

Review

# Trichoderma Diversity in Mexico: A Systematic Review and Meta-Analysis

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**Abstract:** *Trichoderma* is a genus of cosmopolitan fungi with more than 375 species described today. Despite its global significance in agriculture, ecosystems, and industry, few studies have focused on studying the diversity and distribution of this genus in Mexico. In this systematic review and meta-analysis, we aimed to understand the diversity and distribution of *Trichoderma* species in Mexico, both in ecosystems and agroecosystems. For this systematic review, we used the PRISMA methodology. We reviewed forty-one scientific articles, two book chapters, and the GBIF database. We recorded a total of 1082 isolates, revealing the presence of 57 species of the genus *Trichoderma* in 29 states of Mexico. We found that species from the genus *Trichoderma* were reported in 20 agroecosystems and 6 ecosystems. *T. harzianum* was the predominant species in both agricultural and undisturbed soil. Tabasco and Veracruz were the states with the highest species diversity, with 20 and 14 species reported, respectively. Chiapas had the highest diversity indices (Menhinick had 3.20, Simpson had 0.89, and Margalef had 4.16). The coffee crop was the agroecosystem with the highest diversity, with 12 species reported. In the undisturbed ecosystems, tropical rainforests featured 12 different species. This study highlights the distribution of the genus *Trichoderma* as a cosmopolitan genus. We argue for the importance of the species that comprise the genus and its applications for social benefits.

**Keywords:** biodiversity; soil diversity; biodiversity index; fungi; GBIF; PRISMA; Shannon index



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## 1. Introduction

*Trichoderma* is a genus that belongs to the Fungi Kingdom, Ascomycota Division, Pezizomycotina Subdivision, Sordariomycetes Class, Hypocreales Order, and Hypocreaceae Family. Globally, 375 species have been described and validated [1]. Species of this genus exhibit a cosmopolitan distribution, inhabiting various ecosystems and substrates, including agricultural fields, grasslands, swamps, forests, marshes, deserts, and water bodies [2,3].

The *Trichoderma* species play crucial roles in ecosystems and agroecosystems by controlling plant pests and diseases, acting as a biofertilizer, degrading organic matter, and participating in multitrophic interactions along with insects [4–6]. Therefore, researchers have been exploring ways to harness the properties of *Trichoderma* species for their application in agriculture, industry, and environmental bioremediation.

In Mexico, studies addressing this fungi genus have focused on its efficacy as a biological control agent against diseases in crops such as agave (*Agave tequilana*), avocado (*Persea americana*), garlic (*Allium sativum*), lettuce (*Lactuca sativa*), peanuts (*Arachis hypogaea*), cocoa (*Theobroma cacao*), coffee (*Coffea arabica*), cinnamon (*Cinnamomum verum*), onion (*Allium cepa*), chili (*Capsicum annuum*), hibiscus (*Hibiscus sabdariffa*), corn (*Zea mays*), beans

(*Phaseolus vulgare*), apples (*Malus domestica*), mango (*Mangifera indica*), walnuts (*Juglans regia*) and bananas (*Musa × paradisiaca*) [7–22].

In the industrial context, Hernández-Melchor et al. (2019) [23] underscored the importance of *Trichoderma* during the process of biofuel production. Biofuels are produced through the secretion of enzymes and the production of secondary metabolites of the *Trichoderma* species. On an environmental front, *Trichoderma* has demonstrated its capability to degrade polycyclic aromatic hydrocarbons in soil contaminated with crude oil [24]. Consequently, a study on the biodiversity and distribution of species of the genus *Trichoderma* is paramount, offering crucial insights into the potential of native species and their application in biotechnology.

Studies addressing the diversity and distribution of the genus *Trichoderma* are scarce in Mexico. One approach to address the lack of information on this genus is through a systematic review that provides reliable and accurate information. Utilizing contextual data and gene sequences accessible through digital databases enables the acquisition and generation of novel knowledge [25]. In this study, we conducted a systematic review to comprehensively address the knowledge gaps and furnish dependable insights into the diversity and distribution of *Trichoderma* species.

In a meta-analysis, ensuring transparency, completeness, and accuracy is essential for the reproducibility of these analyses and for promoting valid cross-comparisons among studies. In this context, the PRISMA methodology (Reference Elements for Publishing Systematic Reviews and Meta-Analyses) functions as a valuable tool that standardizes systematic reviews and facilitates the collection of reproducible information [26]. Thus, when using the PRISMA methodology, we can obtain data on the abundance and presence of *Trichoderma* species, the number of species, geographical locations, dates, and other data that allow us to conduct ecological analyses. While ecological information is often overlooked in the study of microorganisms, it holds significant value. Ecological studies can provide valuable insights to generate novel study approaches and applications for microorganisms such as the fungi of the genus *Trichoderma* [27].

The limited number of studies on the genus *Trichoderma* available in Mexico cover various areas of knowledge. Thus, we can obtain information that generates more analysis and new studies on the ecology and diversity of this genus. Some studies on the diversity of the genus *Trichoderma* in Mexico focus on calculating indices based on the quantification of the number of present species. Examples of such studies are those conducted by Sánchez & Rebolledo (2010) [22], Torres-De la Cruz et al. (2015) [28], and Sánchez Hernández et al. (2018) [29], who calculated Margalef indices for this genus, obtaining values of 0.71 (in *Agave tequilana*), 1.75, and 2.48 (in *Theobroma cacao*), respectively.

To date, no systematic review with meta-analysis has been conducted to analyze the diversity and distribution of species of the genus *Trichoderma* in Mexico. This paper aims to fill this knowledge gap by providing a systematic review and meta-analysis to understand the biodiversity and distribution of this genus in Mexico.

This is the first attempt to understand the diversity of the genus *Trichoderma* and its distribution in Mexico, providing a reference regarding the ecological aspects of the genus *Trichoderma* for future research.

## 2. Materials and Methods

We conducted a systematic review and meta-analysis using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [26].

### 2.1. Study Area

We searched the primary literature, which encompassed studies conducted in Mexico.

### 2.2. Searching for Information

We conducted a search using the following electronic databases: Scopus, Springer, BioOne, Web of Science, Google Scholar, Pubmed, and Science Direct, as well as the

Global Biodiversity Information Facility (GBIF, <https://www.gbif.org/es/> accessed on 16 November 2021) platform. Our search spanned articles, reviews, and book chapters, along with georeferenced records of fungal species belonging to the genus *Trichoderma* (GBIF platform). Grey unpublished literature was not used for the analyses.

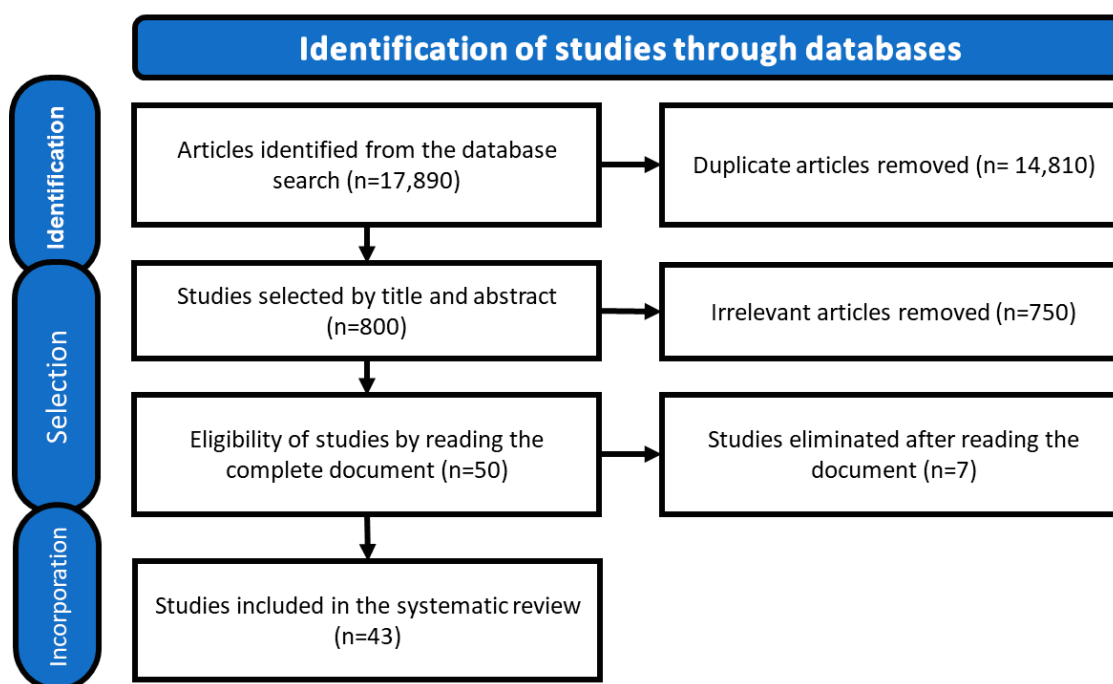
To conduct our search, we used the following search terms: “fungal diversity”, “fungal biodiversity”, “*Trichoderma*”, “*Trichoderma* biodiversity”, “ascomycetes biodiversity”, “ascomycetes”, “micromycetes”, “soil microbiology”, “Hypocreales”. We combined the above terms with the words “Mexico” and with the names of each of its states. To broaden our search, we used Boolean operators (AND, OR, NOT) to combine the search terms. The search period extended from January 2000 to January 2022.

### 2.3. Eligibility Criteria in Published Articles

Articles that met the following criteria were included in the review and meta-analysis:

1. Research articles and book chapters in English and Spanish in which the isolation and identification of native strains belonging to the genus *Trichoderma* within the Mexican territory was mentioned.
2. Articles in which the identification of the fungus was conducted at the species level, either morphologically, molecularly, or both.
3. Articles that presented a description of the sampling area where the species was recorded by mentioning the locality, geographical coordinates, or other georeferencing parameters.
4. Articles that featured the use of commercial species were discarded.
5. We also discarded articles that reported repeated strains of species for the same sampling site.

The process of document acquisition is explained in Figure 1.



**Figure 1.** The search strategy implemented in the review and meta-analysis using the PRISMA method. This flowchart represents the searching and screening workflow, as well as the eligibility criteria applied to include/discard the documents used for the review.

### 2.4. Eligibility Criteria for Data on the GBIF Platform

1. We included records where the fungus strains were identified at the species levels.

2. We included records that provided information about the sampling site or the georeferenced location where the strains were isolated.
3. Records from the platform that were repeated in any other document found from other databases were discarded.

### 2.5. Data Extraction and Conditioning Process

We systematically extracted the following information from the documents: (1) the document type (article, book chapter, or review), (2) document title, (3) author's name, (4) publication year, (5) state, (6) municipality, (7) the substrate or crop in which the strain was isolated, (8) identification type (morphological, molecular or both), (9) access code to the Digital Database of Genetic Sequences (GENBANK) for species identified molecularly, (10) the identifier assigned by the author to the species in the article. To ensure accuracy, we cross-validated the species' reported names using the International Commission on the Taxonomy of *Trichoderma* website (<https://trichoderma.info/> accessed on 1 November 2021) in order to use currently valid names for this review.

For the records obtained from the GBIF database, we included strains identified at the species level that provided geographical information. To prevent duplicates, we also looked on the internet for the authors who studied this species to investigate whether data had already been published in a scientific article or other type of document.

