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Article

Publication Performance and Trends in Ontology Research in Computer Science Areas: A Bibliometric Analysis

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Abstract: Ontologies play a significant role in knowledge structure as they enable the exchange of information among various elements of AI. When fostering standardized data representations, ontologies contribute to knowledge organization and system interoperability. The current research investigates the evolution of the influence of ontology-based research from 1991 to 2022, using data from the Science Citation Index Expanded (SCI-EXPANDED) database. It sheds light on the dynamic ontology research landscape and its contributions to the broader field of artificial intelligence. The study identified a total of 12,500 ontology-related articles, with the highest number of contributions from the United States, China, the United Kingdom, and Spain. Some of these papers are considered citation classics, serving as foundational pillars in the field or introducing valuable FAIR resources for ontology research. These citation classics are mainly developed by the United States, the United Kingdom, Germany, and Belgium. The article explores various aspects of ontology research, including document types, publication outputs, Web of Science categories, journals, reviews, countries, and research trends and surveys. The illustrative findings give insights into the ever-evolving nature of ontologies, research foci, and influential contributors, as the field of ontology research can help guide researchers, practitioners, and stakeholders, enabling them to harness the full potential of ontologies for advancing intelligent systems and knowledge management.

Keywords: ontology engineering; bibliometrics; ontologies; semantic web; research trends

1. Introduction

Knowledge resources are fundamental to the development of intelligent systems [1], serving as crucial inputs for Artificial Intelligence (AI) and Machine Learning (ML) to drive understanding, reasoning, and innovation across various fields [2]. Among these resources, ontologies play a pivotal role by structuring knowledge, enabling seamless information exchange between AI components, and promoting standardized data representations [3].

An ontology is a formal representation of concepts, categories, properties, and relationships within a specific domain [4]. It is a structured framework for organizing knowledge and fostering a shared understanding among individuals or systems, facilitating communication and interoperability across domains [5,6]. In areas such as information science, computer science, and AI, ontologies are key in supporting standardized data representation, enhancing interoperability, and enabling reasoning processes. These are particularly critical in applications like knowledge management, the semantic web, and natural language processing [7,8].

Ontology engineering involves the systematic design and management of these formal knowledge structures. The process begins by defining the scope of a domain and identifying key entities and relationships, which are then formalized using the Web Ontology Language (OWL) to create machine-readable models [9,10]. Development tools offer features like visualization, reasoning, and collaboration to ensure accuracy and consistency. Moreover, an ontology's life cycle extends beyond creation, requiring ongoing maintenance to reflect changes in the domain [11,12].

This structured framework enhances system interoperability, enabling AI systems to collaborate and generate insights that contribute to more advanced intelligent systems [13]. While much research has focused on ontology design and application, recent studies have shifted toward exploring its evolution as a research domain. For instance, Zhu et al. (2015) [3] conducted a bibliometric analysis of global ontology research trends. It should be noted, however, that there is some gap between the way regional development is understood and the way it matches global trends. The current research aims, therefore, to go a step beyond and scrutinize research outputs produced from 1991 to 2022, paying special attention to the types of documents, publications, institutions, and key research work in the area examined. Additionally, a more nuanced analysis based on topic clusters is suggested to put emerging research priorities at the forefront of attention in the field. This is made possible by using advanced bibliometric tools to delve into influential research publications and scholars, while at the same time dealing with the limitations of simple citation metrics. This analysis contributes to a deeper understanding of the historical development of ontology research and identifies potential directions for future studies.

In this paper, we assess scholarly contributions to ontology research from 1991 to 2022 using data from the Science Citation Index Expanded. Section 2 provides a literature review of scientometric studies related to ontologies, followed by a detailed outline of the methodology in Section 3. Section 4 presents the results of the bibliometric study, accompanied by a discussion engaging with relevant literature. Section 5 concludes with insights on future research directions, highlighting the ongoing evolution of ontology research.

2. Related Works

The field of ontologies has gained significant attention across various disciplines due to its potential to improve information understanding, organization, and management. This literature review examines recent bibliometric studies that analyze the trends, impacts, and characteristics of ontology research. By synthesizing findings from several key publications, we aim to provide a comprehensive overview of the current state of bibliometric studies in ontology research.

Zhu et al. (2015) [3] conducted a pioneering bibliometric analysis of global ontology research from 1900 to 2012, utilizing data from the Web of Science. Their study revealed that ontology research has entered a "soaring stage" marked by increased participation and collaboration, particularly from North America, Europe, and East Asia. The authors highlighted four major keyword categories, including applications in the Semantic Web and bioinformatics, and emphasized a shift in focus from philosophy to information science. This study was notable for its comprehensive approach to quantifying research patterns and trends in ontology.

Li et al. (2017) [14] provided a bibliometric and visual analysis specifically targeting geo-ontology research articles published between 1999 and 2014. Their findings indicated that the USA was the leading contributor to geo-ontology research, with significant publications emerging from institutions like Wuhan University and the University of Munster. The study employed various visualization techniques, including global research heat maps and co-citation analysis, to identify key research areas and emerging trends, such as the need for improved semantic granularity in geographic information systems.

Wu and Ye (2021) [15] focused on bibliometric analyses within the domain of ontology research, revealing that semantic web and gene ontology are two prevalent research topics. Their study spanned literature from 1986 to 2020, using citation analysis and knowledge graphs to visualize research networks. The results underscored the critical role of ontology engineering in information sharing and system integration, providing a broader understanding of collaborative networks in the field.

Zhong et al. (2019) [16] employed scientometric analysis to explore ontology research related to construction published in the Scopus database between 2007 and 2017. This research identified dominant themes, including project management and building information modeling. Through co-authorship and co-word analysis, the study visualized collaboration patterns and highlighted the evolution of keywords in the context of technological advancements in the construction industry.

Kalibatienė et al. (2024) [17] conducted a bibliometric analysis on the integration of ontologies and fuzzy theory within information systems. Their research emphasized the evolution of traditional information systems into intelligent systems capable of managing fuzzy and semantically rich information. The study serves as a conceptual framework for understanding the intersection of ontologies and fuzzy logic in enhancing information systems.

Machado et al. (2020) [18] explored the evolving concept of ontologies, particularly in the context of information systems, through an analysis of articles published in 2018. They found a prevailing focus on the computer science perspective of ontologies, with notable contributions from biomedicine that reflect a more philosophical approach. This ongoing dialogue highlights the conceptual shifts and adaptations of ontologies as they bridge different disciplinary contexts.

3. Methods

In this study, we collected our data from the Science Citation Index Expanded (SCI-EXPANDED) along with the Clarivate Analytics Web of Science Core Collection, and the dataset was updated on October 21st, 2023. The period covered in the data analysis extends from 1991 to 2022 to allow researchers to have a full picture of the most important developments in Ontology research, with a special focus on the emerging field of semantic web and related developments in Knowledge representation and AI [3]. To provide a comprehensive overview, the study examines both publication performances and main research topics alongside their development trends, from early foundational work to recent innovations in the field. To guarantee a detailed fine-tuned overview of the data collected, this research offers insights into publication performances. It also examines major research topics and outlines their developmental stages as they existed in their early foundations to the most recent innovations.

Additionally, the evaluation of publication performance was based on the analysis of document types, journals, Web of Science categories, countries, and institutions. To achieve this goal and to guarantee accuracy, we resorted to refined citation indicators. Article metrics were used to assess publications' impact and only the most frequently cited and influential factors were reported. We did not, however, conduct an analysis network as only specific salient bibliometric distinctions were meant to be highlighted in this study.

For example, in the Journal Citation Reports of 2022 (indexed 9,537 across a whole set of 178 Web of Science categories), emphasis was put on ontology research works selected out of seven computer science categories, with a total of 522 journals. "Front page" filter [searching titles (TI) and abstracts (AB)] was used to select the most relevant publications, while author keyboards (AK) were used to select ontology-related terms [19,20]. Included in the search terms are "ontology*," "ontological*," "ontologies*," and "ontologic*." These terms were selected based on refined bibliometric search methods proposed by Wang and Ho (2011) [21] to ensure detailed accurate coverage of ontology research. It should be noted that these search methods were applied in studies in the field of nanocellulose and environmental remediation [22,23] and were found to bring about interesting findings. This study, therefore, identified 13,109 documents out of which 12,994 were published in computer science-related Web of Science categories over the period of 1991 to 2022.

For each document, citation metrics were obtained and processed with Microsoft Office Excel 365 [24]. In addition to overall citation counts, we included advanced citation indicators, as recommended by reviewers, to explore trends beyond simple citation counts:

- C_{year}: Citations received in a particular year (e.g., C_{2022} for citations in 2022) [25].
- TC_{year}: Total citations from the publication year until 2022 (TC_{2022} in this study) [21].
- CPP_{year}: Citations per publication ($CPP_{2022} = TC_{2022}$/total publications) [26].

