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Review

A Bibliometric Analysis of the Global Research in Odonata: Trends and Gaps

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Abstract: Insects of the order Odonata have been used as indicators of environmental quality in different aquatic systems around the world. In this context, we conducted a bibliometric analysis to understand the general patterns of research on Odonata published in the past decade (2012–2021). We extracted literature from the Web of Science (WoS) in the advanced search option and used search terms related to Odonata plus search strings for each term. A total of 2764 Odonata publications were identified. The journals with the most published articles on Odonata were *Zootaxa*, *International Journal of Odonatology* and *Odonatologica*. The countries with the most Odonata publications were the USA, Brazil and China. Most studies were conducted on streams, ponds and rivers. Ecology, taxonomy and behavior were the main study topics. Of the total articles on Odonata, 982 involved Zygoptera and 946 Anisoptera. Another 756 studies were focused on both suborders. The increase in ecological and taxonomic studies of Odonata reflects the dynamic characteristics of this order, and its relatively well-defined systematics, especially in the case of adults. Despite the recent increase in the number of publications, there are still many gaps related to topics such as biogeography, parasitism, competition within and between species, evolutionary and phylogenetic relationships, as well as studies of the eggs (e.g., their development) and larval exuviae (e.g., their morphological features).

Keywords: Anisoptera; Zygoptera; dragonflies; damselflies; tendencies and shortfalls; global research; scientific production

1. Introduction

Aquatic insects have been employed as indicators of environmental quality in various types of freshwater systems worldwide [1]. Among the aquatic insect orders, Odonata (dragonflies and damselflies—see Supplementary Material Figure S1) have stood out because of their high habitat specificity and well-resolved taxonomy [2–4]. Furthermore, compared to aquatic macroinvertebrates, the use of Odonata adults for biomonitoring has several advantages. For instance, most species can be recognized quickly and captured in the field; they are distributed in a wide range of habitats, are sensitive to changes in water quality and ecological conditions of the surrounding environment, and the species assembly is typically large enough for assessments, especially in the tropics [5,6]. In addition, there are some Odonata species with antagonistic interactions, allowing the development of environmental quality indices [7,8].

Equally important, dragonflies arouse both cultural and academic interest [9]. The charisma of these animals, their grand flight maneuvers and vibrant colors attract the attention of many people, which explains the increasing number of partnership networks between researchers and dragonfly lovers [10–12], as well as citizen science programs [13–15]. Furthermore, because of their rich evolutionary history [16,17] and their ecological [18] and taxonomic particularities [3,4], dragonflies have been the focus of numerous investigations.

Currently, around 6376 species of odonates are known worldwide, with estimations suggesting that between 1000 and 1500 species have yet to be discovered [19,20]. Except for Antarctica, dragonflies are distributed on all continents, with the greatest diversity found in the Tropics (Paleotropics and Neotropics) [19]. Throughout their distribution range, it is possible to find them associated with different lentic (ponds, swamps, marshes, pools, wells) or lotic (rivers, streams, waterfalls, springs) water bodies, where they perform their development, hunting and breeding activities [2].

Odonates have an amphibious life cycle, meaning that part of their life is spent in the water as larvae and the other part is spent in the environment adjacent to the water bodies, as flying adults [2]. Both life stages have unique characteristics, causing them to respond differently to environmental changes. For example, Odonata larvae are more sensitive to changes in water's physical and chemical characteristics [21], whereas adults are more sensitive to changes in riparian vegetation [22]. Therefore, Odonata are widely used as indicators of environmental quality. They respond very well to changes in ecosystems, which can be evaluated using different methods such as: surrogates; taxa/species richness; species composition and the ratio between the suborders based on adult studies conducted at certain localities [23–26]; the developmental stage [21,27]; multimeric indices [28,29]; fluctuating asymmetry [30]; behavioral diversity [31]; ethodiversity [32]; phylogenetic diversity [33,34]; morphology [25,34] or the taxonomic level used (for establishing cost-benefit monitoring programs), see [27,35].

There has been an increase in odonate research globally since the beginning of the century, with an increase of 76.27% in publications between 2000 and 2013 [36]. The main Odonata research focus has been ecology, followed by taxonomy, morphology, phylogeny, and biomonitoring [36]. Despite the increase in published studies, most research is published in peer-reviewed journals with restricted and difficult access to their content (i.e., without open access) [37,38].

Therefore, we used a bibliometric analysis to understand the general patterns of Odonata research published between 2012 and 2021. Bibliometric analysis is a popular and rigorous method for exploring and analyzing large volumes of scientific data [39]. Specifically, we assessed nine questions: (i) what was the year and (ii) which were the journals were the articles were published; (iii) in which countries did the studies occur; (iv) in which habitats where the studies conducted; (v) what was the research focus; (vi) which suborders were studied; (vii) which life stage was studied; (viii) what was the taxonomic resolution, and (ix) which were the most commonly used keywords? This type of analysis provides information that enables clarification of the context of Odonata research and serves as a basis for directing future research efforts towards areas that need it most.

2. Materials and Methods

2.1. Database Search Using Keywords

We used a systematic method to identify, analyze, and summarize studies published on Odonata from 2012 to 2021 in the Web of Science (WoS) database (main collection—

https://www.webofscience.com/ accessed on 3 March 2022). WoS is one of the world's leading citation databases, and an increasing number of articles have used (or at least mentioned) this database for academic research [40].

We extracted the literature by using the WoS advanced search option and Odonata related keywords with synonyms or terms with related meaning, and search strings for each term. The search strings for the terms were connected by the boolean OR operator, using the search type "Topical" type in the WoS. The studies were compiled using the following keywords: odonat* OR dragonfl* OR damselfl* OR anisopter* OR zygopter* OR anisozygopter* (Figure 1). The search was carried out on 3 March 2022.