### 2.6. Data Analysis

We conducted the following two types of analyses: (1) qualitative (a descriptive summary) and (2) quantitative (the correlation analysis, a biodiversity permutation test, calculation of diversity indices, and calculation of Bray–Curtis similarity indices).

For the quantitative analyses, we calculated the correlations between the following variables: Year, N° of articles, species, N° of isolates. We conducted a biodiversity permutation test using abundance and species diversity by source of information (GBIF and Systematic review). For the calculation of diversity indices, and calculation of Bray–Curtis similarity indices, we built a matrix with the variables, abundance, sampling site (states), and vegetation type in which the strain was recorded. We processed these data in the statistical program "Paleontological Statistics for Education and Data Analysis version 4.0" (PAST) [30]. We calculated diversity indices separately for the systematic review (SR) and for the GBIF database. We also ran the analyses, including both sources of information (SR + GBIF), in the same analysis. For a more nuanced understanding, we computed Diversity indices and Bray–Curtis similarity indices for the crops and non-disturbed areas separately.

## 3. Result

### 3.1. Qualitative Analysis

In the systematic review (SR), the search was extended across 29 scientific journals. We included in the review a total of 41 scientific articles and two book chapters that met the inclusion criteria (Table S1). To enhance organization, we categorized articles and book chapters by the following areas of knowledge: biofuels, ecology, biofertilization, biological control, biological control and biofertilization, and bioremediation (Figure 2).

In terms of publication year, our findings indicate that in 2001, only one published article authored by Michel-Aceves et al., 2001 [31] was identified. Notably, 2020 was the year with the highest number of published articles, with a total of six published articles focused on some aspect of *Trichoderma* (Figure 3).

Most of the articles found were published in the *Mexican Journal of Phytopathology* and the *Mexican Journal of Mycology*, with 6 and 4 articles, respectively (Table 1).

Our findings indicate that species from the genus *Trichoderma* were reported in 25 states of Mexico (871 isolates representing 38 species). We found that the state of Guerrero contributed the highest number of articles (7 articles reporting 7 species), while the state of

Tabasco contributed the highest number of isolates (318 isolates reporting 17 species) (See Table 2).

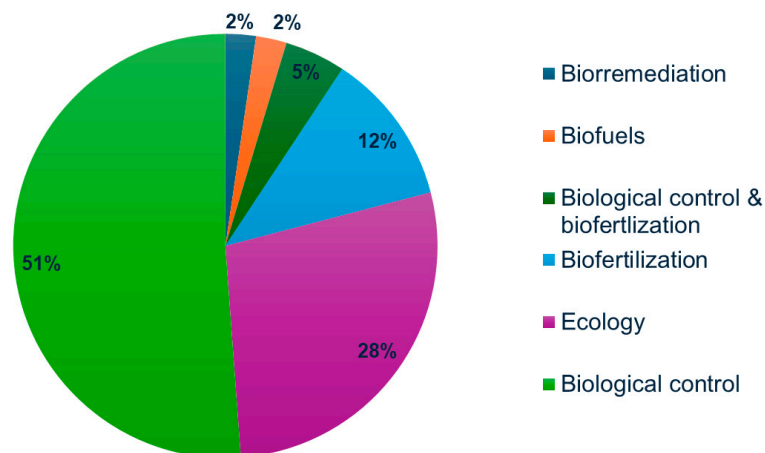


Figure 2. Percentage of documents found in the review by areas of knowledge.

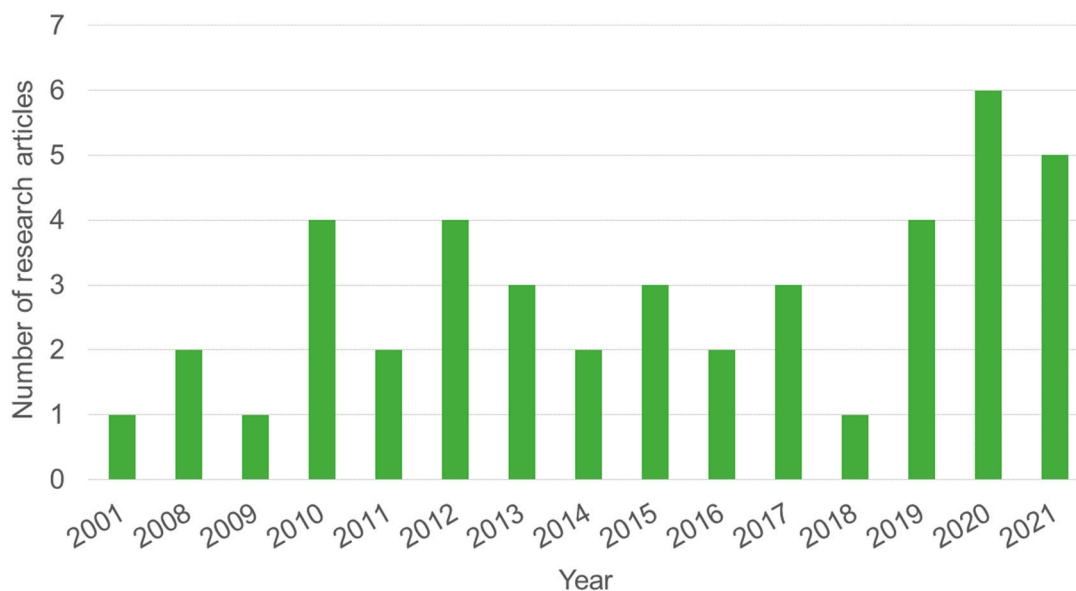


Figure 3. The number of research articles published by year that were found in the systematic review.

Table 1. Journals and articles found in the systematic review.

| Journal                                               | Articles   |
|-------------------------------------------------------|------------|
| <i>Acta Botánica Mexicana</i>                         | [29,32,33] |
| <i>African Journal of Agricultural Research</i>       | [34]       |
| <i>African Journal of Biotechnology</i>               | [35]       |
| <i>Agrociencia</i>                                    | [17,36]    |
| <i>Applied Microbiology and Biotechnology</i>         | [37]       |
| <i>Avances en Investigación Agropecuaria</i>          | [10]       |
| <i>Bioagro</i>                                        | [15]       |
| <i>Biological control</i>                             | [19]       |
| <i>Biotechnology &amp; Biotechnological Equipment</i> | [38]       |
| <i>Revista de Ciencias Biológicas y de la Salud</i>   | [21]       |
| <i>Boletín de la Sociedad Micológica de Madrid</i>    | [39]       |

**Table 1.** *Cont.*

| Journal                                                                                    | Articles      |
|--------------------------------------------------------------------------------------------|---------------|
| <i>Electronic Journal of Biotechnology</i>                                                 | [40]          |
| <i>Fungal Genetics and Biology</i>                                                         | [41]          |
| <i>Investigación y Ciencia de la Universidad Autónoma de Aguascalientes</i>                | [42]          |
| <i>información Técnica Económica Agraria</i>                                               | [43]          |
| <i>Journal of Fertilizers and Pesticides</i>                                               | [44]          |
| <i>Microorganisms</i>                                                                      | [45]          |
| <i>Phytotaxa</i>                                                                           | [46]          |
| <i>Plants</i>                                                                              | [7]           |
| <i>Revista Colombiana de Biotecnología</i>                                                 | [47]          |
| <i>Revista Fitotecnia Mexicana</i>                                                         | [48]          |
| <i>Revista Mexicana de Biodiversidad</i>                                                   | [28,49]       |
| <i>Revista Mexicana de Fitopatología</i>                                                   | [18,31,50–53] |
| <i>Revista Mexicana de Micología</i>                                                       | [8,22,54,55]  |
| <i>Terra Latinoamericana</i>                                                               | [56]          |
| <i>Tropical and Subtropical Agroecosystems</i>                                             | [57,58]       |
| <i>Water, Air Soil Pollution</i>                                                           | [24]          |
| Book: <i>Agroecosistemas cafetaleros de Veracruz: biodiversidad, manejo y conservación</i> | [59]          |
| Book: <i>Investigación en Matemáticas, Economía, Ciencias sociales y Agronomía</i>         | [60]          |

**Table 2.** The number of articles, total isolates, and species of the genus *Trichoderma* found by state in the systematic review and the GBIF platform.

| States                | Systematic Review  |                    |   | GBIF               |    |
|-----------------------|--------------------|--------------------|---|--------------------|----|
|                       | Number of Articles | Number of Isolates | S | Number of Isolates | S  |
| Aguascalientes        | -                  | -                  | - | 7                  | 5  |
| Baja California       | 1                  | 1                  | 1 | 1                  | 1  |
| Baja California Sur   | 1                  | 6                  | 6 | -                  | -  |
| Campeche              | -                  | -                  | - | 3                  | 3  |
| Mexico City           | 1                  | 3                  | 3 | 1                  | 1  |
| Chiapas               | 1                  | 4                  | 2 | 10                 | 10 |
| Chihuahua de Zaragoza | 3                  | 26                 | 5 | 3                  | 3  |
| Coahuila              | 2                  | 32                 | 4 | -                  | -  |
| Colima                | 2                  | 9                  | 3 | 3                  | 2  |
| Durango               | -                  | -                  | - | 31                 | 13 |
| Mexico state          | 1                  | 9                  | 2 | 14                 | 7  |
| Guanajuato            | 3                  | 46                 | 5 | -                  | -  |
| Guerrero              | 7                  | 36                 | 7 | 1                  | 1  |
| Hidalgo               | 3                  | 5                  | 3 | -                  | -  |
| Jalisco               | 4                  | 13                 | 7 | 10                 | 2  |
| Michoacan             | 2                  | 8                  | 4 | 57                 | 11 |
| Morelos               | 2                  | 10                 | 5 | -                  | -  |

Table 2. Cont.

| States          | Systematic Review  |                    |    | GBIF               |    |
|-----------------|--------------------|--------------------|----|--------------------|----|
|                 | Number of Articles | Number of Isolates | S  | Number of Isolates | S  |
| Nayarit         | 1                  | 4                  | 3  | -                  | -  |
| Oaxaca          | 3                  | 17                 | 3  | 5                  | 5  |
| Puebla          | 2                  | 2                  | 2  | 1                  | 1  |
| Quintana Roo    | 1                  | 9                  | 2  | 8                  | 6  |
| San Luis Potosi | -                  | -                  | -  | 27                 | 10 |
| Sinaloa         | 1                  | 3                  | 3  | -                  | -  |
| Sonora          | 2                  | 5                  | 2  | -                  | -  |
| Tabasco         | 4                  | 318                | 17 | 17                 | 8  |
| Tamaulipas      | 2                  | 12                 | 7  | 1                  | 1  |
| Tlaxcala        | 2                  | 2                  | 1  | -                  | -  |
| Veracruz        | 3                  | 288                | 14 | 1                  | 1  |
| Yucatan         | 2                  | 5                  | 3  | 6                  | 5  |

"-" Not applicable, "S" species of the genus *Trichoderma*.

We found that the GBIF database (Table S2) reports species of *Trichoderma* in 20 Mexican states, with 207 isolates and 38 species (the species reported in GBIF may differ from those found in electronic journals). According to the GBIF database, Michoacán had the highest number of isolates (57), while Durango had the highest number of species (13).