These indicators provide stability and repeatability in bibliometric analysis compared to raw citation counts and were specifically chosen for their precision, despite limitations like time or journal openness. Ho's group has pioneered the use of these indicators, which have been integral to bibliometric studies since 2011 [27].

Further, we examined the publication performance of countries and institutions using six indicators [28]:

- *TP*: Total number of articles.
- *IP*: Single-country (IP_{C}) or single-institution (IP_{I}) articles.
- *CP*: Internationally collaborative (CP_{C}) or inter-institutional collaborative (CP_{I}) articles.
- *FP*: First-author articles.
- *RP*: Corresponding-author articles.
- *SP*: Single-author articles.

The average citation impact (CPP_{2022}) was calculated for each indicator to assess the influence of publications across countries and institutions [20]. By focusing on these structured and repeatable indicators, we aim to provide a detailed and reliable view of the ontology research landscape.

The analysis of research topics and trends in ontology research was conducted by examining keyword distributions in the titles, abstracts, author keywords, and *Keywords Plus* of articles from the SCI-

EXPANDED database. Using word cluster analysis, key research clusters were identified, allowing for the categorization of prominent topics and the tracking of developmental trends over time. This approach builds on previous studies, utilizing keyword distributions as a "word bank" to systematically capture research areas and their evolution.

4. Results and Discussion

4.1. Characteristics of Document Types

The types of documents related to ontology research were categorized by their average number of citations per publication (CPP_{year}) and average number of authors per publication (*APP*). Using TC_{2022} and CPP_{2022} offers stability and repeatability in bibliometric analysis compared to relying on raw citation counts from the Web of Science Core Collection [27]. A total of 12,994 ontology-related documents, published in computer science categories within SCI-EXPANDED from 1991 to 2022, were classified into 14 document types (Table 1). Articles made up the majority, representing 96% of the documents, with an average of 3.6 authors per publication. Interestingly, data papers, despite comprising only two documents, had the highest CPP_{2022} value of 277 citations, demonstrating their impact relative to their small number. Review papers also showed a significant citation rate, with a CPP_{2022} 2.4 times higher than journal articles, likely due to their comprehensive nature and frequent reference as foundational texts. The standout review, "Knowledge Engineering: Principles and Methods" by Studer et al. (1998) [29], had a TC_{2022} of 1,688 and continues to be recognized as a pivotal work in ontology engineering [3,14]. Document classification in Web of Science often overlaps, with some articles being categorized as proceedings papers, early accesses, or retracted publications, among others [23]. As a result, cumulative percentages sometimes exceed 100%, reflecting the multifaceted nature of publication outputs. Notably, letters to the editor—a form of rapid, informal communication—are under-utilized in the ontology field [30,31], even though they provide opportunities for timely contributions.

Table 1. Citations and authors according to the document type.

Document Type	*TP*	%	*AU*	*APP*	TC_{2022}	CPP_{2022}
Article	12,500	96	44,380	3.6	271,508	22
Proceedings paper	3,001	23	9,488	3.2	43,541	15
Review	270	2.1	926	3.4	13,831	51
Editorial material	169	1.3	446	2.7	1,849	11
Early access	40	0.31	165	4.1	49	1.2
Correction	26	0.20	126	4.8	12	0.46
Meeting abstract	13	0.10	46	3.5	5	0.38
Book review	7	0.054	7	1.0	12	1.7
Letter	7	0.054	12	2.0	60	8.6
Book chapter	3	0.023	4	1.3	6	2.0
Retracted publication	3	0.023	20	6.7	136	45
Data paper	2	0.015	7	3.5	554	277
Addition correction	1	0.0077	1	1.0	0	0

TP: number of publications; *AU*: number of authors; *APP*: average number of authors per publication; TC_{2022}: the total number of citations from Web of Science Core Collection since publication year to the end of 2022; CPP_{2022}: average number of citations per publication (TC_{2022}/TP).

4.2. Characteristics of Publication Outputs

An analysis of the annual number of ontology-related publications (*TP*) and their CPP_{2022} shows fluctuating trends in the field's development (Figure 1). The data reveals a steady increase in publication output from 1991 to 2001, followed by a marked surge between 2001 and 2005, likely driven by the rise of the Semantic Web and the growing recognition of ontologies as essential for AI and data integration [32]. However, a sharp decline in output was observed between 2006 and 2007, which contrasts with the sustained growth seen in related fields like knowledge engineering [33]. Zhu et al. (2015) [3] attribute this decline to a reduction in acceptance rates for ontology-related papers that merely describe new ontologies, without novel methodologies or applications. A notable factor influencing this trend is the emergence of knowledge graphs, which provide a distributed and scalable approach to semantic data management, posing a potential challenge for traditional ontology approaches, which are typically more centralized [34]. Knowledge graphs, due to their flexible structure and ability to handle diverse datasets, have increasingly been adopted as an alternative or complement to ontology-based models, contributing to the temporary decline in ontology-focused publications. Despite this, the last decade has seen a resurgence in ontology research, with 643 articles published in 2022. This recovery is partly driven by the integration of ontologies into knowledge graph data modeling [34] and the continued growth of computer science research more broadly [35]. The mean TC_{2022} was 22 citations, with a maximum of 8,426 citations for an article by Conesa et al. (2005) [36]. Notably, the highest CPP_{2022} occurred in 1993, largely due to Gruber's classic article (1993) [37], which remains a foundational work in ontology research, with a TC_{2022} of 6,239 citations.

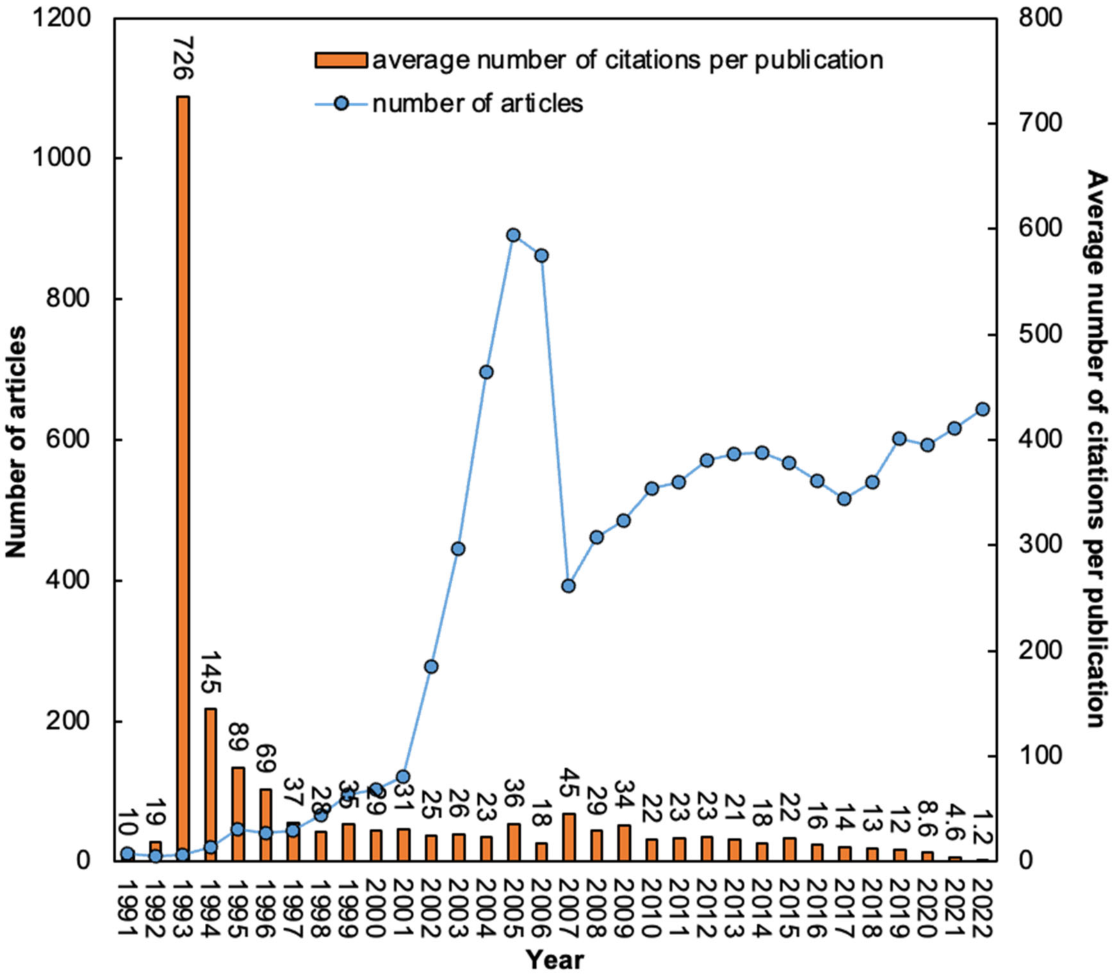

Figure 1. Number of ontology-related articles in computer science categories in SCI-EXPANDED and average number of citations per publication by year.