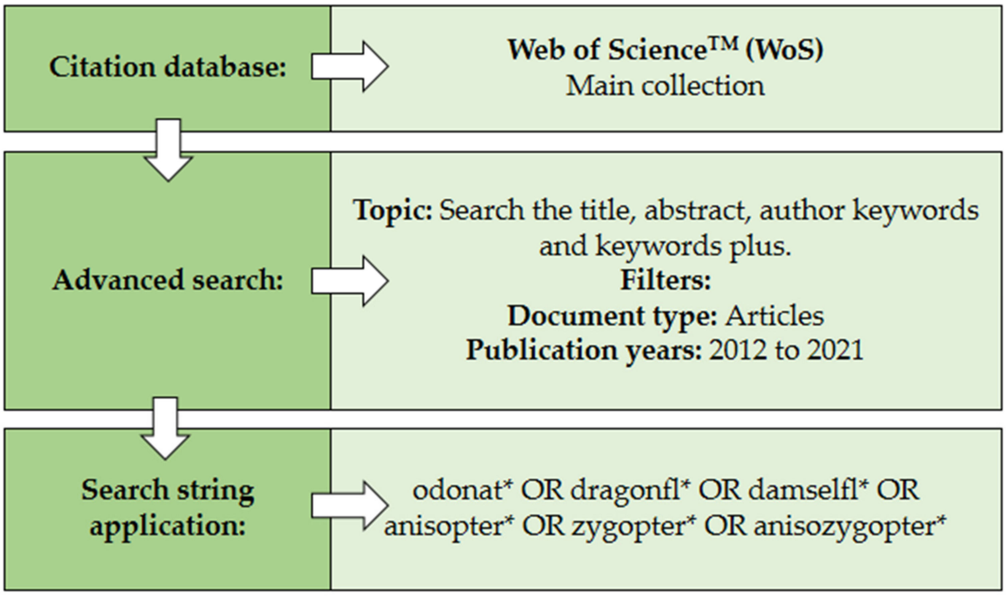

Figure 1. Methodology overview, with search terms and search strings (boolean operator) used to obtain global research on Odonata, available from the Web of Science database (2012–2021).

2.2. Criteria to Include or Exclude Studies

We created a spreadsheet that included the results from the WoS database. We then downloaded all the studies in the spreadsheet with institutional support from the Federal University of Western Pará (Ufopa) via the Federated Academic Community (CAFe). We thoroughly analyzed the title, abstract, keywords, materials and methods, and results of selected studies, looking for approaches that included Odonata. Only documents containing the following three scopes were considered: (1) studies focused on Odonata, regardless of the life stage or study subject; (2) articles (excluding literature reviews, books or book chapters); (3) papers published between 2012 and 2021 (both years included). The study selection was carried out and revised by all authors to ensure the correct exclusion and inclusion.

Subsequently, from each document we extracted the following information: (i) year of publication; (ii) publishing journal; (iii) continent and country where the study was conducted; (iv) habitat where the study was conducted; (v) research focus; (vi) the target Odonata suborder/s; (vii) life stage studied; (viii) taxonomic resolution; and (ix) article keywords.

Information on taxonomic resolution, level of organization, type of study and analyzed life stages were classified as follows [36]:

Taxonomic resolution: (a) species; (b) genus; (c) family; or (d) order.

Type of study: (a) ecological—studies involving theoretical approaches, modeling, macroecology or intra/interspecific relationships; (b) taxonomic—studies that described or redescribed species, identification keys or inventories; (c) phylogenetic—studies emphasizing relationships among taxa; (d) morphometric—studies that emphasized the description of bodily structures in larvae or adults; (e) teaching—studies focused on teaching activities (e.g., games). Any paper incorporating two or more of these approaches was counted separately for each type of study.

Life stage: (a) egg; (b) larva; (c) exuvia; or (d) adult.

2.3. Countries Where the Studies Were Conducted

For experiments carried out in laboratories, we defined the studies host country as the country where the laboratory was located. For field research in the natural environment, the place where the study was conducted was identified as the host country. To assess this, we checked the "Methods" section of each article for information on where the work was developed.

2.4. Data Analysis

To assess our nine (i–ix) objective questions, we checked the information extracted from the articles in the database. We express the following data through histograms: (i) temporal trend (year); (ii) journal of publications; (iii) number of publications by country; (iv) habitat type studied; (v) research focus; (vi) suborder; (vii) life stage; and (viii) taxonomic resolution. Finally, we performed a keyword cloud analysis of the articles (ix), using the online program ShapeWordle (https://www.shapewordle.com/ accessed on 2 July 2022) [41]. We created a cloud, where each word is sized according to its number of occurrences, in which the program assigns a weight from 0 to 1 (from lowest to highest occurrence). A maximum word limit of 50 was set. For each continent, we selected the five countries with the highest number of articles, and then plotted in a bar graph the three research focuses with the highest number of articles.

3. Results and Discussion

We found a total of 4121 published studies in the Web of Science database (step 1). We removed 1357 studies that did not comply with any of the categories we defined: not dealing with Odonata; and not being an article (e.g., books, book chapter) (step 2). The 2764 remaining papers were used for further analyses (step 3) (Figure 2).

3.1. Temporal Trend (Year), Journal Publications and Keywords Cloud

The lowest number of published articles occurred in 2014 (n = 244; 8.83%); however, after 2014 there was an increase in the number of publications, with 2019 being the year with the highest number (n = 302; 10.93%) (Figure 3). The journal with the highest number of published articles on Odonata was *Zootaxa*, with a total of 284 publications (10.27%), followed by the *International Journal of Odonatology* (226 publications; 8.18%), and *Odonatologica* (202 publications; 7.31%). Other important journals (an additional 497 journals) included fewer than 56 articles each (Figure 4, Table S1). The five most prominent words highlighted in the keywords cloud were 'Odonata' (weight = 1.00), 'dragonfly' (weight = 0.95), 'damselfly' (weight = 0.56), 'species' (weight = 0.53) and 'Zygoptera' (weight = 0.38) (Figure 5, Table S2).