Combining data from the systematic review (electronic journals) and the GBIF database, we found that species of *Trichoderma* were reported in 29 of the 32 Mexican states, with 1082 isolates and a diversity of 57 species (Table 2).

When analyzing the results at the species level, *Trichoderma harzianum* stands out as the most frequently reported species. In this systematic review, the species appears in 161 isolates. By contrast, the GBIF platform's data show 49 isolates of *T. harzianum*. When combining data from the systematic review (electronic journals) and the GBIF platform, we found 210 *T. harzianum* isolates (Figure 4).

In our systematic review (electronic journals), Tabasco had the highest diversity of *Trichoderma* species (17 species). Based on the information obtained from the GBIF platform, Durango appears as the state with the greatest species diversity (13 species). However, when we merged data from both the systematic review and GBIF, Tabasco appeared as the state with the highest diversity and number of isolates (20 species and 335 isolates, respectively) (Figures 5 and 6).

In our systematic review, we reported different *Trichoderma* species in agricultural and disturbed soil. The crops associated with these types of soil included the following 20 species: agave (*Agave tequilana*), avocado (*Persea americana*), garlic (*Allium sativum*), lettuce (*Lactuca sativa*), peanuts (*Arachis hypogaea*), cocoa (*Theobroma cacao* L.), coffee (*Coffea arabica*), cinnamon (*Cinnamomum verum*), onion (*Allium cepa*), chili (*Capsicum annuum*), sunflower (*Helianthus annuus*), hibiscus (*Hibiscus sabdariffa*), corn (*Zea mays*), beans (*Phaseolus vulgaris*), apples (*Malus domestica*), mango (*Mangifera indica*), walnuts (*Juglans regia*), bananas (*Musa × paradisiaca*), sorghum (*Sorghum* spp.) and wheat (*Triticum* spp.). Coffee appeared as the crop with the highest associated species diversity (13 species). *Trichoderma harzianum* appeared as the most abundant species in agricultural soil. This species appeared in 14 of the 20 reported crops (Figure 7).

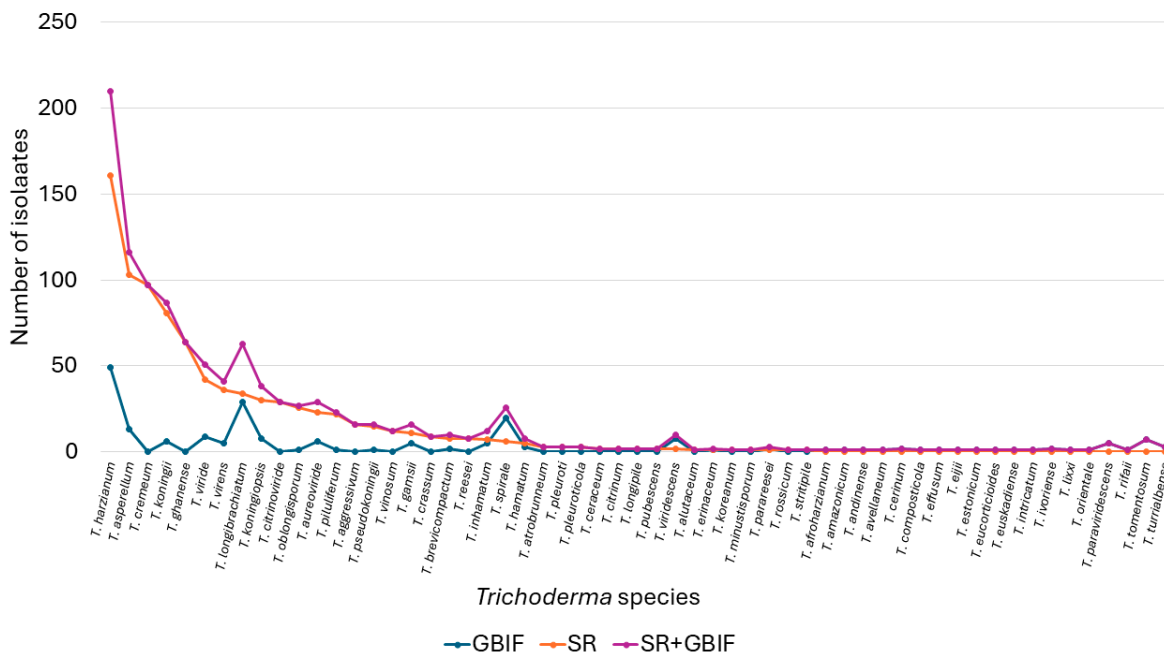


Figure 4. The number of isolates per species found in the systematic review (SR), GBIF, and SR + GBIF combined, respectively.

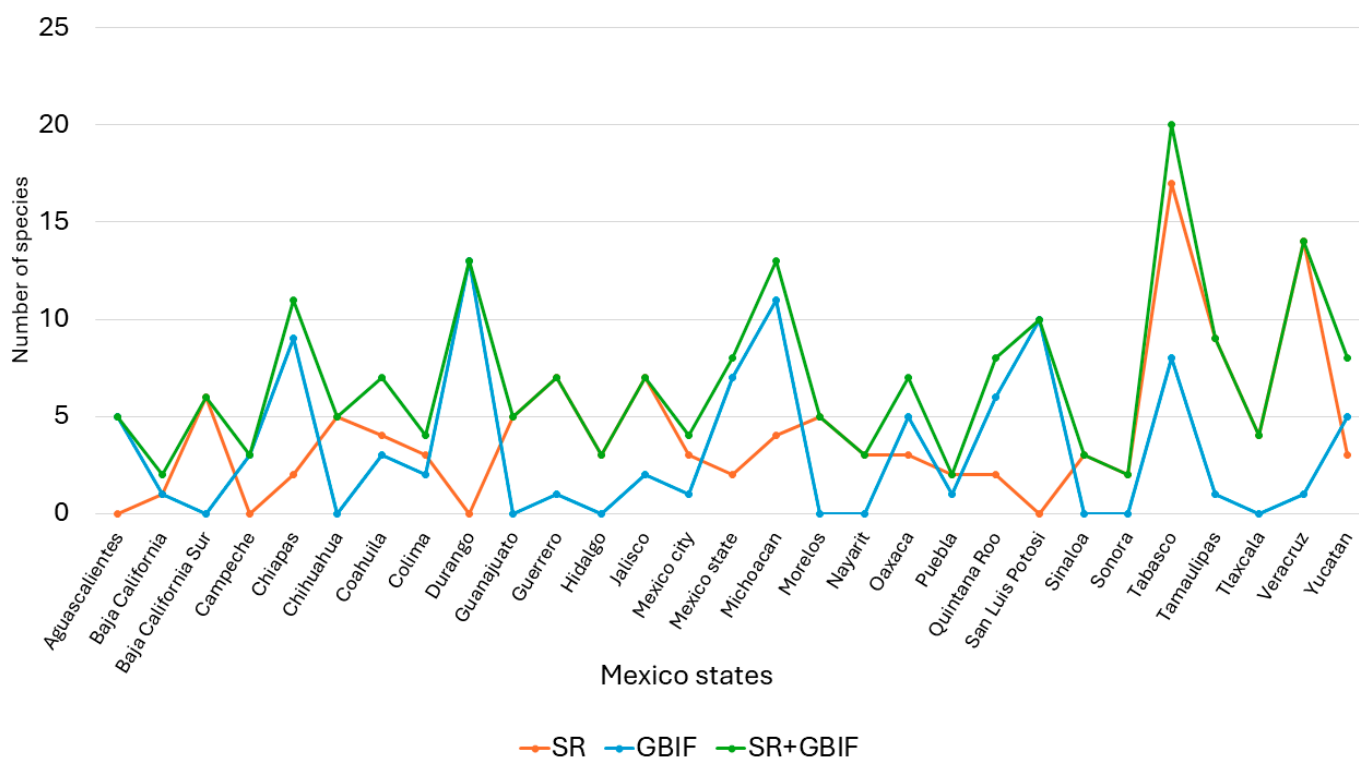


Figure 5. The number of *Trichoderma* species per state reported in this systematic review with (SR), GBIF, and SR + GBIF combined, respectively.

The undisturbed soil reported in our review included soil from the mountain mesophyll forest, temperate forest, xerophytic scrub, tropical rainforest, tropical semideciduous forest, and mountain cloud forest. We found that the most common *Trichoderma* species reported in undisturbed soil was *T. harzianum*, occurring in four soil types. We also found that the tropical rainforests were reported to have the highest species diversity (12 species reported). In total, 16 species of *Trichoderma* were reported in undisturbed soil (Figure 8).



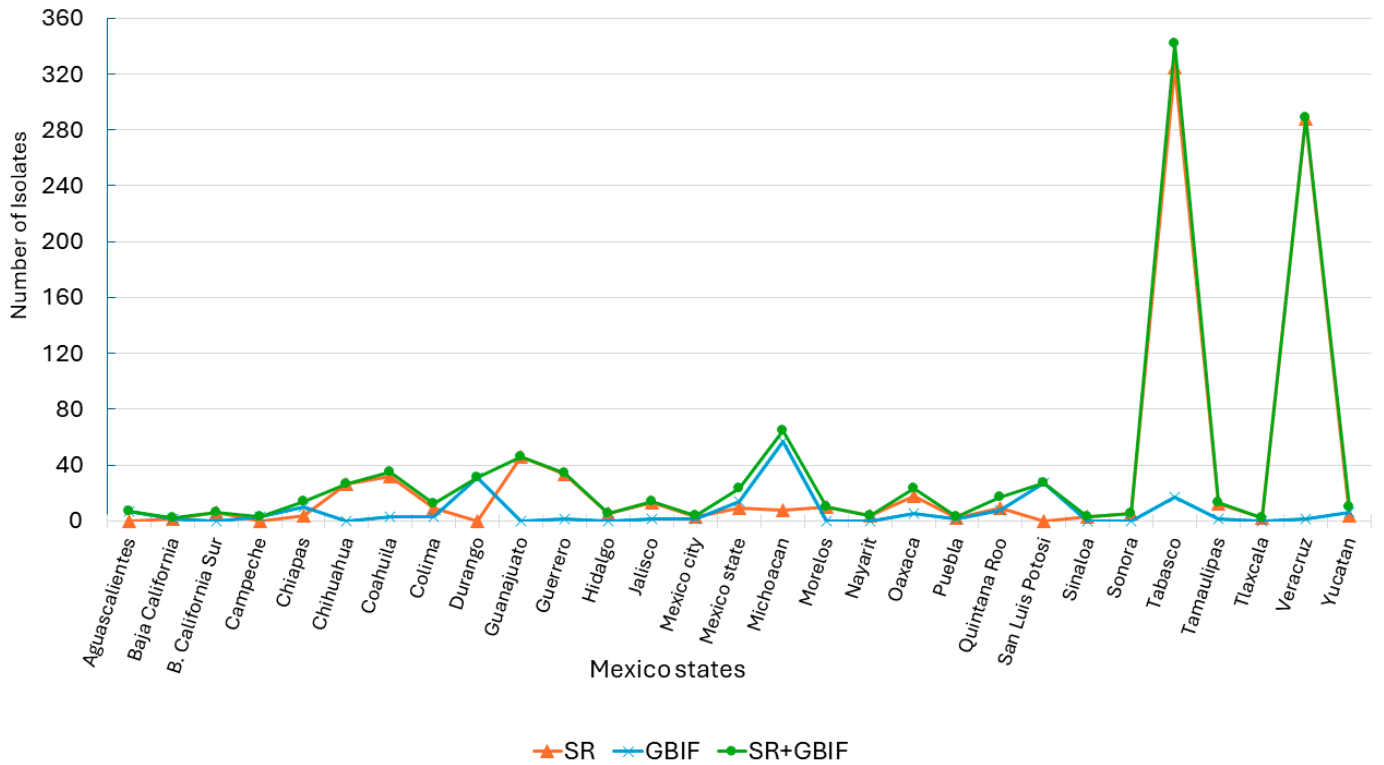


Figure 6. The number of isolates per state found in this systematic review (RS) in GBIF and SR + GBIF combined, respectively.