4.3. Web of Science Categories and Journals

A total of 12,500 ontology-related articles were published in 1,047 journals, spanning several computer science categories in SCI-EXPANDED. Notably, 2,804 articles (22%) were published in 631 journals (60%) that did not have an impact factor in 2022 (IF_{2022}). This suggests that ontology research is disseminated across a wide range of outlets, including many emerging journals. In terms of productivity, the Artificial Intelligence (AI) Computer Science category led with 145 journals contributing 5,332 articles (43%), followed by Information Systems Computer Science (158 journals, 5,316 articles, 43%). The Theory and Methods Computer Science category ranked third, with 111 journals contributing 3,223 articles (26%). These categories closely align with ontology research's core areas, reflecting the heavy integration of ontologies into AI, information systems, and theoretical computer science. The "interdisciplinary applications computer science" category includes an average of 4.3 scholars per publication, which is considered the highest among the seven categories. This underlines the collaborative nature of interdisciplinary ontology research. In addition to that, the interdisciplinary applications computer science category showed a considerably high CPP_{2022} of 33 citations, indicating the significantly remarkable impact of interdisciplinary research. This confirms earlier findings about the domination of interdisciplinary outputs in semantic web and ontology research [3,34].

By contrast to the interdisciplinary applications computer science category, the cybernetics computer science category, while smaller in terms of total publications (356 articles), showed a strong CPP_{2022} of 29 citations, suggesting that this field, though niche, is producing highly influential work. This goes in line with the findings of other bibliometric studies on the development of the cybernetics field in general [38].

The fluctuation in publication trends across the seven categories (Figure 2) mirrors the overall trends in ontology research: a surge in publications between 2001 and 2004, a peak around 2005–2006, followed by a decline in 2007, and then a steady recovery through 2022. This pattern reflects the maturation of the field during the early 2000s as ontologies became essential for AI and the Semantic Web [32] before knowledge graphs and other technologies began to share the spotlight [34]. Moreover, the analysis reveals that specialized journals (Table 2), such as bioinformatics and expert systems with applications, are among the most productive outlets for ontology-related research. *Bioinformatics*, with an IF_{2022} of 5.8, had the highest CPP_{2022} (86 citations), further emphasizing the interdisciplinary value of ontologies in domains like biomedical research. Conversely, articles in *IEEE Access* had a much lower CPP_{2022} (7.8 citations), reflecting the varying levels of impact across different publication venues. The *IEEE Communications Surveys and Tutorials* topped the list of highest-impact journals with an IF_{2022} of 35.6, though it published only one article on ontology. *Nature Machine Intelligence* also stands out, ranking at the top of the artificial intelligence and interdisciplinary applications categories, with a high IF_{2022} of 23.8. These results align with earlier studies, which identified key publication venues in the semantic web [32] and AI fields [35]. This indicates a consistent trend in the scholarly community's preference for high-impact journals in these areas.

Table 2. The top 10 most productive journals.

Journal	***TP* (%)**	IF_{2022}	***APP***	CPP_{2022}
Bioinformatics	606 (4.8)	5.8	4.8	86
Expert Systems with Applications	435 (3.5)	8.5	3.4	21
Journal of Biomedical Informatics	273 (2.2)	4.5	4.7	28
IEEE Access	270 (2.2)	3.9	4.0	7.8
Journal of Web Semantics	245 (2.0)	2.5	4.2	42
Applied Ontology	215 (1.7)	1.0	3.6	13
Knowledge-Based Systems	202 (1.6)	8.8	3.3	22
Semantic Web	196 (1.6)	3.0	3.8	25
Data & Knowledge Engineering	158 (1.3)	2.5	3.2	32
International Journal on Semantic Web and Information Systems	142 (1.1)	3.2	3.2	12

TP: total number of articles; %: percentage of articles; IF_{2022}: journal's impact factor in 2022; *APP*: average number of authors per article; CPP_{2022}: average number of citations per paper (TC_{2022}/TP).

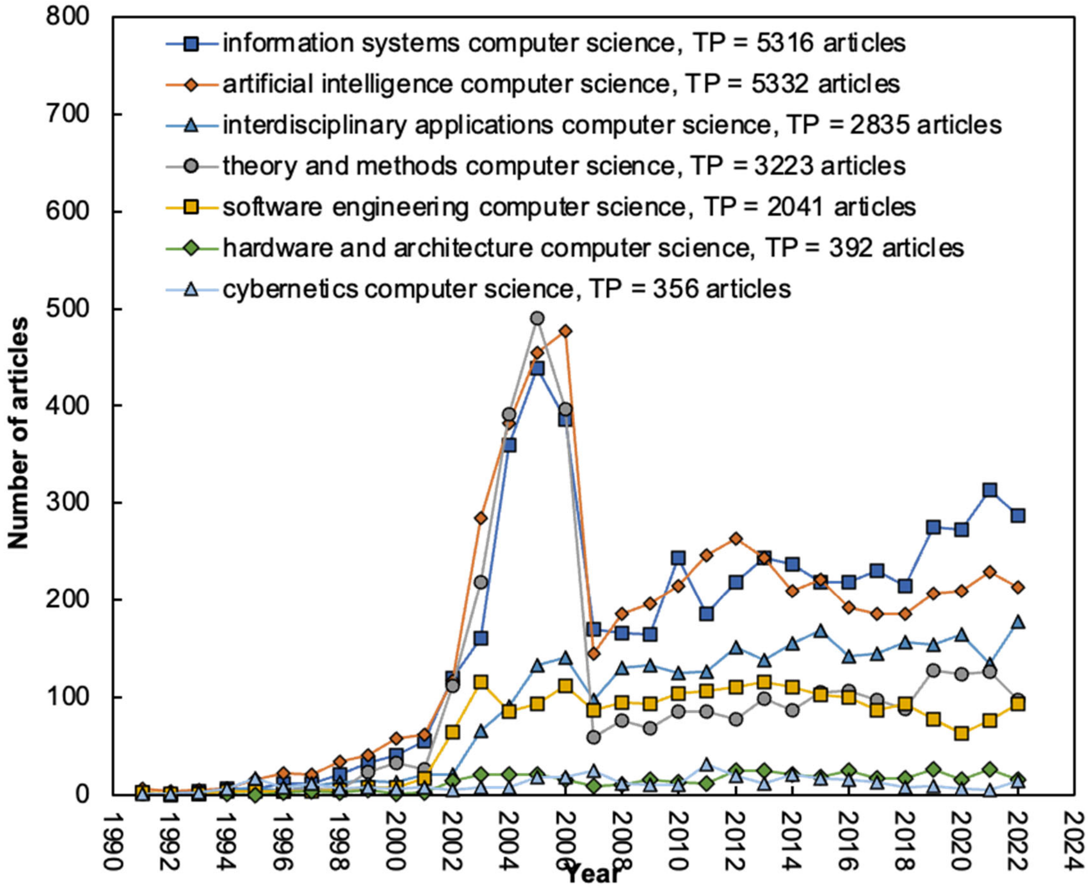

Figure 2. Development trends of the computer science-related Web of Science categories in SCI-EXPANDED.

4.4. Publication Performances: Countries and Institutions

Out of 12,500 ontology-related articles, 12,420 (99.4%) included author affiliation information, representing 109 countries. Among these, 9,366 (75%) were single-country articles with a CPP_{2022} of 21 citations, while 3,054 (25%) were internationally collaborative articles, with a slightly higher CPP_{2022} of 25 citations. The higher citation rate for collaborative articles indicates that international collaboration tends to enhance the impact of ontology research. Using six key publication and citation indicators [20,28], we compared the top 10 productive countries (Table 3). The results show that five European countries, two Asian countries, two American countries, and one Oceanian country were among the leaders in ontology research. Notably, Tunisia, ranked 34th with 94 articles, is the most productive country in Africa. This contrasts with other computer science fields like machine learning, where Egypt and South Africa often lead [39]. Tunisia's strength in ontology research can be attributed to research structures like MIR@CL (http://www.miracl.rnu.tn/) and the Data Engineering and Semantics Research Unit (https://www.deslab.org/) at the University of Sfax and LARODEC (http://www.larodec.com/) at the University of Tunis, which have strong focuses on ontology engineering and expert systems [40].

Table 3. Top 10 productive countries.