There was an increase in the number of publications and the frequencies and trends changed over the time analyzed in this study. Although there are years with low production during the period analyzed, the trend towards an increase in the number of studies on dragonflies is maintained when compared with previous analyses [36] but reaches a plateau after 2017. This growth is about 36% in relation to the immediately preceding decade, when a 76% growth was recorded [36]. This interpretation must be taken with caution because during the period analyzed in this study, ~1000 more articles were produced than in the previous decade.

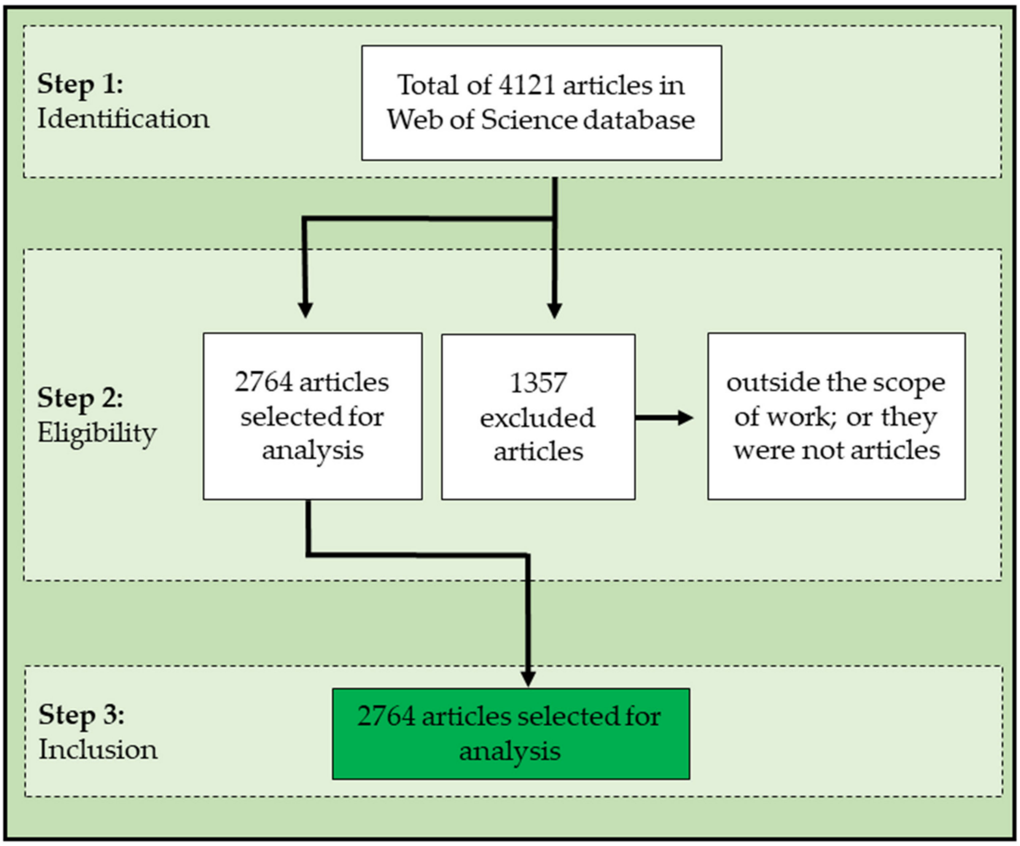

Figure 2. Flowchart of the steps used to extract the final number of articles about Odonata from the Web of Science database, from 2012 to 2021.

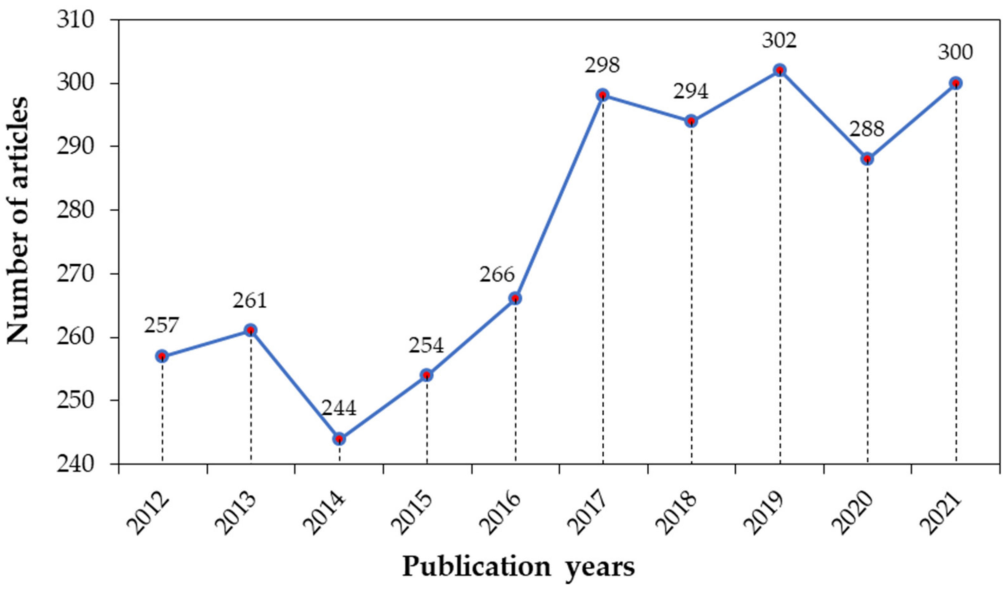

Figure 3. Scientific articles on Odonata available from the Web of Science database, per year of publication (2012–2021).