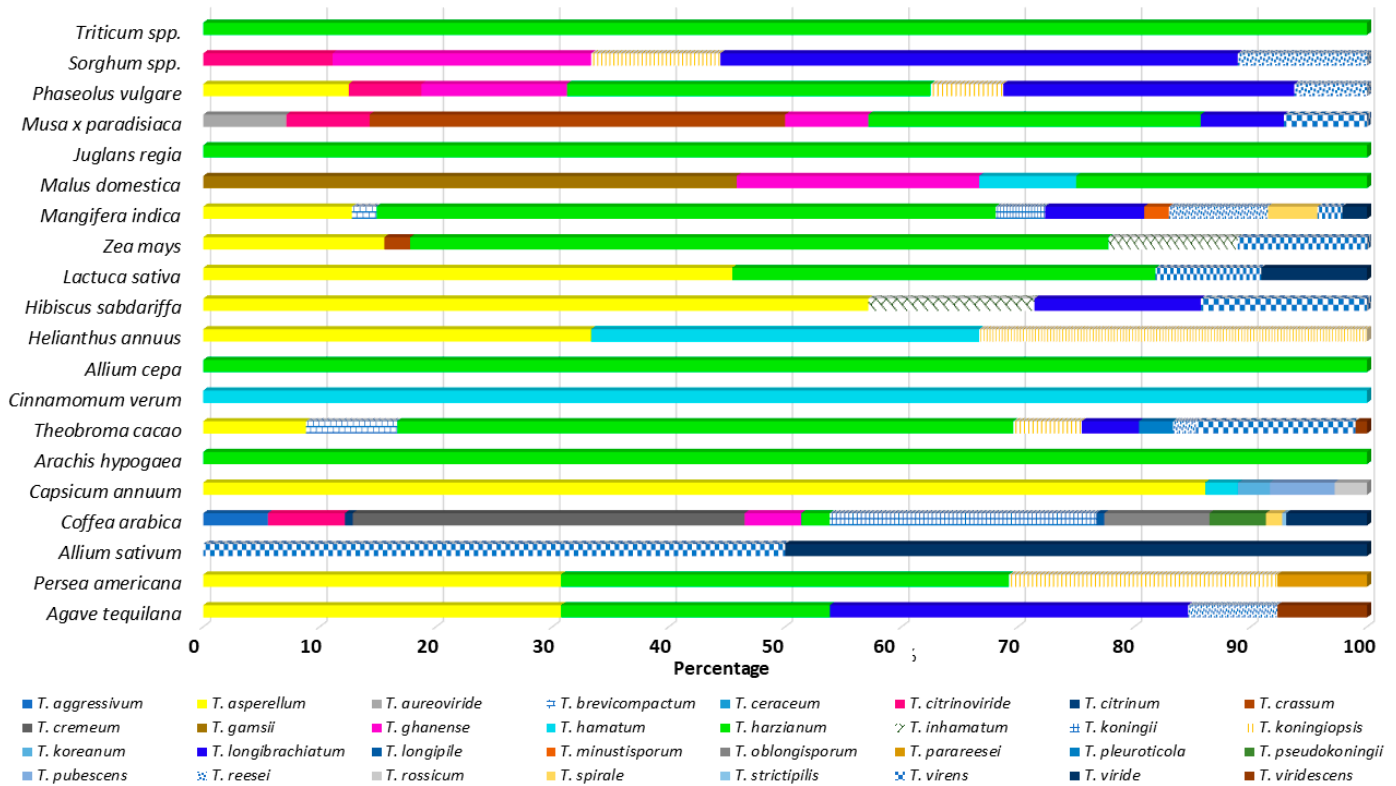
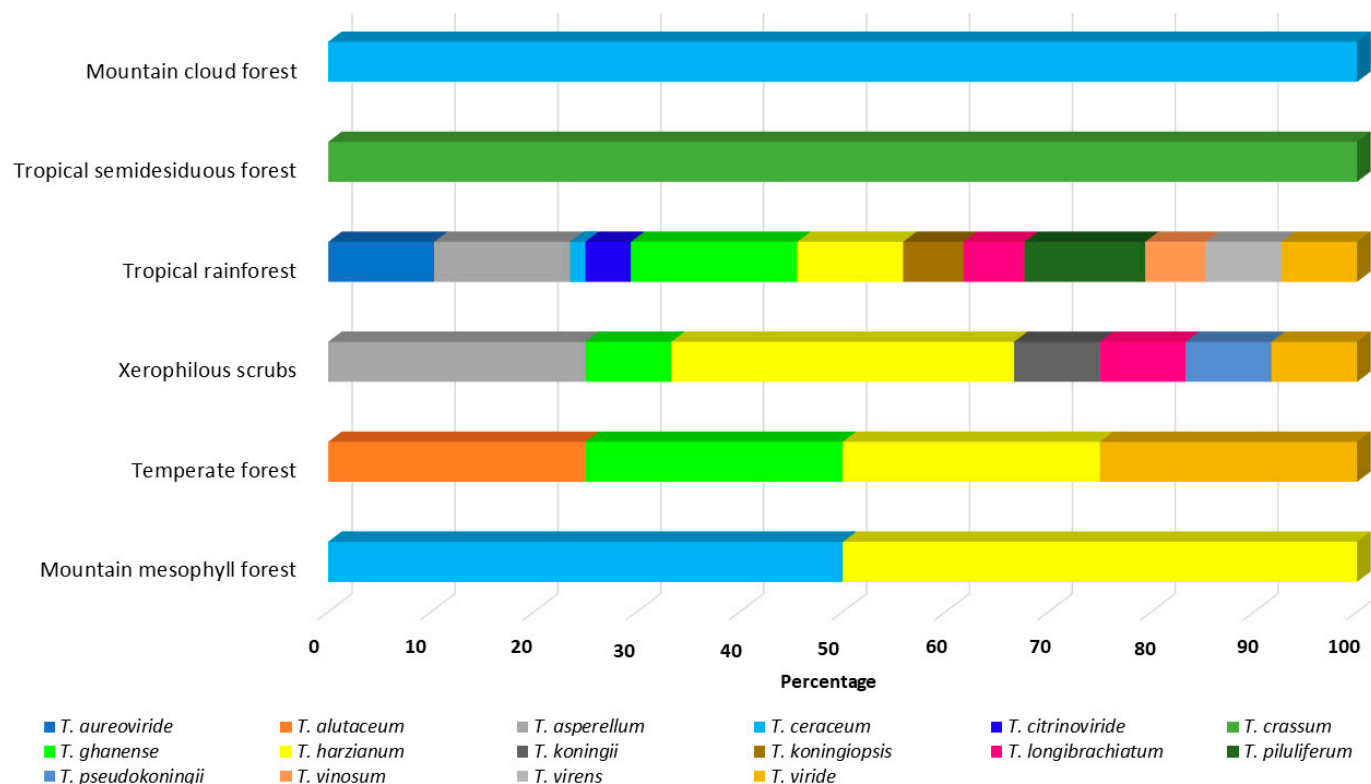


Figure 7. Species of Trichoderma present in the different crops reported in the systematic review (x-axes represent the percentage of isolates in which each species was reported). Different colors shadings in the horizontal bars correspond to the different Trichoderma species listed at the bottom of the figure.



**Figure 8.** *Trichoderma* species found in this review present in undisturbed soil in México (x-axes represent the percentage of isolates in which each species was present). Different color-shadings in the horizontal bars correspond to the different *Trichoderma* species listed at the bottom of the figure.

### 3.2. Quantitative Analysis

We found a positive correlation ( $R = 0.58$ ) between the number of articles and the year of publication, indicating a linear increment in the number of publications over time. We found a strong correlation between the number of isolates and the number of species reported in the systematic review ( $R = 0.76$ ).

The results of the diversity permutation test show no statistically significant difference between the species diversity found using our search in electronic journals (systematic review) and the GBIF platform.

An analysis of diversity indices based on the systematic review data showed that Tabasco had the highest diversity indices (Shannon index: 2.54; Margalef index: 2.94; Figure 9).

Using the data from GBIF, we found that Chiapas had the highest biodiversity indices (Shannon index: 2.753; Margalef index: 3.909; Menhinick index: 3.20; Figure 10).

Using the data obtained from electronic journals (in the systematic review) combined with the data obtained from GBIF, we found that Chiapas had the highest diversity indices (Margalef index: 4.16; Shannon index: 2.80; and Menhinick index: 3.20; Figure 11).

The results of the Bray–Curtis index analysis showed two distinct groups with no shared similarities. The first group was unique to the state of Morelos, characterized by the exclusive presence of species such as *Trichoderma crassum*, *T. atrobrunneum*, *T. koreanum*, *T. pleuroti*, and *T. pubescens*. Within these species, *T. crassum* was the only species shared with other states. The second group included all the remaining states, which were further divided into two subgroups. The first of these subgroups contained Tabasco and Veracruz (Bray–Curtis index: 0.22). The remaining states collectively formed the second subgroup (Figure 12).