Country	*TP*	*TP*		*IP*$_C$		*CP*$_C$		*FP*		*RP*		*SP*	
		R **(%)**	CPP_{2022}	***R*** **(%)**	CPP_{2022}	***R*** **(%)**	CPP_{2022}	***R*** **(%)**	CPP_{2022}	***R*** **(%)**	CPP_{2022}	***R*** **(%)**	CPP_{2022}
USA	2,345	1 (19)	37	1 (15)	38	1 (29)	36	1 (14)	38	1 (14)	38	1 (20)	63
China	1,583	2 (13)	16	2 (12)	13	3 (16)	22	2 (12)	15	2 (12)	15	5 (4.5)	8.9
UK	1,324	3 (11)	28	4 (6.8)	25	2 (23)	31	4 (7.3)	26	3 (7.5)	27	2 (9.2)	17
Spain	1,132	4 (9.1)	27	3 (7.6)	30	5 (14)	22	3 (7.4)	27	3 (7.5)	27	14 (2.4)	16
Italy	993	5 (8.0)	21	5 (6.6)	19	7 (12)	23	5 (6.4)	20	5 (6.5)	20	4 (7.3)	31

Germany	983	6 (7.9)	26	6 (5.9)	25	4 (14)	27	6 (5.9)	26	6 (5.9)	26	3 (8.8)	11
France	761	7 (6.1)	24	8 (4.0)	15	6 (13)	32	7 (4.1)	23	7 (4.3)	22	6 (4.0)	15
Australia	530	8 (4.3)	21	10 (2.8)	19	9 (8.7)	22	9 (3.0)	21	9 (3.1)	21	7 (3.7)	10
South Korea	522	9 (4.2)	14	7 (4.1)	11	12 (4.6)	24	8 (3.6)	12	8 (3.7)	12	7 (3.7)	20
Canada	479	10 (3.9)	25	13 (2.3)	18	8 (8.7)	30	10 (2.6)	22	10 (2.6)	22	10 (3.0)	17

TP: number of total articles; *TP R* (%): total number of articles and the percentage of total articles; IP_C *R* (%): rank and percentage of single-country articles in all single-country articles; CP_C *R* (%): rank and percentage of internationally collaborative articles in all internationally collaborative articles; *FP R* (%): rank and percentage of first-author articles in all first-author articles; *RP R* (%): rank and percentage of corresponding-author articles in all corresponding-author articles; *SP R* (%): rank and percentage of single-author articles in all first-author articles; CPP_{2022}: average number of citations per publication ($CPP_{2022} = TC_{2022}/TP$); N/A: not available.

The USA dominated all six publication indicators, with 2,347 total publications (*TP*) accounting for 19% of the articles, and it also led in internationally collaborative publications (CP_C), first-author publications (*FP*), and single-author publications (*SP*). The USA's CPP_{2022} was consistently high across all indicators, confirming its leading role in ontology research. Other highly productive countries, such as China, the UK, Spain, and Germany, also maintained strong performances across both publication and citation metrics, reflecting their ongoing dominance in computer science and AI research [3,35]. Figure 3 illustrates the developmental trends of the top six productive countries from 1991 to 2022. The USA showed a significant rise in output early on, while countries like China, India, and Spain experienced sharp growth between 2002 and 2006, followed by a decline in 2007. This decline could be linked to the shift in focus towards knowledge graphs and other technologies that reduced the centrality of traditional ontologies [34]. In recent years, China and India have significantly expanded their research, while the USA and Spain have reduced their efforts, signaling a shift in the global landscape of ontology research [3,34]. The narrowing gap between the USA and other nations, particularly China and India, indicates the growing influence of these countries in the field [3,34].

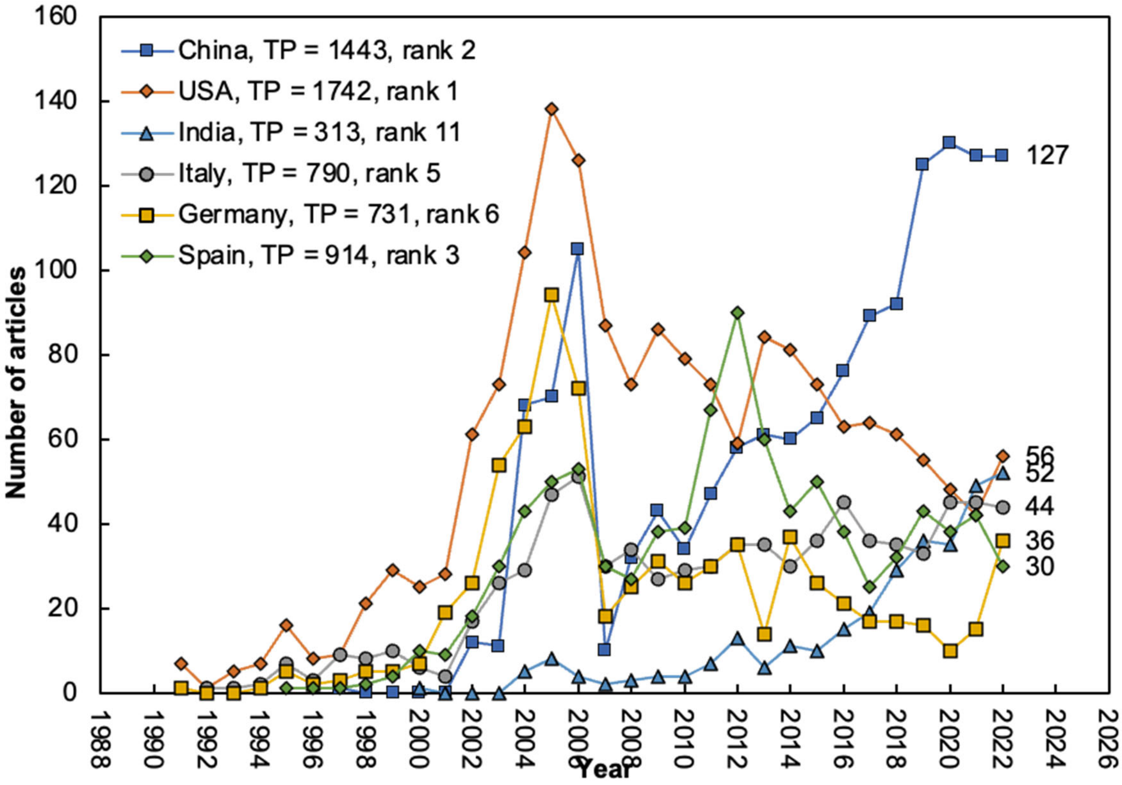

Figure 3. Development trends of the top six productive countries in 2022.

Regarding institutions, 5,989 articles (48%) were single-institution publications with a CPP_{2022} of 21 citations, while 6,431 (52%) were inter-institutional collaborative articles, also with a CPP_{2022} of 21 citations. Unlike international collaborations, inter-institutional collaborations did not significantly boost citation impact, suggesting that collaboration across institutions may not have the same influence on research visibility as cross-country partnerships. Table 4 lists the top 10 productive institutions. The University of Manchester in the UK led in four out of six indicators, including total publications (*TP*), single-institution publications (IP_I), first-author publications (*FP*), and corresponding-author publications (*RP*). Stanford University in the USA, known for its excellence in AI and computer science [35], was the leader in inter-institutional collaborative publications (CP_I). It also had the highest CPP_{2022} across several indicators, further solidifying its status as a hub for influential ontology research. Additionally, Yeungnam University in South Korea ranked highest in single-author publications (*SP*), reflecting its contribution to individual research efforts in the field. Meanwhile, the Polytechnic University of Madrid in Spain had the highest CPP_{2022} for single-author publications, a testament to its leadership in semantic interoperability research [41], a key area within ontology research.

Table 4. Top 10 productive institutions.