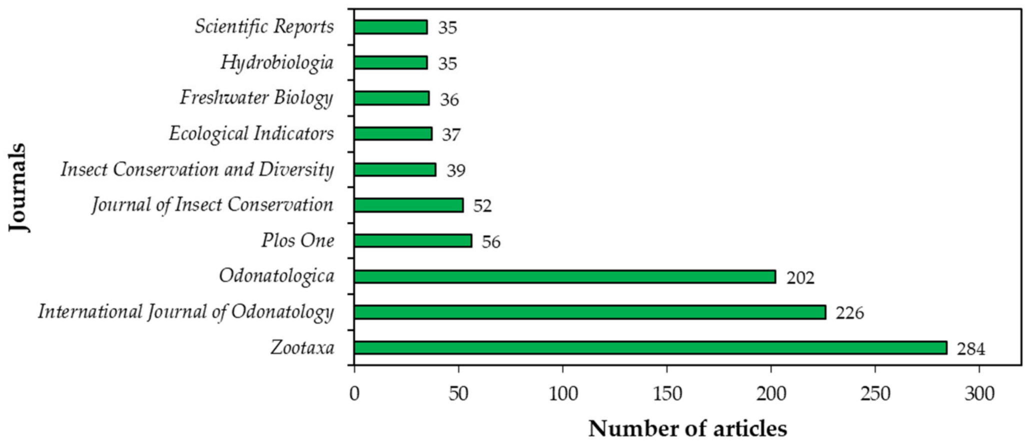

Figure 4. Scientific articles on Odonata available from the Web of Science database, per journal of publication. Plotted are the ten journals with the highest number of publications between 2012 and 2021.

Figure 5. Keywords Cloud of scientific articles on Odonata, available from the Web of Science database (2012–2021). The five most frequent keywords are highlighted in green.

Zootaxa, *International Journal of Odonatology* and *Odonatologica*, are the journals with the highest number of papers published on Odonata. All are international, specialized, and peer-reviewed journals, but there are differences between them, which can be used to better interpret the results. *Zootaxa* is a broad scope journal, with a preference for papers in zoology (any animal taxa), mainly focused on the systematic review of groups and/or description of new taxa, in a fast, high-quality format. Its wide scope, frequency of publication, and review system have allowed this journal to have a positive impact on the advancement of knowledge of many groups, including Odonata [42]. On the other hand, it was expected that the *International Journal of Odonatology* and *Odonatologica*, specialized journals in Odonatology, would also have many publications. Both accept any type of research related to dragonflies, so their spectrum includes broader fields of research such as ecology, conservation, ethology, and reproduction.

However, other journals publishing a broader range of papers also showed increases, suggesting diverse and continued growth in Odonata research. Moreover, these journals cover a broad spectrum of research topics ranging from experimental to applied sciences. This is partly due to the numerous advances in knowledge about this insect group, indicating that dragonflies are an important model organism for research in ecology and evolution [6,18,23,43,44]. Equally important is the organization of researchers in professional societies, such as the Dragonfly Society of the Americas (https://www.dragonflysocietyamericas.org/ accessed on 4 July 2022), Sociedad de Odonatologia Latinoamericana (https://www.odonatasol.org/ accessed on 4 July 2022) and the Worldwide Dragonfly Association (https://worlddragonfly.org/ accessed on 4 July 2022), which facilitate greater interaction and academic partnerships, especially amongst young odonatologists.

The most prominent keywords reflect the context in which the research was conducted [45]. Thus, it makes sense that our findings of the most frequent keywords in the articles were Odonata, dragonfly, damselfly, species, and Zygoptera. We expected that the most frequent word would be Odonata. However, dragonfly is the common and most widespread name for odonates globally [9]. Finally, the keywords indicate that the species level was the most commonly used taxonomic resolution in the articles, and that Zygoptera was the most studied suborder, presumably because of their generally greater sensitivity to disturbance and subsequent use in ecological impact studies.

3.2. Spatial Trend of Publications (Across Countries)

The ten countries with the most publications were the USA (n = 346), Brazil (n = 272), China (n = 204), Germany (n = 135), Japan (n = 132), Canada (n = 122), Sweden (n = 121), France (n = 110), Mexico (n = 103) and India (n = 83) (Figure 6). Several other countries had >10 publications (Figure 6; Table S3), indicating the global interest on the Odonata as a target organism for research.

Regarding the countries with the largest number of publications, for the American continents, the USA (first place) and Brazil (second place) remain the countries with the largest number of publications. This reaffirms the importance of the work developed by these two countries, which have a broad tradition of research contributing considerably to the knowledge of Neotropical dragonflies [36]. The case is similar in the African context, where the countries that maintain the highest number of publications are South Africa and Algeria, places where leading odonatologists have been established for many years. Likewise in Europe and Asia, the greater number of publications are in countries with a long history and tradition of Odonata research such as Germany in Europe, or China and Japan in Asia [36].

3.3. Research Focus

Most studies focused on Odonata ecology (n = 717), followed by studies on taxonomy (n = 584), behavior (n = 576), morphology (n = 343) and ecological monitoring (n = 207) (Figure 7; Table S4).

The studies show a great diversity of research areas in which dragonflies have been used as research targets. However, it was expected that the largest number of publications would be focused on ecology and biodiversity studies, because many journals publish articles on Odonata that are not specific to taxonomy or phylogeny. Miguel et al. [36] found the same trend worldwide. Moreover, areas such as ecology and behavior are constantly growing, so periodically new metrics, approaches and methodologies are published, generating interest to replicate them in different parts of the world [46,47]. Ecology is the main research focus on the American and African continents. In Asia and Oceania, taxonomy is the main type of study, while in Europe, behavior studies stand out (Figure 8; Table S5).