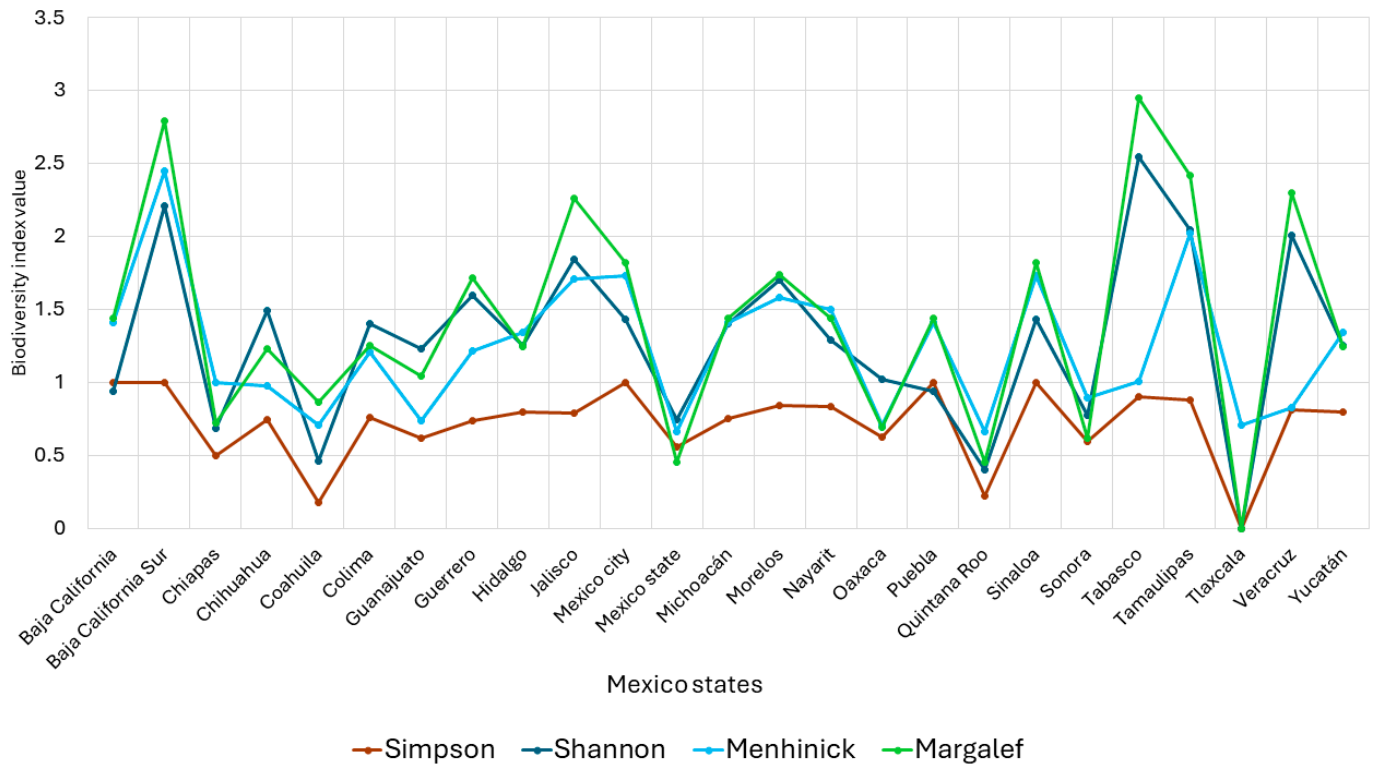


Figure 9. Values of the diversity indices by state calculated using the data obtained from the literature from searching electronic journals.

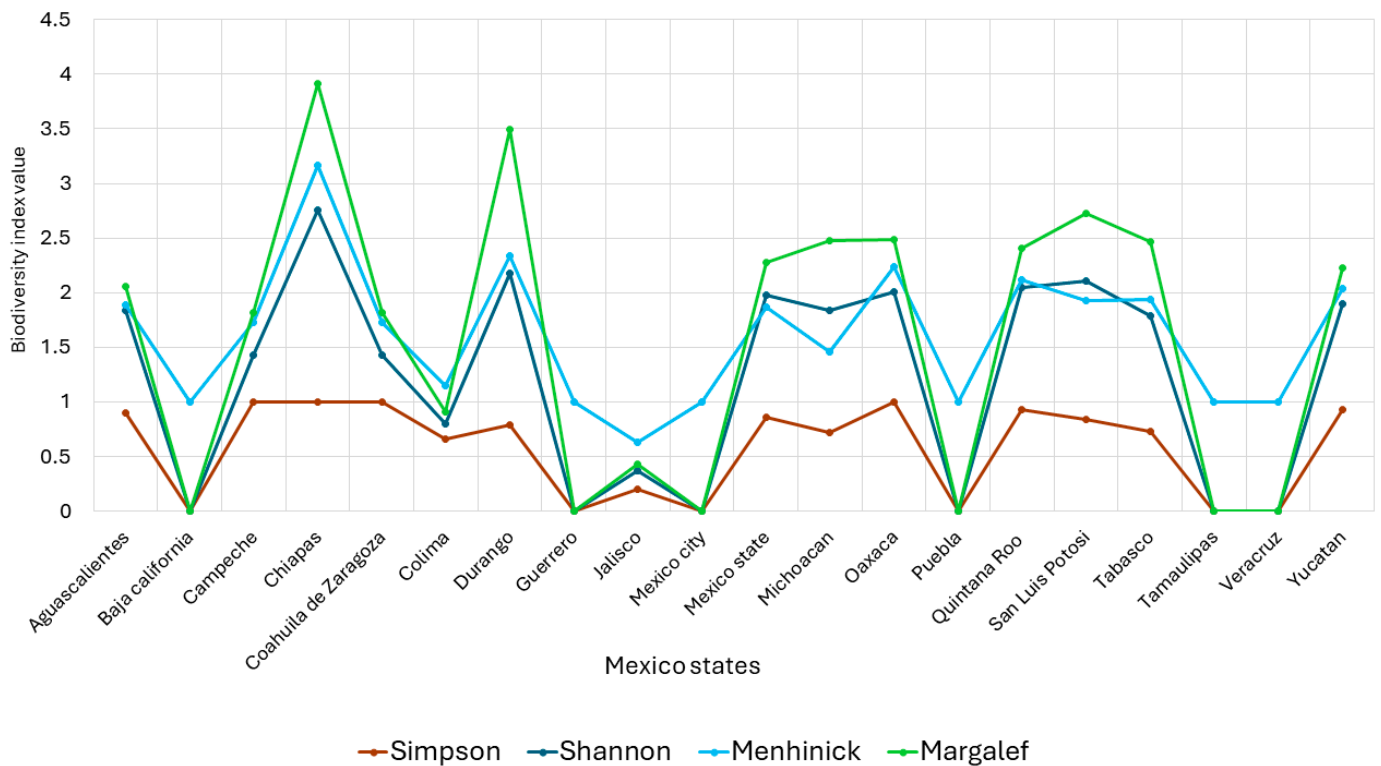


Figure 10. Values of the diversity indices by state calculated using the data extracted from the GBIF platform.

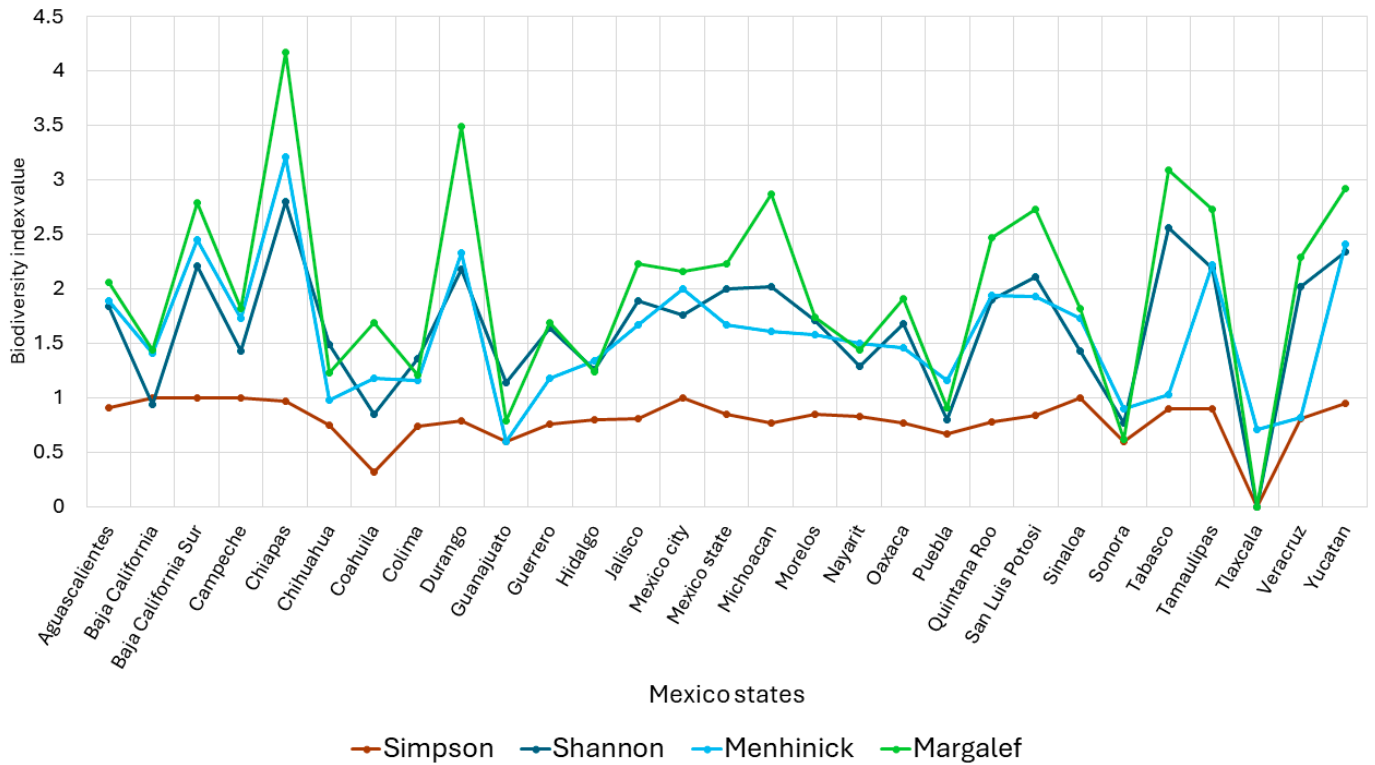


Figure 11. Values of the diversity indices by state calculated using the data obtained from electronic journals (in the systematic review) combined with the data obtained from the GBIF platform.

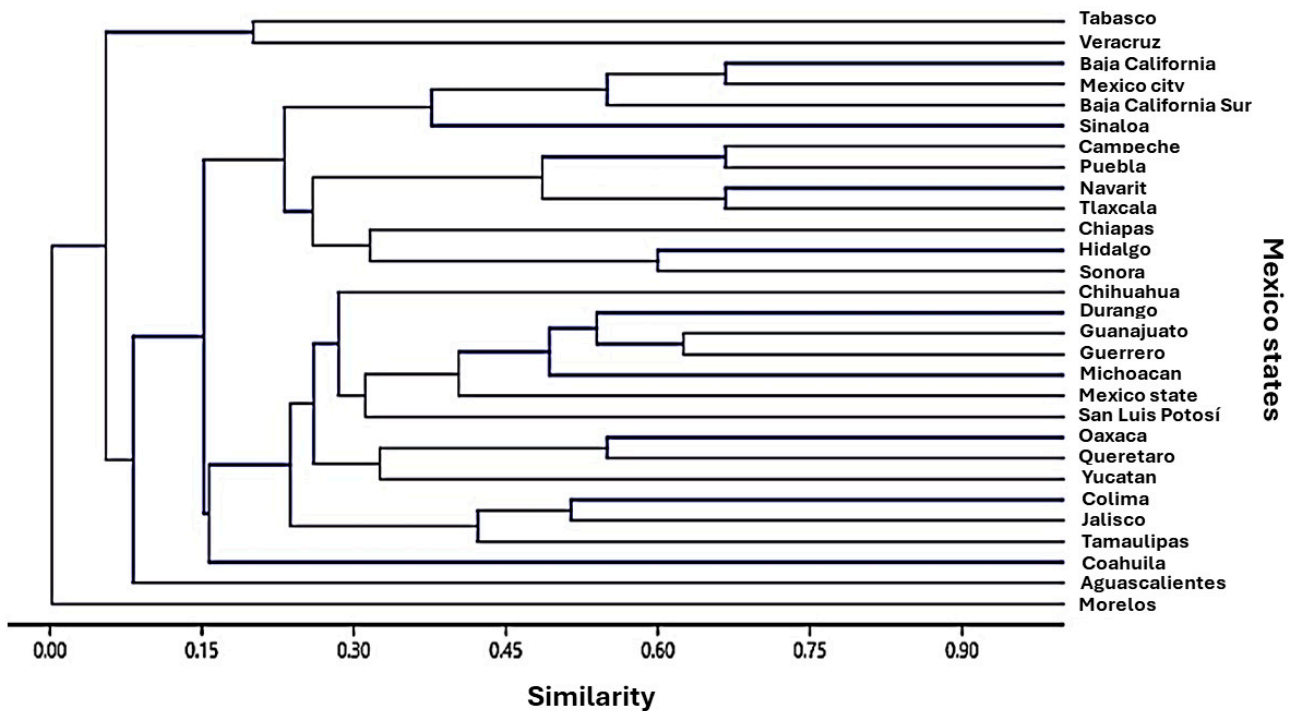


Figure 12. Clusters obtained from the calculation of the Bray–Curtis index between states.