Institution	*TP*	*TP*		IP_I		CP_I		*FP*		*RP*		*SP*	
		R (%)	CPP_{2022}	*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}			*R* (%)	CPP_{2022}	*R* (%)	CPP_{2022}
UoM	153	1 (1.2)	40	1 (1.0)	51	3 (1.4)	34	1 (0.75)	42	1 (0.78)	41	5 (1.0)	20
Stanford U	149	2 (1.2)	65	4 (0.78)	83	1 (1.6)	57	5 (0.64)	67	7 (0.63)	69	5 (1.0)	62
UPM	135	3 (1.1)	31	5 (0.75)	32	4 (1.4)	30	3 (0.68)	26	3 (0.71)	25	90 (0.18)	109
CNR	130	4 (1.0)	32	6 (0.73)	50	5 (1.3)	23	3 (0.68)	40	4 (0.69)	40	2 (1.6)	61
CAS	126	5 (1.0)	17	20 (0.45)	11	2 (1.5)	18	8 (0.54)	12	8 (0.57)	13	26 (0.46)	7.2
U Karlsruhe	114	6 (0.92)	44	2 (0.85)	45	8 (1.0)	43	2 (0.73)	46	2 (0.73)	47	4 (1.2)	7.0
U Oxford	108	7 (0.87)	38	27 (0.37)	33	5 (1.3)	39	9 (0.48)	35	9 (0.48)	45	26 (0.46)	41
U Murcia	107	8 (0.86)	20	8 (0.57)	23	7 (1.1)	19	7 (0.62)	23	5 (0.64)	22	N/A	N/A
SJTU	89	9 (0.72)	20	2 (0.85)	12	33 (0.59)	31	6 (0.64)	18	5 (0.64)	19	N/A	N/A
U Granada	87	10 (0.70)	21	14 (0.47)	14	9 (0.92)	25	12 (0.40)	19	12 (0.43)	22	N/A	N/A

TP: total number of articles; *TP R* (%): total number of articles and percentage of total articles; IP_I *R* (%): rank and percentage of single-institution articles in all single-institution articles; CP_I *R* (%): rank and percentage of inter-institutionally collaborative articles in all inter-institutionally collaborative articles; *FP R* (%): rank and percentage of first-author articles in all first-author articles; *RP R* (%): rank and percentage of corresponding-author articles in all corresponding-author articles; *SP R* (%): rank and percentage of single-author articles in all first-author articles; CPP_{2022}: average number of citations per publication ($CPP_{2022} = TC_{2022}/TP$); N/A: not available.

UoM: University of Manchester, UK
Stanford U: Stanford University, USA
UPM: Polytechnic University of Madrid, Spain
CNR, National Research Council, Italy
CAS: Chinese Academy of Sciences, China
U Karlsruhe: University of Karlsruhe, Germany
U Oxford: University of Oxford, UK
U Murcia: University or Murcia, Spain
SJTU: Shanghai Jiao Tong University, China
U Granada: University of Granada, Spain

4.5. Citation Histories of the Classic Articles

In our bibliometric analysis, we calculated the total number of citations from the Web of Science Core Collection from the year of publication until 2022, denoted as TC_{2022} [21]. Among the 15 classic articles with a TC_{2022} of 1,000 or more, seven include ontology-related keywords in their titles, and all but one (due to missing abstract information) contain keywords in their abstracts. Interestingly, only three articles included author keywords in the SCI-EXPANDED database, with just one article, published in the Journal of Web Semantics, listing ontology-related keywords in its author keywords. The limited use of search keywords in titles and keywords underscores the challenge of accurately capturing key works through traditional bibliometric search strategies, as suggested by Ho and Mukul (2021) [20].

Table 5 displays the 15 classic articles in ontology research. The USA contributed the most, with 10 of these articles, followed by the UK with three, and Germany and Belgium with two each. Gruber authored two of these classic works entirely solo, marking a significant individual contribution to the field. Other countries contributing to this influential body of work include Spain, Canada, Austria, China, and France. These highly cited articles demonstrate significant global contributions to ontology research and highlight the field's interdisciplinary and international scope [3].

Table 5. The 15 classic articles in ontology research in computer science areas.

Rank (TC_{2022})	Rank (C_{2022})	Title	Country	Reference
1 (8,426)	2 (606)	Blast2GO: A universal tool for annotation, visualization and analysis in functional genomics research	Spain	Conesa et al. (2005) [36]
2 (6,239)	7 (186)	A translation approach to portable ontology specifications	USA	Gruber (1993) [37]
3 (3,696)	1 (662)	ClueGO: A Cytoscape plug-in to decipher functionally grouped gene ontology and pathway annotation networks	France, Austria	Bindea et al. (2009) [42]
4 (3,015)	6 (189)	BiNGO: A Cytoscape plugin to assess overrepresentation of Gene Ontology categories in Biological Networks	Belgium	Maere et al. (2005) [43]
5 (2,870)	11 (148)	Toward principles for the design of ontologies used for knowledge sharing	USA	Gruber (1995) [44]
6 (2,747)	17 (106)	A metrics suite for object-oriented design	USA	Chidamber and Kemerer (1994) [45]
7 (2,241)	3 (471)	Automated genome annotation and pathway identification using the KEGG Orthology (KO) as a controlled vocabulary	China, USA	Mao et al. (2005) [46]
8 (1,414)	33 (51)	Ontologies: Principles, methods and applications	UK, Canada	Uschold and Gruninger (1996) [47]
9 (1,385)	24 (81)	Using GOstats to test gene lists for GO term association	USA	Falcon and Gentleman (2007) [48]
10 (1,364)	17 (106)	GO:TermFinder - open source software for accessing Gene Ontology information and finding significantly enriched Gene Ontology terms associated with a list of genes	USA	Boyle et al. (2004) [49]
11 (1,294)	13 (140)	Improved scoring of functional groups from gene expression data by decorrelating GO graph structure	Germany	Alexa et al. (2006) [50]
12 (1,255)	29 (63)	Pellet: A practical OWL-DL reasoner	USA	Sirin et al. (2007) [51]
13 (1,232)	5 (233)	DBpedia - A large-scale, multilingual knowledge base extracted from Wikipedia	Germany, USA	Lehmann et al. (2015) [52]
14 (1,118)	16 (110)	AmiGO: Online access to ontology and annotation data	USA, UK	Carbon et al. (2009) [53]
15 (1,052)	10 (167)	BioMart and Bioconductor: A powerful link between biological databases and microarray data analysis	Belgium, UK, USA	Durinck et al. (2005) [54]

TC_{2022}: the total number of citations from Web of Science Core Collection since the publication year to the end of 2022; C_{2022}: the number of citations of an article in 2022 only.

4.5.1. Citation Trends and Classic Articles

The citation histories of the 15 classic articles, shown in Figures 4 and 5, reveal interesting trends. Some works, such as the paper by Uschold and Gruninger (1996) [47], have seen a decline in citations over the past few years, accruing 51 citations in 2022 (C_{2022}). Similarly, Conesa et al. (2005) [36] and Gruber (1993) [37], despite being ranked highly in terms of total citations, have also experienced a downturn in recent citations, with C_{2022} counts of 606 and 185, respectively.

In contrast, other articles, like those authored by Bindea et al. (2009) [42], Mao et al. (2005) [46], and Lehmann et al. (2015) [52], continue to see a sharp increase in citations. These works remain highly influential, reflecting the ongoing relevance of their contributions in fields such as functional genomics, bioinformatics, and semantic web technologies [3]. The rise in citations for these articles underscores the dynamic nature of ontology research, where certain works continue to shape and influence the field long after their publication [3].