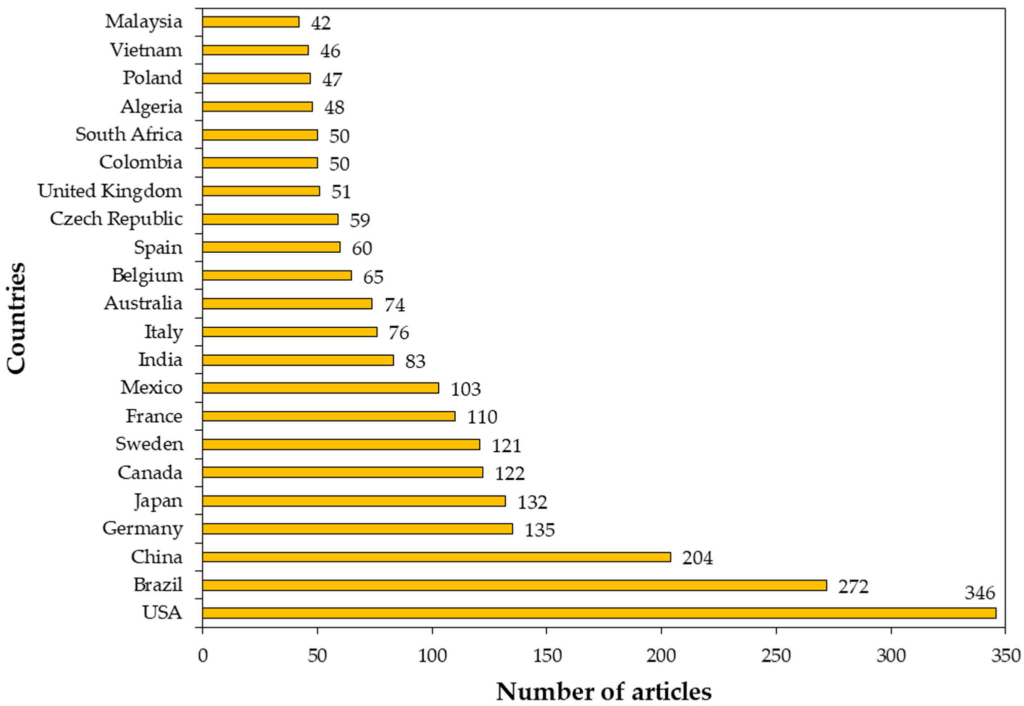

Figure 6. Global production of scientific articles on Odonata, available from the Web of Science database (2012 to 2021). The figure shows only those countries with >40 publications each.

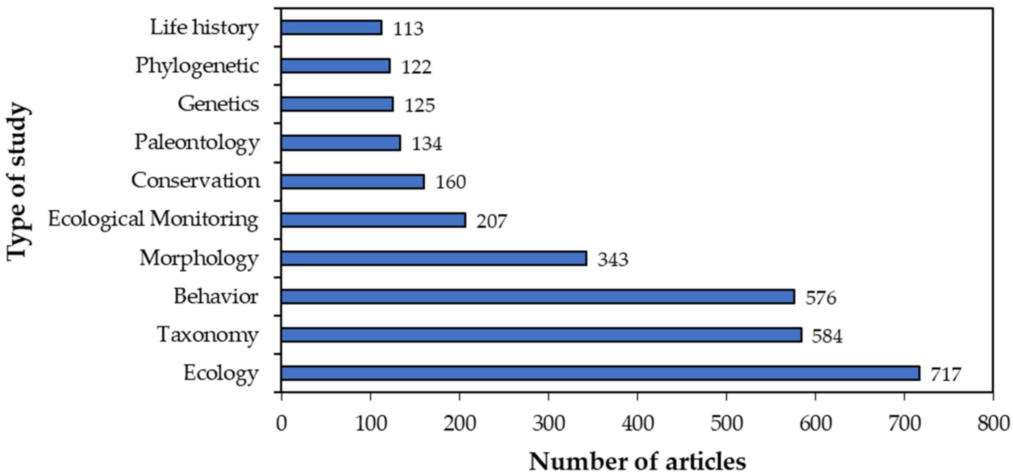

Figure 7. Research focus (top 10) to the scientific articles published on Odonata, available from the Web of Science database (2012–2021).

Although studies in genetics have increased, there are disadvantages in their replicability, especially in developing countries, because of both financial and equipment limitations [36]. Finally, topics of decreasing scientific interest and funding are associated with fewer publications (e.g., natural history and basic species biology).