The analysis of crop diversity indices revealed that coffee crops (*Coffea arabica*) exhibited the highest values for the Simpson index (0.80) and the Shannon index (1.95). By contrast, mango crops (*Mangifera indica*) stood as the crops showing the highest Margalef index (2.33), while banana crops (*Musa × paradisiaca*) showed the highest Menhinick index value (1.87) (Figure 13).

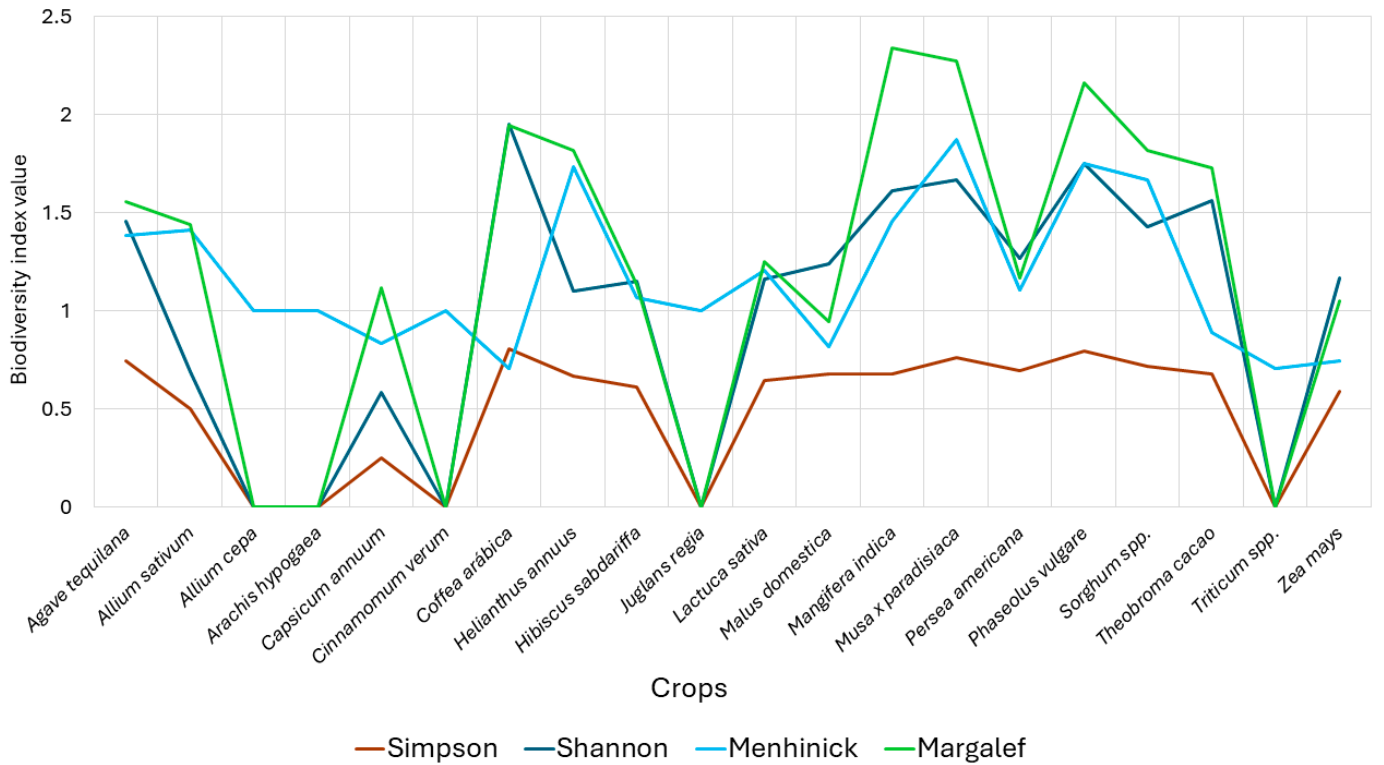


Figure 13. Values of diversity indices for the different crops analyzed in this review.

We also found that the crops of sunflower (*Helianthus annuus*), cinnamon (*Cinnamomum verum*), and chili (*Capsicum annuum*) showed lower similarity compared to the second group comprising other crops (Figure 14).

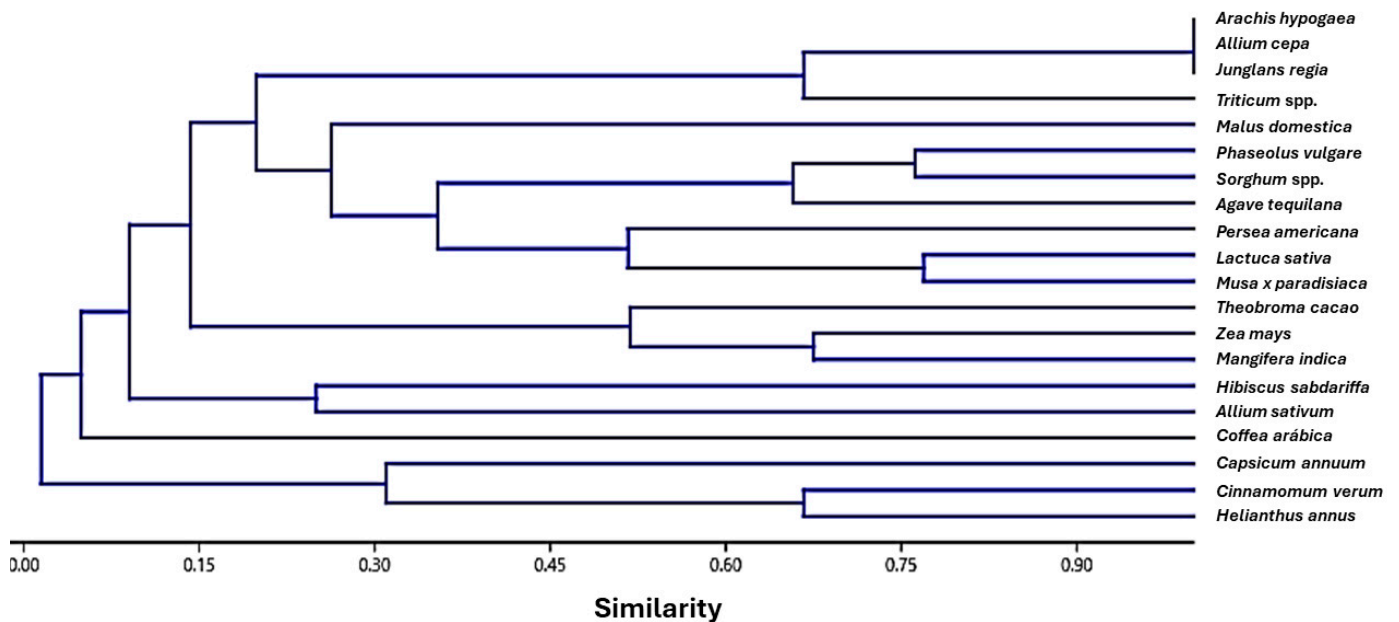
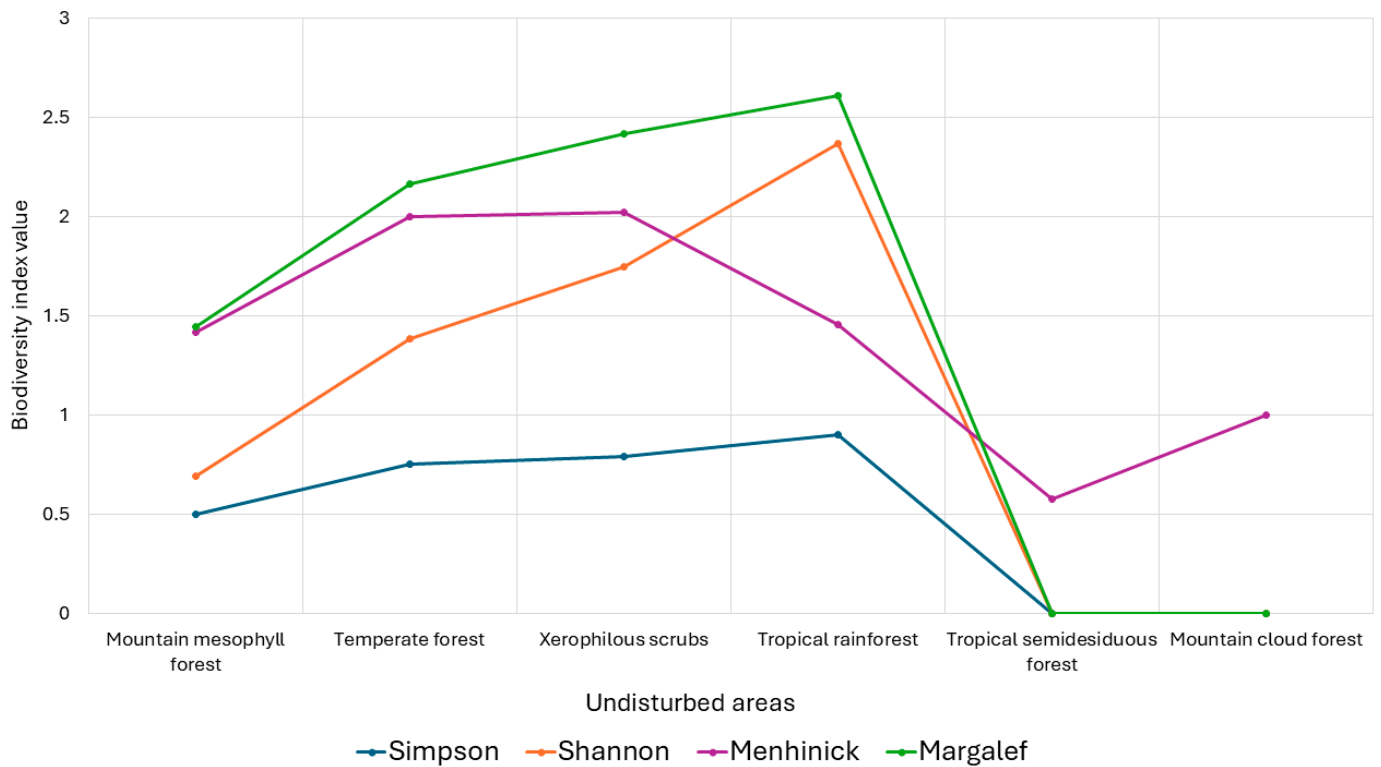