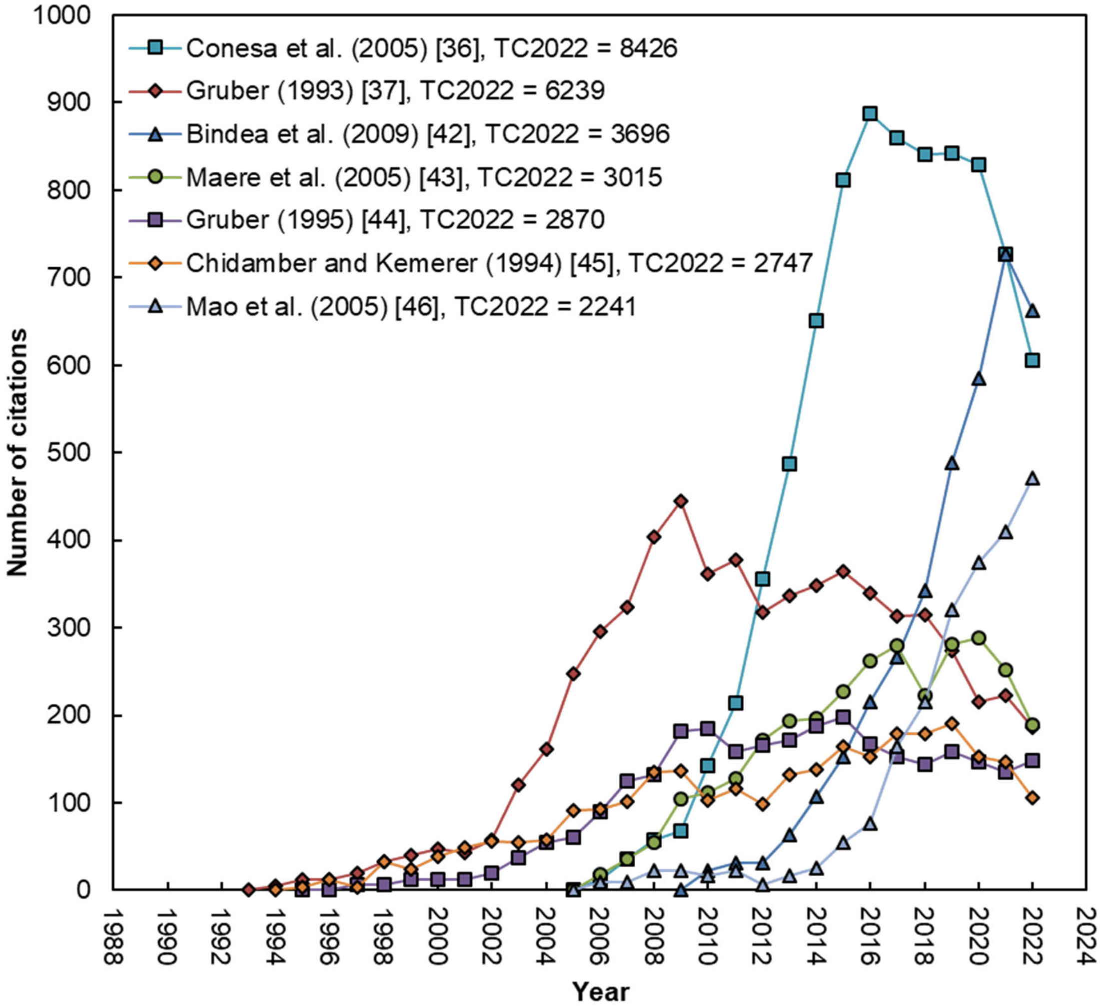

Figure 4. The citation histories of the top seven most frequently cited articles with TC_{2022} > 2,000, [36,37,42–46].

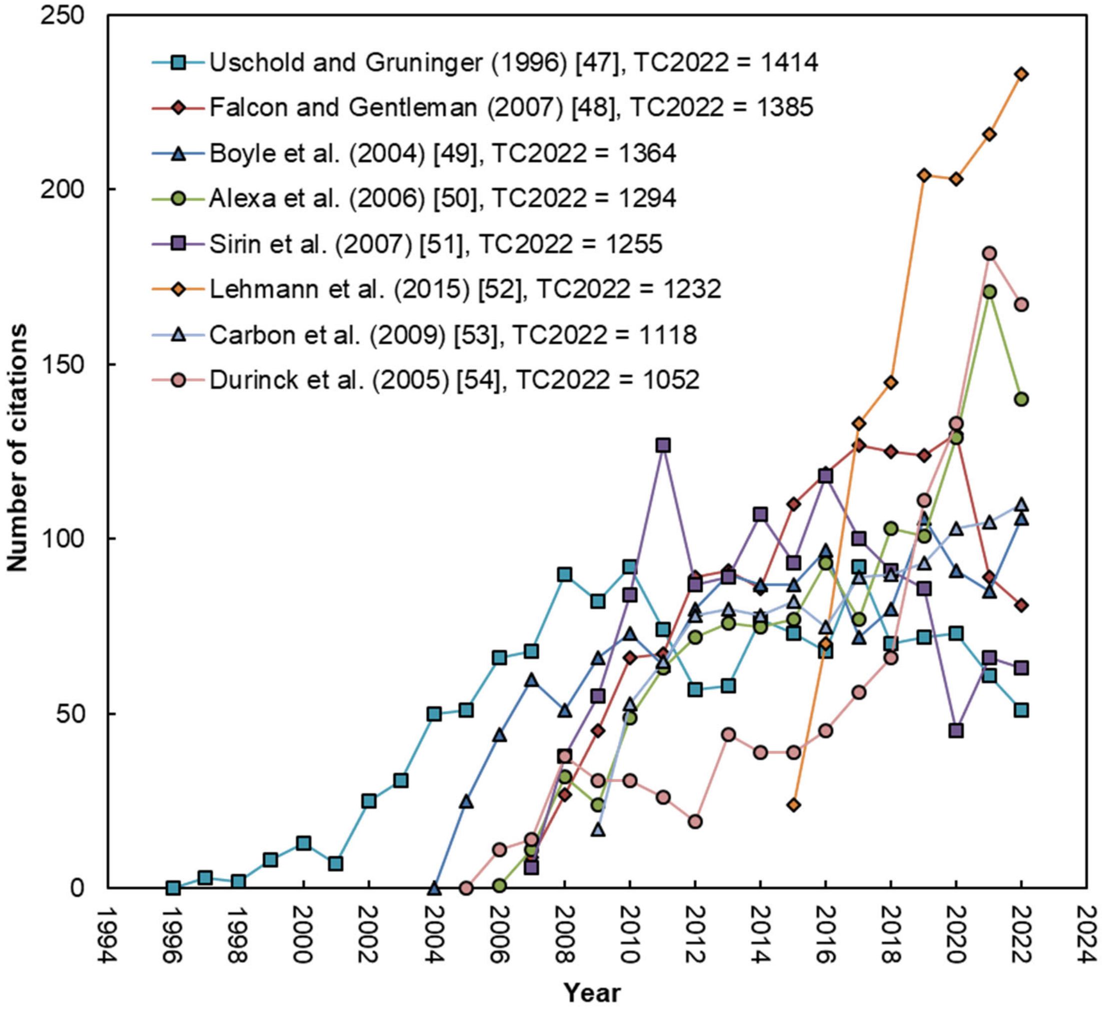

Figure 5. The citation histories of the top 8–15 most frequently cited articles [47–54].

4.5.2. Enduring Impact of Classic Articles

The classic works of Gruber, including his theoretical contributions to ontology engineering, remain highly influential. His 1993 and 1995 papers on portable ontology specifications and design principles have become essential reading for researchers and practitioners alike. Other highly cited works, such as Blast2GO [36] and ClueGO [42], have contributed valuable ontology-based solutions for managing open resources like Gene Ontology, KEGG, and DBpedia. These tools facilitate the findability, accessibility, interoperability, and reusability (FAIR) of biological data, confirming the critical role that open science and open sharing play in advancing ontology management [34,55].

4.5.3. Notable Achievements of Citation Classics

Several landmark publications have made significant and lasting contributions to the fields of ontology and functional genomics research. Blast2GO [36], with a TC_{2022} of 8,426 citations and C_{2022} of 606 citations, introduced a groundbreaking tool that revolutionized functional genomics by enabling Gene Ontology (GO)-based data mining on sequence data without requiring pre-existing GO annotations. Its ability to support diverse genomics and transcriptomics studies across multiple species has made it a cornerstone of bioinformatics research. Gruber's seminal article, A Translation Approach to Portable Ontology Specifications (1993) [37], with a TC_{2022} of 6,239 citations and C_{2022} of 186 citations, provided one of the earliest frameworks for creating reusable and shareable ontologies across different systems, offering a solution to the challenges of system interoperability. This work laid the foundation for modern ontology development and continues to be a pivotal reference in the field [3].

ClueGO [42], with a TC_{2022} of 3,696 citations and C_{2022} of 662 citations, offers a user-friendly integration of GO terms into functionally organized networks, significantly advancing biological data interpretation. Its popularity lies in its ability to bridge the gap between high-throughput gene expression data and meaningful biological insights, making it indispensable for functional genomics studies.

Similarly, BiNGO [43], with a TC_{2022} of 3,015 citations and C_{2022} of 189 citations, has become a critical tool for detecting overrepresented GO categories in gene sets. Its impact on pathway analysis and network biology demonstrates the enduring value of GO-based analytical tools in genomics research [56].

Gruber's Toward Principles for the Design of Ontologies (1995) [44], with a TC_{2022} of 2,870 citations and C_{2022} of 148, has shaped both theoretical and practical approaches to ontology design. This work formalized a set of principles that guide the creation of ontologies for knowledge sharing, influencing how ontologies are evaluated and deployed in AI and semantic web applications. The KO-Based Annotation System (KOBAS) [46], with a TC_{2022} of 2,241 and C_{2022} of 471 citations, has had a profound impact on genome annotation and pathway analysis, providing an automated system that simplifies the functional annotation of gene sequences and identifies enriched pathways, streamlining biological data analysis workflows [57].

Improved Scoring of Functional Groups from Gene Expression Data [50], with a TC_{2022} of 1,294 and C_{2022} of 140 citations, introduced innovative algorithms that enhanced the accuracy of functional group scoring in gene expression data, contributing to more precise biological interpretations. DBpedia [52], with a TC_{2022} of 1,232 citations and C_{2022} of 233 citations, is a pioneering project that extracts structured knowledge from Wikipedia and represents one of the largest and most widely used ontology-based linked data resources in the world. DBpedia has become central to the Semantic Web and linked data movements, facilitating the interoperability of datasets across different languages and domains [34].