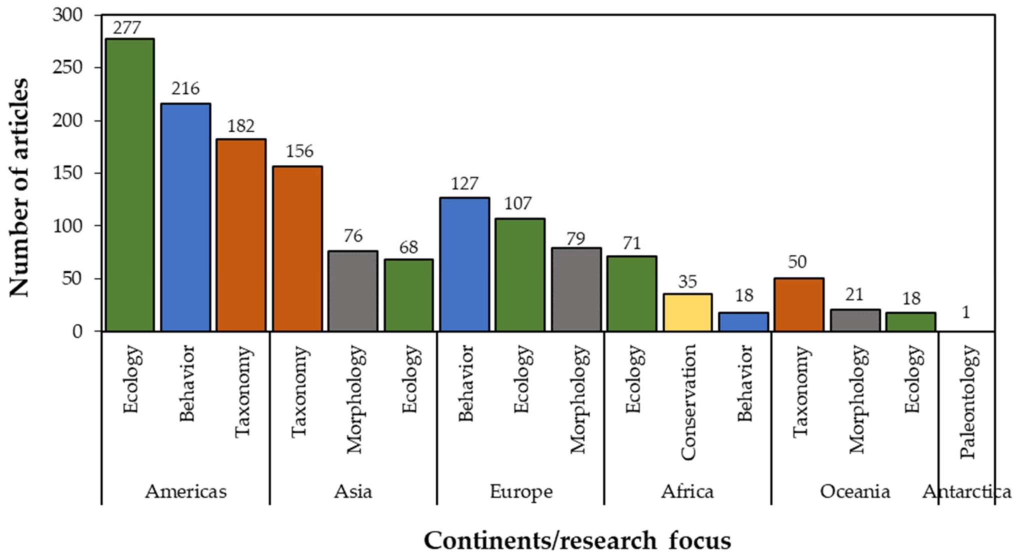

Figure 8. The top three study topics, by continent, in the scientific articles published on Odonata, available from the Web of Science database (2012–2021).

The focus of research on each continent is varied and likely related to who lives where. For example, the fact that the Americas contain the largest number of researchers in ecology, behavior and taxonomy is directly related to the establishment and growth of different research groups, mainly in Argentina, Brazil, Colombia, the United States, and Mexico (e.g., Dragonfly Society of the Americas and Sociedad de Odonatologia Latinoamericana) [36,48–51]. Asia and Oceania each show the same research patterns, mainly taxonomy, morphology, and ecology. In all three continents, there is a history of taxonomic studies which is maintained today. In Europe, the main research focus is behavior, ecology, and morphology. European odonate biodiversity has been well known for a century, and only after more than 100 years was a new species described there [52]. Africa is the only continent where the main lines of research are also focused on conservation. This is certainly related to the studies developed by several research groups that are focused on conservation, especially in South Africa, such as the research group led by Michael J. Samways and John P. Simaika. M.J. Samways has published extensively on various aspects of Odonata ecology and conservation [53], especially regarding landscape ecology and insect conservation in general [54]. J.P. Simaika has more than a decade of experience working in rivers, lakes, wetlands and artificial ponds in Africa. Their research has led of public conservation policies at the international level [54].

3.4. Study Habitat Types

The highest number of published articles on Odonata were conducted in the field (Figure 9), i.e., in streams (n = 668), ponds (n = 437), rivers (n = 318), and lakes (n = 278), but many were also part of laboratory experiments (n = 364) or involved fossilized material (n = 125) (Figure 9). Markedly fewer studies have been conducted in pools (n = 42), reservoirs (n = 20), mesocosms (n = 10), and plants (n = 3) (Figure 9; Table S6).

Because of the strong relationship between dragonflies and aquatic environments, it is reasonable that research on Odonata focused on some of these environments. Most of the research has been conducted in lotic environments, such as rivers and streams, systems that are under constant anthropogenic threats [55]. The type of impact, as well as the degree of intensity, affects the complex dynamics of functioning and interconnection in this habitat, generating serious effects on their health as well as on the biodiversity that inhabits them [56]. Because of this, numerous environmental laws across the world stress the evaluation and monitoring of lotic bodies as a priority [1,57].

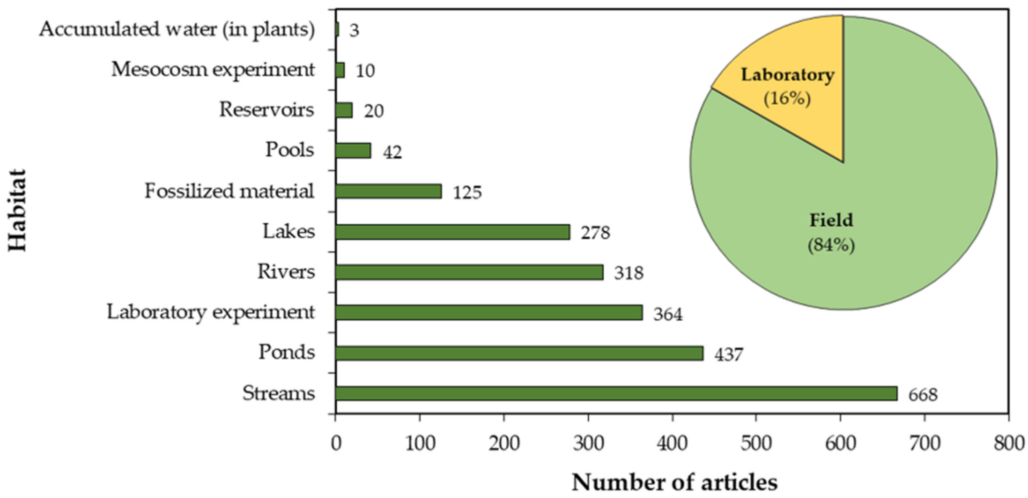

Figure 9. Top 10 habitat types for scientific articles on Odonata, available from the Web of Science database (2012–2021).

3.5. Suborder, Life Stage and Taxonomic Resolution Most Used in Studies

Of the total articles on Odonata, 982 involved the Zygoptera, 946 Anisoptera and 15 the Anisozygoptera. Another 756 studies were focused on both main suborders, i.e., Anisoptera and Zygoptera (Figure 10a). Most studies (n = 1662) were focused only on adults, 714 only on the nymphs, 160 on adults and nymphs, and 40 on nymphs and eggs. It is noteworthy that several articles focused on more than one life stage (Figure 10b). Most articles (n = 2381) used species-level taxonomy (Figure 11).