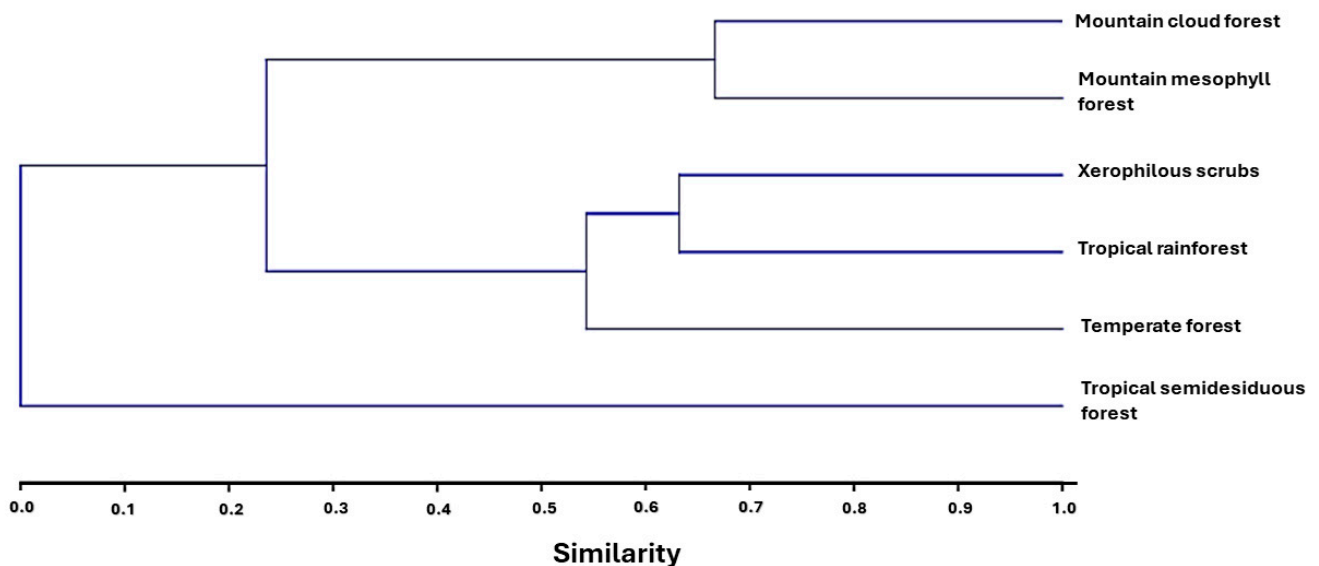
Figure 14. Bray–Curtis clustering for crops calculated using the data obtained in this review.

Regarding the undisturbed areas, the rainforest had the highest diversity values considering the Simpson (0.8979), Shannon (2.366), and Margalef (2.607) indices. Temperate forests and the Xerophilus scrub showed higher diversity values considering the Menhinick index (Figure 15).



**Figure 15.** The diversity indices calculated using the data obtained through this review for undisturbed areas.

The Bray–Curtis analysis identified two distinct groups. The first group, associated with the tropical semideciduous forest, showed no similarities with the second group. In contrast, the second group showed more resemblance among its members (Figure 16).



**Figure 16.** Bray–Curtis clustering calculated using the data obtained from this review for undisturbed areas, calculated using the PAST software package.

#### 4. Discussion

This study represents the first systematic review of aspects of the *Trichoderma* genus in Mexico. The results revealed a significant diversity of species, with 57 species identified in Mexico. Given the global count of 375 species registered [1], this is a noteworthy

contribution, implying that 15.2% of the global *Trichoderma* species diversity is currently registered in Mexico. Therefore, it is essential to continue exploring and sampling to better understand the diversity of the species of *Trichoderma* in this country.

Notably, 22 articles in our review were focused on biological control, underscoring the importance and effectiveness of using native *Trichoderma* species for controlling plant diseases [61]. This trend aligns with other findings from China, where native species have also been used for biological control applications [62].

Further, this work reports a total of 57 *Trichoderma* species in México. This diversity is higher compared to the 75 species reported across 14 European countries [63,64] and the 91 species reported in China [65]. Our findings highlight Mexico's potential as a megadiverse country for *Trichoderma* species. This underscores the importance of continuing research, which could have significant implications for biodiversity studies and practical applications in agriculture and biological control.

The state of Guerrero stands out for its high volume of research articles that address the presence of *Trichoderma*. Intriguingly, this abundance of research does not correlate with the higher diversity or number of isolates reported for the state. However, we report a positive relationship ( $R = 0.76$ ) between species diversity and abundance. This finding suggests that the extent of sampling efforts, which is reflected by the number of isolates collected, is a crucial factor in accurately assessing species diversity in each area. Studies in the literature, such as those by Trapero-Quintana et al. (2011) [66] and Chao et al. (2009) [67], explain the importance of increasing the sampling effort to improve the expected richness that can be reported in an area. The observed diversity of *Trichoderma* species may also be influenced by other variables, such as the season of sampling and its interactions with other organisms in the ecosystem [68]. This indicates the need for additional research on how seasonal variations in crop fields impact *Trichoderma* species populations.

Therefore, our study highlights the importance of comprehensive sampling strategies and acknowledges the influence of environmental factors on *Trichoderma* species diversity. This opens avenues for future research, especially focused on understanding the intricate relationships between *Trichoderma* species, their environment, and other coexisting organisms.

Regarding the presence of this fungus in ecosystems and agroecosystems, 20 crop types were reported with the presence of some species of *Trichoderma*. Species of *Trichoderma* were also reported in six types of ecosystems. The crop with the highest reported diversity indices was coffee (*Coffea arabica*). De Sousa et al. (2022) [69] mentioned that species from the genus *Trichoderma* are part of the microbiome present in coffee soil, and they can promote root growth and play a role in the biological control of disease. Studies such as those of Mulaw et al. (2013) [70] and Alfredo et al. (2021) [71] confirm the potential of *Trichoderma* in the biological control of coffee crop diseases.

In undisturbed soil, the rainforest showed the highest species richness, with 12 reported species of *Trichoderma*. Guzmán (1998) [72] mentions that Mexican fungal diversity is usually higher in tropical and subtropical forests than in cold, temperate, and arid zones. Studies like those of Hoyos-Carvajal et al. (2009) [41] also showed the higher species diversity of *Trichoderma* in tropical areas. Mexico has an extension of 315,868 km of rainforests [73]; thus, there are still unexplored areas that need to be studied. Mexico presents 34 different ecosystems, as reported by [73]. However, in this document, we only analyzed six ecosystems with 12 *Trichoderma* species reported. According to Sharma et al. (2019) [2], fungal species from the genus *Trichoderma* can adapt to various ecosystems due to their ability to effectively take advantage of different substrates. Samuels (1996) [74] confirmed this, emphasizing that *Trichoderma* can be found in diverse environments ranging from the tundra to the tropics.

This research confirmed that *Trichoderma harzianum* is the most abundant species in both agricultural and undisturbed soil in México compared to global studies, such as those by Jiang et al. (2016) [75], with 429 isolates, Kubicek et al. (2003) [3] with 37 isolates and Dou et al. (2019) [62], who reported 1454 isolates. Gupta et al. (2014) [76] mentioned that the higher abundance of *T. harzianum* can be attributed to its remarkable metabolic

diversity. Its adaptability is evident in various substrates across Mexican soil, remarking this fungus's growth capacity. *T. harzianum* also exhibits multiple biotechnological applications such as a fungicide, degrading pesticide molecules, remediating soils contaminated with heavy metals, and producing valuable compounds for the pharmaceutical and industrial sectors. Thus, *T. harzianum* has a significant biotechnological importance. Its potential applications across various sectors of the Mexican economy highlight its value not only in environmental science, but also in economic development [76–78].

The Chiapas state showed the highest Shannon (2.75), Margalef (4.168), and Menhinick (3.207) indices regarding the species diversity among all states. However, it is crucial to consider the context of these findings. In the systematic review, only four species were identified in Chiapas (six isolations) based on a single research article. In contrast, the data obtained from the GBIF platform showed ten species (ten isolates). This discrepancy highlights an important point: if our analysis were limited to research articles alone, Chiapas might have appeared as one of the most diverse states. González-Oreja and Lou (2012) [79] pointed out that we must be cautious when interpreting diversity indices, as making conclusions based solely on these values may not be valid.

Tabasco showed the highest number of species, with 20 species reported, followed by Veracruz, with 14 species reported. Aguirre Acosta et al. (2014) [80] indicated that Veracruz has the highest fungal diversity, followed by Jalisco and Mexico state. Tabasco and Veracruz are states with tropical climates benefiting the presence of fungi due to the conditions of high humidity and temperatures. Lodge (1997) [81] mentions that organic-degrading fungi such as *Trichoderma* are more likely to occur in tropical climates than temperate ones.

*Trichoderma* was present throughout the country, which indicates its cosmopolitan distribution across ecosystems and agroecosystems. However, there remain unsampled areas in Mexican states. There are also a few studies focused on the diversity of *Trichoderma* species. We found six articles carried out in the state of Guerrero; the diversity and number of isolates found in this state may not be considered exceptional. However, the number of articles does not necessarily indicate a higher number of species or isolates. The sampling effort determines the true measure of species diversity based on the number of isolates obtained during the study. To better understand the diversity of species of *Trichoderma* in a particular area, researchers should report the sampling effort in any research paper as a crucial step during this study. This can help to determine whether there are sample-related limitations that contribute to the observed diversity of *Trichoderma* species in a given area.

In this review, we found the same number of species reported by the Global Biodiversity Information Facility (GBIF) and through the data obtained from the systematic review; however, the species reported in the GBIF and the review were not the same. Furthermore, there was a significant difference in the number of isolates, with 207 versus 872, respectively. This highlights the importance of sharing data collected in the field through platforms such as GBIF. A study by Devkota et al. (2023) [27] revealed that research on fungal diversity is scarce, and increasing changes in land use have threatened the diversity of fungal species. Therefore, it is necessary to share knowledge on databases such as GBIF to contribute to the understanding of species diversity in unexplored areas and prevent further biodiversity losses. Dou et al. (2019) [62] also suggested that studying the diversity of *Trichoderma* species can help to better understand their distribution and promote the study of their ecology and evolution.

We found 57 species of *Trichoderma* through data obtained from GBIF and the systematic review of 1078 isolates in Mexico. This comprehensive data set allows us to place the diversity of the Mexican *Trichoderma* species in a global context. For instance, Zhang et al. (2005) [82] reported 13 species from 135 isolates in China; Jaklitsch & Volgmayr (2015) [83] obtained 90 species and 650 isolates from southern Europe and Micronesia; and Ma et al. (2020) [84] reported 23 species from 312 isolates in northern Xinjiang, China. Thus, our results contribute significantly to the collective knowledge of the *Trichoderma* species diversity in the world. Our data provide a comprehensive reference for the diversity of *Trichoderma* species in Mexico, facilitating direct comparisons and analyses with global data.