Finally, BioMart and Bioconductor [54], with a TC_{2022} of 1,052 citations and C_{2022} of 167 citations, integrate biological databases with Bioconductor to provide essential tools for the search and analysis of the selected biological data. In fact, researchers embarking on large-scale biological studies consider Biocondcutor a crucial resource for them because of its ability to relate biological databases to microarray data analysis and because it provides researchers with access to a wide range of genomic data [58]. Not only did these publications positively impact the development of respective fields but have also given the space to the use of ontological methodologies and bioinformatics to move forward [58]. Their enduring impact is a testament to their foundational contributions to ontology, semantic web technologies, and functional genomics.

4.6. Research Foci

The research topics covered in this research were identified by resorting to the title, abstract, author keywords, and *Keywords Plus*, as reliable sources of information. Indeed, analyzing word distributions could be considered a powerful tool to evaluate research foci and track evolving trends (Wand and Ho, 2016). It was thanks to Ho's team that using word distributions as a word bank to track main research areas and their development was introduced [59,60]. While abstracts featured in 99 percent out of the 12.500 articles retrieved from the SCI-EXPANDED database, author keywords appeared in 71 percent of the total set of articles, search keywords in 42 percent, and titles in 91 percent. The use of these keywords was essential in highlighting the main topics and the evolving nature of ontology research over time. Table 6 presents the top 20 overwhelmingly used author keywords across the following sub-periods (1991-1998, 1999-2006, 2007-2014, and 2015-2022). Over the period of 1991 to 2022, the "Semantic Web," "Knowledge representation," "semantics," and "OWL" keywords dominated the ontology research articles. The high frequency of these keywords indicates the importance of the areas investigated. It should be noted, however, that while the keywords "natural language processing," "linked data," "machine learning," and "data mining" have increasingly risen recently, "Web services" has significantly declined. The eight research topic clusters identified from the sum of the top keywords (Figure 6) represent the focal points of ontology research. These clusters are consistent with trends observed in previous bibliometric studies on semantic web and ontology research [15,41], confirming that fluctuations in publication productivity are not due to shifts in research topics, but rather other external factors [3,32].

Table 6. The 20 most frequently used author keywords.

Author Keywords	***TP***	**91-22 Rank (%)**	**91-98 Rank (%)**	**99-06 Rank (%)**	**07-14 Rank (%)**	**15-22 Rank (%)**
semantic web	882	1 (10)	N/A	1 (12)	1 (13)	1 (7.2)
knowledge representation	281	2 (3.2)	1 (15)	2 (5.1)	3 (2.8)	4 (2.7)
Semantics	251	3 (2.8)	12 (2.0)	7 (2.3)	6 (2.2)	2 (3.5)
OWL	223	4 (2.5)	N/A	29 (1.0)	2 (3.6)	8 (2.0)

Interoperability	187	5 (2.1)	43 (1.0)	9 (1.9)	8 (2.0)	7 (2.3)
knowledge management	182	6 (2.0)	43 (1.0)	3 (3.6)	4 (2.7)	27 (1.1)
natural language processing	173	7 (1.9)	12 (2.0)	8 (2.2)	35 (0.9)	3 (2.8)
information retrieval	168	8 (1.9)	43 (1.0)	5 (2.9)	7 (2.1)	16 (1.4)
gene ontology	160	9 (1.8)	N/A	16 (1.5)	10 (1.8)	10 (1.9)
linked data	157	10 (1.8)	N/A	N/A	13 (1.5)	5 (2.5)
description logics	150	11 (1.7)	43 (1.0)	12 (1.6)	5 (2.4)	24 (1.2)
machine learning	141	12 (1.6)	N/A	16 (1.5)	41 (0.82)	6 (2.3)
data mining	140	13 (1.6)	N/A	36 (0.92)	14 (1.4)	9 (1.9)
semantic similarity	132	14 (1.5)	N/A	49 (0.74)	11 (1.7)	13 (1.5)
web services	127	15 (1.4)	N/A	4 (3.0)	9 (1.9)	53 (0.62)
data integration	121	16 (1.4)	N/A	25 (1.2)	20 (1.3)	13 (1.5)
ontology engineering	121	16 (1.4)	N/A	41 (0.83)	12 (1.6)	20 (1.3)
semantic interoperability	117	18 (1.3)	43 (1.0)	16 (1.5)	22 (1.2)	20 (1.3)
Reasoning	113	19 (1.3)	N/A	58 (0.65)	16 (1.3)	17 (1.4)
information extraction	106	20 (1.2)	N/A	20 (1.3)	16 (1.3)	30 (1.1)

TP: number of articles containing the keywords; %: percentage in each period; N/A: not available.

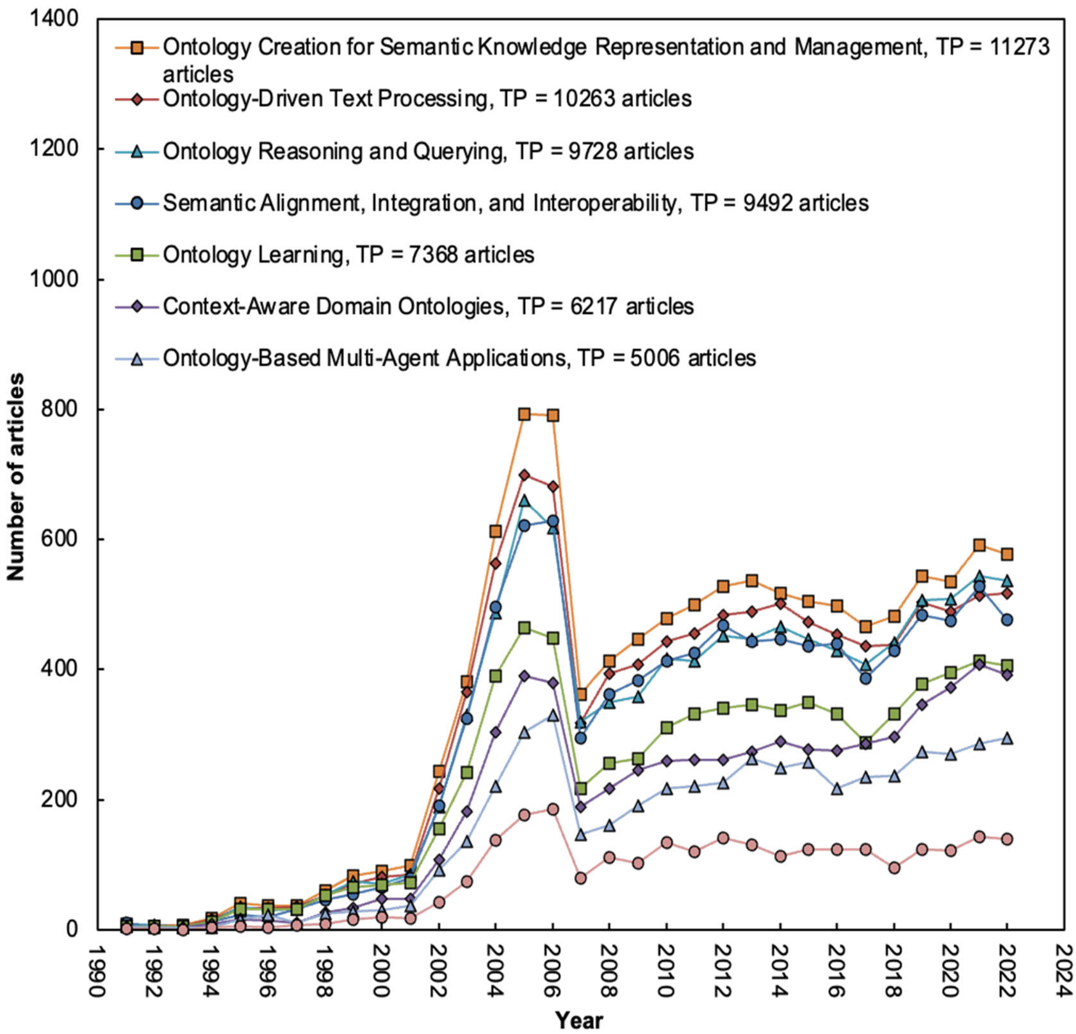

Figure 6. Development trends of the eight topics in ontology research.