Most studies focused on Odonata, including the suborders Anisoptera and Zygoptera in their analyses. Numerous studies included both suborders to compare the responses among their species [23,44]. When a single suborder was analyzed, the Zygoptera and Anisoptera were used with similar frequencies. Thus, there was no clear pattern or preference for a specific suborder. One reason for this tendency is the well resolved taxonomy in both suborders [43], because a resolved taxonomy is the basis for asking different questions in areas such as evolution, systematics, or ecology.

Adults or larvae were the stages most commonly used in research. Presumably, this is because adult Odonata are visible in the field, their collection requires only an insect net, excellent taxonomic keys for most species are available and easily accessible, and the adults can be identified to the species level [3,4,9]. This is partially true for larvae, the second stage with the most publications, particularly in regions with a long tradition in larval dragonfly research [58]. On the other hand, in regions where this tradition is more recent, there are fewer larval studies [36]. Furthermore, only the larvae of 1/3 of the Odonata species are described [59] and larvae detection and transportation from the field to the laboratory is more complex [36]. Research studies on both adults and larvae are numerous, which is especially useful when one may want to compare responses between the two phases to provide a more comprehensive analysis [27]. There has also been research on three or more phases (Figure 10), presumably when one wants to evaluate ontogenetic development, for which the collection of eggs and the development of larvae are needed [60]. This also applies in the case of larvae and exuviae and larvae and adults, where the association of the different stages is important for taxonomic description [61].

Despite not being an official life stage, research on exuviae shows great potential for tracing the route of environmental contaminants [62] or for adults that are difficult to find or capture [63]. Exuviae also provide proof of life cycle completion at particular habitats [62]. However, exuvia research requires investing much field time, considerable care in transportation and storage of such fragile specimens, and identification problems similar to those with larvae. Incidentally, the results reinforce the evidence that shows how different life stages in Odonata are useful for evaluating different research questions. Finally, it is not surprising that fossil studies are numerous in Odonata because there are many odonate fossil records, which provide the basis for studies of evolutionary relationships within the order [64].

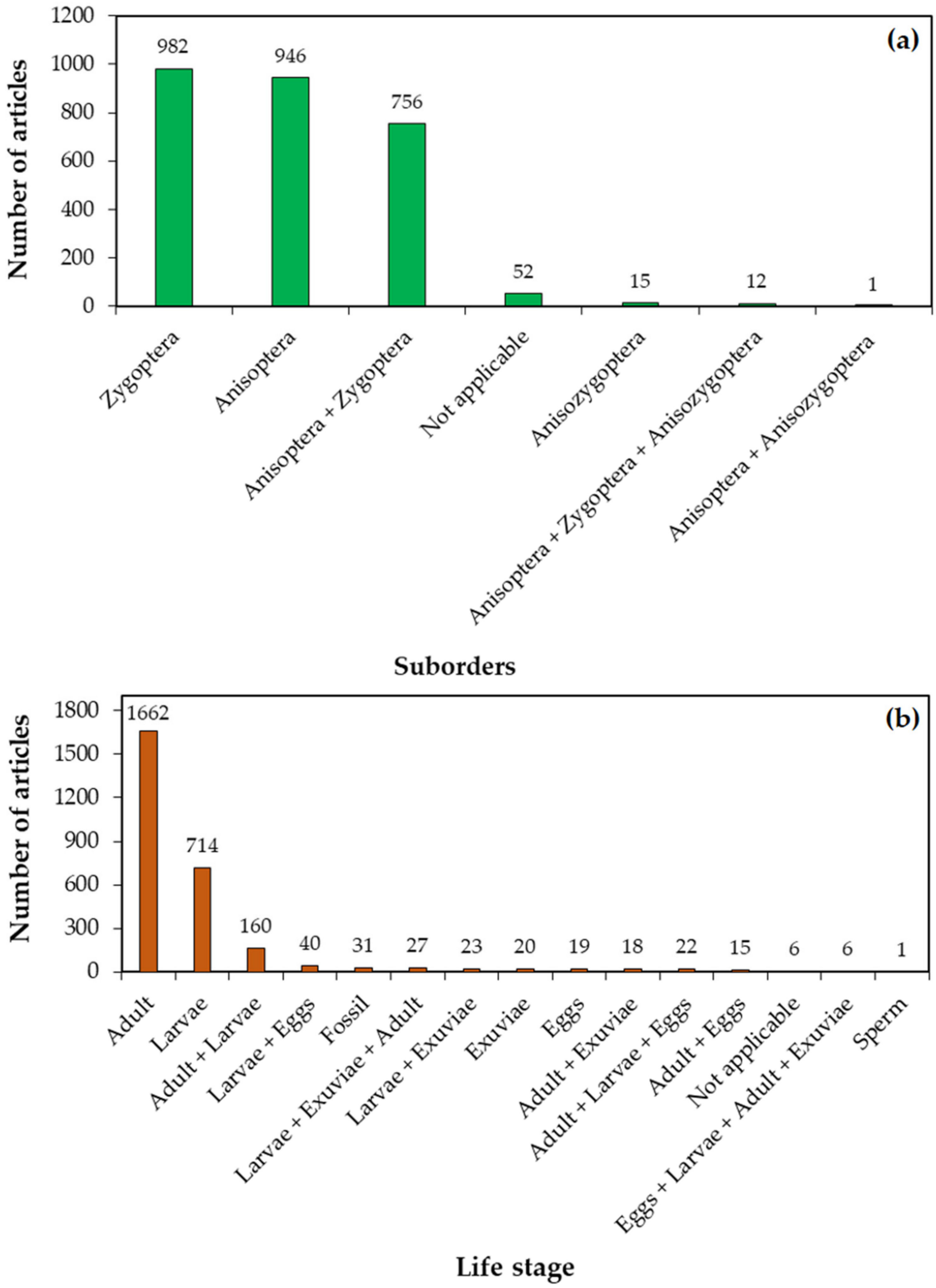

Figure 10. Number of scientific articles on Odonata, available from the Web of Science database (2012–2021), classified by: (**a**) suborders; and (**b**) life stage and/or analyzed material. Not applicable refers to studies where the life stage is not indicated.