This synthesis of information in a single document offers valuable insights for researchers studying *Trichoderma* species' biodiversity and evolutionary trends worldwide.

An essential factor in species diversity is their identification through molecular biology. The results of Jaklitsch & Volgmayr (2015) [83] with a significantly higher number of species might be due to the use of 3 molecular markers (*tef1*, *rpb2*, *act1*) since usually only 1 or 2 markers (ITS and *rpb2*) were used for the identification of *Trichoderma* species in the studies cited here.

In the systematic review, 541 isolates, corresponding to 50% of the total isolates, presented molecular identification (28 species). *T. harzianum* was the most abundant of the identified species, with 214 isolates. It should be noted that the data from GBIF do not mention the type of identification used.

We report that *Trichoderma* species occurred in both disturbed and undisturbed areas. In agricultural soil, 643 isolates with 33 species were obtained. *T. harzianum* is the species with the highest abundance, with 148 isolates. This is similar to the data reported by Jiang et al., 2016 [75], where *T. harzianum* was predominant in agricultural soil.

Concerning the number of *Trichoderma* species present per crop, Manzar et al. (2021) [85] obtained 19 isolates of *T. asperellum* and 1 of *T. harzianum* in *Sorghum bicolor* L. crops. In our study, *T. longibrachiatum* was reported as the most abundant species for the *S. bicolor* crop, with positive results for its use in the biological control of diseases [37].

Bechem & Afanga (2018) [86] found *T. harzianum*/*H. lixii* to inhabit endophytically in *Musa* × *paradisiaca*. *M. paradisiaca* is reported to have seven endophytic species in Mexico, with *T. crassum* being the most abundant [21]. Therefore, understanding the effects and functions of *Trichoderma* species that are endophytically associated with crops is necessary, as endophytic species play important roles in the promotion of plant growth.

In the *Juglans regia* crop, *T. harzianum* was the only species reported [20]. Ahmad et al. (2012) [87] reported that *T. harzianum* successfully controlled the *Phymatotrichopsis omnivora* pest in the *J. regia* crop.

In the *Malus domestica* crop, four species of *Trichoderma* were reported, with *T. gamsii* being the most abundant [18]. Wang et al. (2021, 2022) [88,89] reported *T. asperellum* and *T. virens* in China on the same crop. *T. gamsii* had successful results in controlling apple tree rhizosphere diseases in both cases.

Kumar et al. 2012 [90] isolated three *Trichoderma* species, *T. viride*, *T. virens*, and *T. harzianum*, from the *Mangifera indica* L. crop. Interestingly, similar species were reported in México for the same crop [31]. These parallel findings underscore the need for more comprehensive research in Mexico, focusing specifically on *Trichoderma* species and their interactions with various mango species that are cultivated in the country.

Jiang et al. (2016) [75] obtained 15 species from 3 crops (corn, oats, and rice). *T. asperellum* was the most abundant in the corn crop (*Zea mays*), which differs from the patterns found in this study, where *T. harzianum* was the most abundant in the corn crop [16]. More studies focused on the diversity of *Trichoderma* species should be conducted in corn crops, especially because corn is one of the main crops involved in the diet of Mexicans [91].

In the sunflower (*Helianthus annuus*) crop, Kostyuchenko and Lyakh (2018) [92] found that *T. viride* was present at the flowering stage. This review reported *T. asperellum*, *T. hamatum*, and *T. koningiopsis* in this crop [47]. However, it is necessary to conduct research on the functions and interactions of *Trichoderma* species in this crop.

In the onion (*Allium cepa*) crop, Inglis et al. (2020) [93] reported the presence of eight species of *Trichoderma*. In this study, *T. harzianum* was reported in the same crop [13]. However, in Mexico, there are few reports of *Trichoderma* effects in this crop; again, more research should be conducted to fully understand the function and the relationships between *Trichoderma* species and onion crops.

Cocoa (*Theobroma cacao*) is a widely studied crop. Pavon and Rivas (2010) [94] reported a diversity of *Trichoderma* species in Venezuelan crops and obtained an abundance of 46% for *T. harzianum*. In Mexico, *T. harzianum* was reported to have an abundance of 54.9% in

Cocoa crops [95]. Studies on *Trichoderma*'s ability as a biofertilizer or plant growth promoter still need to be conducted in a wide array of crops to assess the efficacy of this fungus.

For the peanut (*Arachis hypogaea*) crop, Ayyandurai et al. (2021) [96] obtained five species of *Trichoderma* in India. This makes this crop more diverse than the Mexican crops analyzed in this work, with the presence of one species, *T. harziaum* [10]. However, *T. harzianum* showed excellent results as a biological control for the pest *Sclerotium rolfsii* Sacc. More studies on the potential of *Trichoderma* remain to be conducted in this crop.

In the chili (*Capsicum annuum*) crop, Nawaz et al. (2018) [97] found nine species of *Trichoderma* compared to the five species reported in this work [14]. Therefore, since chili peppers are part of the Mexican diet, we should better understand more about *Trichoderma*'s interactions with the diversity of chili peppers in Mexico.

Coffee (*Coffea arabica*) was one of the crops with the most remarkable species diversity, with 12 species reported for Mexico. Eight species were found in Ethiopia, with *T. harzianum* and *T. asperellum* being the most abundant [69]. Several studies have been conducted in Mexico on *Trichoderma*'s effects on the biological control of pests, diseases, biofertilization, and plant growth promotion. However, the coffee industry offers other areas where the biological characteristics of *Trichoderma* species can be explored. For instance, Saldaña-Mendoza et al. (2021) [98] pointed out that the *Trichoderma* fungus can be used to degrade coffee pulp residues.

For garlic (*Allium sativum*) crops, the following two *Trichoderma* species were reported in this work: *T. virens* and *T. viride* [8]. Albarado-Marchena and Rivera Méndez (2015) [99] isolated two species, *T. harzianum* and *asperellum*, in the same crops in Costa Rica. These findings emphasize the importance of *Trichoderma* species as part of the microbiota that comprise the rhizosphere of *garlic*. However, information about *Allium sativum* and its interactions with the fungi of the *Trichoderma* genus is scarce in Mexico.

In this study, we found four species of *Trichoderma* in avocado (*Persea americana*) crops, with *T. harzianum* being the most abundant [7,50]. Hermosa et al. (2004) [100] reported four species for crops in Spain. In Mexico, however, more studies focused on the diversity of native *Trichoderma* species are needed. We urge researchers to conduct studies that delve into the diversity of native *Trichoderma* species in Mexico in a wide array of crops for a better understanding of the ecology of both the native and non-native species of *Trichoderma*.

Kashyap et al. (2017) [101] emphasized that the study of the roles of *Trichoderma* species in agriculture is vital since it can be an ally for the study of climate change. Thus, understanding the diversity of species present in agricultural soils opens the possibility of facing climate change using microorganisms such as the *Trichoderma* fungus.

We found reports of 16 species of *Trichoderma* in undisturbed soil with *T. harzianum* being the most predominant species. This result is compatible with studies such as those of Zhang et al. (2005) [82] and Dou et al. (2019) [62], who mention that this is the species with the most significant distribution in their studies.

The mountain cloud forest is one of the most diverse ecosystems in the world [102]. However, only *Trichoderma ceraceum* was reported in this ecosystem, according to our review [103]. Velez et al. (2021) [104] identified six morphotypes of *Trichoderma* in Mexican mountain cloud forests, but they did not identify these strains at the species level.

The xerophytic scrub and grassland ecosystems, characterized by high temperatures and soil of low organic matter, pose significant challenges for the growth of *Trichoderma* species. Despite these harsh conditions, studies like those conducted by Savin-Molina et al. (2021) [105] report the presence of *Trichoderma* species and how its abundance increases after the rainy season. The data obtained in this review showed a total of seven species in this ecosystem. Thus, species of *Trichoderma* adapted to arid zones can be helpful in fulfilling the needs of crops in desert ecosystems [47].

In the case of temperate forests, Blaszczyk et al. (2016) [106] obtained 12 species, with *T. viride* being the most predominant species. An analysis of the distribution of *Trichoderma* species showed that the following species inhabit temperate forests in Mexico: *T. alutaceum*,

*T. ghanense*, *T. harzianum*, and *T. viride*, with *T. harzianum* and *T. viride* being the only species that are similar to the results of temperate forests already indicated [33,39,46].

## 5. Conclusions

In this study, *Trichoderma harzianum* appeared as the predominant species within the *Trichoderma* genus in Mexico. This study emphasizes the distribution of *T. harzianum* in 20 crops and four ecosystems.

A significant challenge in accurately assessing the diversity of *Trichoderma* species in Mexico stems from a combination of factors. For instance, there is a noticeable scarcity of dedicated research entities in Mexico focused on the study of the ecology of *Trichoderma* species. Additionally, the lack of diverse techniques for molecular identification employing various molecular markers complicates the accurate classification and understanding of the ecology and evolutions of the species that comprise this genus. Furthermore, the absence of a standardized methodology for sampling and data collection complicates cross-comparisons between studies, which are useful to infer ecological processes within the genus. All these factors hinder the development of a comprehensive and reliable database, which is crucial for the in-depth biodiversity studies of *Trichoderma* species in Mexico.

Computational tools are invaluable in advancing our understanding of the ecology and evolution of *Trichoderma* species nationally and globally. To achieve this, platforms such as GBIF play key roles. However, these tools exhibit certain limitations. One significant shortcoming is their inability to fully capture the specific characteristics of the study areas, which is crucial for comprehensive biodiversity assessments. Furthermore, the data currently available in these platforms often present errors or are incomplete, impacting the reliability of research results. To address these challenges, developing and implementing a specialized and standardized methodology to accurately manage, curate, and share data on microorganisms such as *Trichoderma* species on these platforms is imperative.

It is vital to accompany the results of diversity analysis with the results of soil analysis and microclimatic characteristics in the sampling area. This could give us a more integrative view of the ecological requirements of different species of *Trichoderma*. As a result, this could enhance our understanding of the ecology and evolution of species that comprise this genus and allow us to take better advantage of the benefits of the species that comprise this genus.

By addressing methodological and data challenges, future research can significantly advance our understanding of the ecological and evolutionary aspects of *Trichoderma* species in Mexico, contributing valuable insights to global biodiversity studies.

This study significantly broadens our understanding of the diverse species of the fungus of the genus *Trichoderma*, particularly in regions with economically important crops. These findings underscore the crucial role of *Trichoderma* as a biological control agent, offering insights into its various associated properties, which include its ability to induce defense responses during plant interactions and its potential as a biofertilizer in agricultural crops.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/d16010068/s1>, Table S1: Systematic Review table; Table S2: GBIF table.

**Author Contributions:** Conceptualization, H.O.A.-Q., T.A.-B. and E.G.-S.; data collection and formal analysis, H.O.A.-Q. and E.G.-S.; methodology PRISMA E.G.-S.; writing—original H.O.A.-Q. and E.G.-S.; writing—review and editing, H.O.A.-Q., T.A.-B., E.G.-S. and Y.D.O.-H. All authors have read and agreed to the published version of the manuscript.

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