and aging	13	Nitrogen	9

Source: Authors (2024)

A network of connections among the most cited keywords revealed the formation of four clusters (Figure 8). In this network, the size of each frame represents the frequency of the keyword's occurrence—the larger the frame, the more frequent the term. As expected, humic substances, humic acid, and root growth stood out as the most recurrent terms. The centrality of humic substances within the network further indicates that this term is frequently used in conjunction with other keywords, especially those within the green cluster.

The red cluster contains 12 keywords, the green cluster 6, the blue cluster 3, and the yellow cluster only 1. These groupings suggest that keywords within each cluster are more frequently co-occurring in individual studies, while inter-cluster connections reveal how certain keywords bridge multiple research themes. The analysis of keyword co-occurrence is particularly valuable in bibliometric studies, as it facilitates content discovery, reflects author intent, and provides a concise summary of article focus areas.

Figure 8 – Occurrence analysis of the most cited keywords related to the topic of humic substances in the growth of forest species and the attenuation of plant water stress in general, from 1997 to 2023



Source: Authors (2024)

The main limitations identified in this systematic and bibliometric study are primarily related to the selection and scope of the information sources used. The choice of databases, although conducted rigorously, may have influenced the results, as relevant studies published in non-indexed journals may not have been included. Furthermore, the adoption of restrictive inclusion criteria, such as publication type filters, may have reduced the representativeness of the analyzed sample, thereby limiting the overall understanding of the scientific development of the topic.

Another limiting factor concerns the absence of complementary databases, such as Web of Science, due to institutional access constraints. This may have restricted the spectrum of studies analyzed, limiting the methodological and geographical diversity of the research. Therefore, although the results hold scientific validity, such limitations should be acknowledged as determining factors in the structure of the study.

4 CONCLUSION

Research on humic substances (HS) as plant growth promoters has been gained momentum since 2009. Despite this growing interest, the field remains relatively recent, with limited literature directly addressing the bioactivity of HS in the growth and development of forest species. Notably, no studies have been yet identified that examine the response of tree species to water stress when treated with HS, indicating a significant gap in the current body of knowledge.

Bibliometric analyses reveal a strong level of collaboration among researchers, contributing to advances in the application of HS to plant metabolism. These findings reinforce the potential of HS as a sustainable alternative to synthetic chemical fertilizers. Moreover, a substantial number of studies focus on the development of new HS-based products, which are being disseminated through reputable scientific journals.

This study also underscores the increasing volume of research on HS, with Brazil emerging as a leading contributor, both in terms of publication output and in fostering international collaborations. In conclusion, the findings highlight the biostimulant

potential of humic substances across various plant types, including vegetables and forest species, and emphasize the growing scientific recognition of their role in promoting sustainable agriculture and forestry.

This systematic and bibliometric review was developed with the purpose of presenting an overview of publications related to the use of humic substances in plant growth and in the mitigation of water stress in forest species, highlighting the scarcity of studies that guide scientific advancement in this field. Furthermore, the study emphasizes the need to deepen experimental investigations that can support practical applications.

The next stages of this research propose the conduction of trials under controlled greenhouse conditions, aiming to evaluate the effects of different types of humic substances on growth and on the mitigation of induced water stress in *Myrciaria floribunda* and *Schinus terebinthifolius*, native species of the Alagoas restinga. These species present relevant potential for use in restoration programs of degraded areas in this ecosystem, which reinforces both the scientific and applied significance of the study.

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