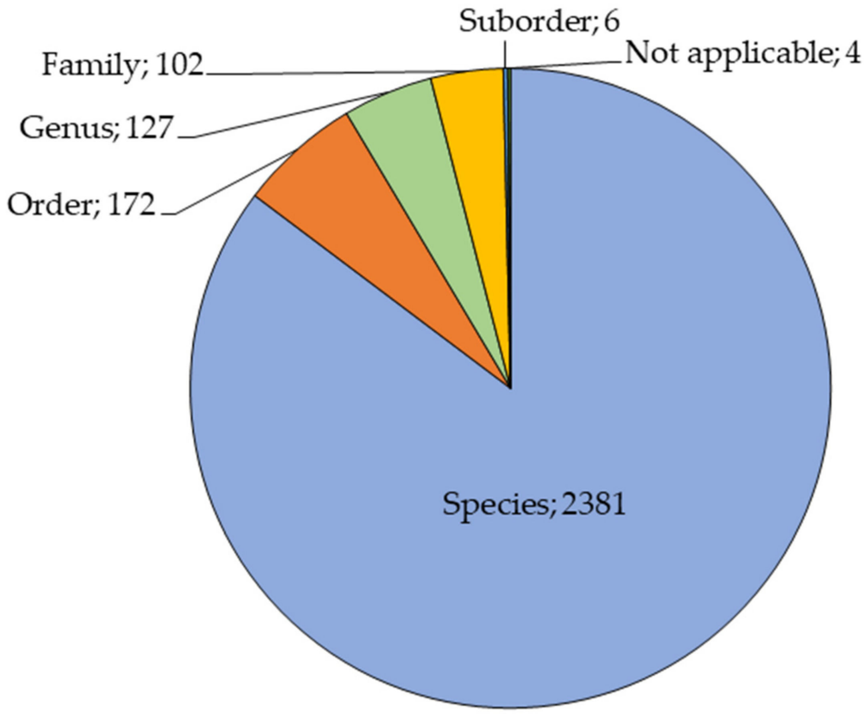

Figure 11. Number of scientific articles on Odonata, available from the Web of Science database (2012–2021), classified by taxonomic resolution. Not applicable refers to studies that do not indicate the taxonomic resolution.

Species is the taxonomic level most often used in most studies, but genus, family, and order are used as well. Identification to species is important because it facilitates more accurate information about a particular taxon. However, this requires more time, taxonomic expertise, and financial resources, which is a disadvantage for projects that need an immediate response or are underfunded [65]. Therefore, there is much discussion in the literature regarding the preferable taxonomic level for studies. For example, Jansen et al. [66] point out that it is challenging to classify organisms into higher-level taxonomic groups, such as families, because many family-specific features may not be distinguishable.

Although most Odonata papers in the WoS database use the species level of taxonomic resolution, Mendoza-Penagos et al. [35] demonstrated that the family level provides an effective tool odonate for biomonitoring of tropical streams by providing ecologically meaningful information. Future studies should evaluate the costs and benefits of diagnosing impacts by comparing multiple taxonomic levels against a common disturbance gradient [67,68].

4. Conclusions

Our results indicate an increase in published research on Odonata available on the WoS, and on a range of topics as diverse as ecology, biomonitoring, genetics, and environmental education. The increase in ecological studies on Odonata may reflect the dynamic characteristics of this order, and its relatively well-defined systematics, especially in the case of adults. Despite the increased number of publications in the WoS database, there are still many spatial gaps (e.g., poorly studied regions/countries), and gaps in study focus, such as basic biology (e.g., life cycle, anatomy, physiology, habitat), biogeography, parasitism, competition within and between species, evolutionary and phylogenetic relationships, and Odonata eggs. This demonstrates that some areas are seriously neglected. However, such studies are essential for a better understanding of how species may respond to different factors (historical, biogeographic, ecological) and to increase the background information necessary in other types of studies. It is especially necessary to increase the number of researchers and research on the larval stage of most Odonata species, as well as the potential effects of climate change on larval and adult stages. Although most Odonata diversity is found in the tropics, historically, countries with greater purchasing or economic power have a larger number of publications [69]. Thus, money and the lack of professional training are important gaps to overcome. One way to alleviate this is to initiate temperate–tropical partnerships for training new people, strengthening tropical research institutions, and conducting more joint research in the tropics.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d14121074/s1, Figure S1: Adult specimens of Odonata (Insecta): (a) *Perithemis thais* (Anisoptera: Libellulidae); and (b) *Hetaerina moribunda* (Zygoptera: Calopterygidae). Source: Cristian C. Mendoza-Penagos. Table S1: Scientific articles on Odonata available from the Web of Science database (between 2012 and 2021), per journal of publication. Table S2: List and weight of the 50 most common keywords in scientific articles on Odonata (Insecta), available from the Web of Science (WoS) (2012–2021). For elaboration, the online program Shape Wordle was used. Table S3: Global production of scientific articles on the Odonata (Insecta), available from the Web of Science database (2012 to 2021), by country in which the research was carried out. Table S4: Contribution of the different types of study (research focus) to the scientific articles published on Odonata, available from the Web of Science database (2012–2021). Table S5: Contribution of the different types of study (research focus) to the scientific articles published on Odonata, available from the Web of Science database (2012–2021), by continent in which the research was carried out. Table S6: Type of habitat for scientific articles on Odonata, available from the Web of Science database (2012–2021).

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