4.6.1. Ontology Creation for Semantic Knowledge Representation and Management

Ontology creation forms the backbone of semantic knowledge representation, where the goal is to develop shared frameworks that provide a structured, machine-interpretable understanding of complex domains [61]. This cluster emphasizes key topics like ontology construction, the Semantic Web, and the use of ontology languages (e.g., OWL) to create interoperable systems [61]. Early foundational papers by Gruber, such as “A translation approach to portable ontology specifications” (1993) [37], introduced methodologies for building reusable and portable ontologies. This was followed by Gruber’s 1995 work, “Toward principles for the design of ontologies used for knowledge sharing,” which set forth guidelines for designing ontologies that can facilitate collaboration and data sharing across systems [44]. Uschold and Gruninger’s (1996) [47] influential review on ontology engineering further refined these approaches, introducing structured phases like specification, conceptualization, and evaluation to systematize ontology development. These works underpin much of today’s ontology creation practices, influencing the development of knowledge representation models in fields ranging from artificial intelligence to healthcare informatics [3]. Modern advancements have built upon these foundations, incorporating collaborative tools and iterative methodologies to make ontology creation more adaptable and scalable across domains [9].

4.6.2. Ontology-Driven Text Processing

The integration of ontologies in text processing has revolutionized how systems handle unstructured data, especially in domains like natural language processing, information retrieval, and text mining [62]. Ontologies enhance text processing by providing a semantic framework that helps disambiguate terms, contextualize language, and categorize information accurately [62]. Tools like Blast2GO [36] demonstrate the power of Ontology-based text processing. They enable researchers to annotate gene sequences in the field of Genomics in a functional way. By including ontologies in text analysis, a large amount of data can be organized and interpreted by the ontology systems, and this simplifies the extraction of information from literature, medical records, or social posts [63]. In addition to this, ontology-based text processing fosters advanced applications including automatic summarization, real-time sentiment analysis, and contextual search [63]. With the increasingly growing data volumes, the capacities of ontology-based text processing are considered very important as they offer scalable methods to manage and extract information from unstructured texts [64].

4.6.3. Ontology-Driven Reasoning, Validation, and Querying

Ontology-based reasoning, validation, and querying are crucial to generating complex inferences and logic-based data exploration within structured datasets [65]. By using formal methods such as Description Logics and SPARQL, this cluster supports systems in making logical inferences, allowing for advanced queries and deductions that reveal deeper insights [65]. Key contributions like “Pellet: A practical OWL-DL reasoner” [51] illustrate how reasoners can validate ontological models, ensuring consistency and supporting the derivation of new knowledge from existing datasets. Similarly, Alexa et al.’s (2006) work on “Improved scoring of functional groups from gene expression data by decorrelating GO graph structure” highlights the role of ontology-based reasoning in bioinformatics, where it supports tasks such as functional annotation and pattern recognition in gene expression [50]. Ontology-driven reasoning has found applications in numerous fields [66], from personalized medicine, where it supports clinical decision-making, to complex scientific research that requires rigorous hypothesis validation and exploration of hierarchical relationships within data [67].

4.6.4. Semantic Alignment, Integration, and Interoperability

Semantic alignment, integration, and interoperability are critical for combining data from different sources, especially in fields like bioinformatics and healthcare as these two fields rely on compatibility across databases [5]. In fact, these two fields explore methods used to align and map ontologies across systems to make the task of semantic interoperability possible. For example, BioMart and Bioconductor [54], are two methods used to integrate biological databases, which enables researchers to conduct data analyses across different datasets. It should be noted that the need for interoperability motivates the development of alignment methods to harmonize data formats and terminologies and to guarantee consistency in the use of terms and the performance of collaborative research [58]. Aligning with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles, these efforts called for the use of standardized approaches to data management [55]. Similarly, semantic alignment encourages the use of applications including federated learning in AI as data coming from several sources should be coherently and interpretably aggregated [68].

4.6.5. Ontology Learning

The field of ontology learning emphasizes the use of both machine learning and data mining. These two methods are used to automate and refine the creation of ontological structures and optimize the use of deep learning, graph embeddings, and NLP to make the discovery of concepts and relationships within data possible [69]. Recent studies by Khadir et al. (2021) [70] and Gao et al. (2022) [35] illustrate the integration of AI and ontology learning, where ontologies are refined through patterns detected in large datasets. This automated approach is crucial in domains like biomedical research, where vast amounts of produced data necessitate the use of scalable adaptive frameworks. Moreover, ontology learning contributes to enhancing the field of social network analysis as it offers insights into the most recent emerging trends and provides users with updated models in real-time [71]. Based on the dynamic evolving nature of the volume, ontology learning stands out as a vital method for the generation of sound adaptable knowledge structures across emerging fields.

4.6.6. Context-Aware Domain Ontologies

Context-aware domain ontologies are highly specialized, capturing knowledge relevant to specific fields such as bioinformatics, healthcare, and conceptual modeling [11]. This cluster emphasizes the development and evaluation of ontologies that adapt to domain-specific requirements, improving the precision and relevance of data interpretation [11]. The Gene Ontology (GO) and KEGG Ontology (KO) are central to this area (Table 5), providing standardized vocabularies that support bioinformatics applications by categorizing genes, proteins, and biological processes [56]. Highly cited tools (Table 5) like ClueGO and BiNGO leverage these ontologies to perform functional enrichment analysis, aiding researchers in linking gene expression data to specific biological functions. Context-aware ontologies ensure that complex, domain-specific concepts are accurately represented, supporting applications like disease classification in healthcare and functional genomics research [72]. Such specialized ontologies are essential for personalized medicine, where nuanced distinctions in data can inform targeted treatment decisions [72].

4.6.7. Ontology-Based Multi-Agent Applications

Ontology-based multi-agent systems facilitate interaction and coordination in distributed environments, such as IoT, big data, cloud computing, and autonomous systems [73]. This cluster addresses the application of ontologies in multi-agent settings, where standardized vocabularies enable agents to interpret and respond to data consistently. GO:TermFinder [49] is an example of an ontology-based tool that allows agents to navigate successfully into the ontological data and, hence, foster interoperability in complex systems. Ontology-based systems in multi-agent settings can, therefore, support applications in different fields including smart cities, industrial automation, and real-time data monitoring [74]. They allow agents to effectively and dynamically collaborate and join their efforts by relying on shared ontological structures [73]. Adopting this approach can promote system resilience and adaptability, which results in the production of coordinated responses to environmental changes or system demands in real-time.

4.6.8. Ontology-Driven Knowledge Graphs

Ontology-driven knowledge graphs represent a rapidly growing field that uses ontologies to structure, organize, and link vast datasets [75]. This cluster highlights the creation and management of knowledge graphs, where ontologies serve as the framework for connecting concepts and relationships. DBpedia [52] illustrates the application of ontologies in knowledge graph construction and demonstrates the way structured data can be used in advanced knowledge retrieval. The construction of those graphs provides major support to applications across AI and data science as it makes conducting complex searches, connecting disparate information possible, and supporting applications including semantic search, recommendation engines, and AI-based analytics [72]. Ontology-driven knowledge graphs are particularly valuable in enhancing machine learning by providing rich, context-aware datasets that improve model training and inference accuracy [72]. They enable more nuanced data exploration, supporting the organization and retrieval of information in diverse fields such as e-commerce, healthcare [76], and scientific research [75].

5. Conclusions

In the current research, a detailed in-depth analysis of ontology-based research publications produced from 1991 to 2022 is conducted. The data collected was retrieved from the Science Citation Expanded database. The findings revealed that the ontology research field thrives with patterns and trends, indicating the importance of this domain. The global nature of ontology research has also been revealed in the findings, with contributions from 109 countries. While the United States emerged as a prominent contributor, it was accompanied by other highly productive nations such as China, the United Kingdom, Spain, and Italy, which consistently maintained their positions across various citation indicators. Two universities were found to contribute to the significant influence of ontology-based research, namely the University of Manchester and Stanford University. Emerging also from the analysis of citation histories is the dynamic connectedness between enduring influences, the ever-changing progressive nature of ontology research, and the importance of scrutinizing the long-term influence of seminal articles. Finally, the examination of different research foci identified eight primary topic clusters, encompassing vital areas like ontology creation, text processing, reasoning, and querying, semantic alignment, ontology learning, domain-specific ontologies, multi-agent applications, and knowledge graphs. These clusters reflected the evolving trends and highlighted the stability in the field's topical coverage.

As a prospective direction to conduct future research, some unique initiatives will be taken to contribute to the ontology research domain, including embarking on interdisciplinary collaborations, incorporating recent emerging technologies, fostering research in ontology alignment and interoperability, implementing knowledge graphs, analyzing the long-term impact of ontology-research, and exploring the ethical and societal implications of conducting ontology-based research. The knowledge and insights presented in this analysis can serve as valuable resources for researchers and practitioners, empowering them to explore emerging research domains and tackle real-world issues through ontological methodologies. By doing so, they can contribute to the evolution of knowledge representation, the advancement of semantic technologies, and the facilitation of data-driven decision-making in the years to come.

Author Contributions

Conceptualization, Y.S.H. and H.T.; methodology, Y.S.H. and H.T.; software, Y.S.H.; validation, Y.S.H., H.T. and A.A.; formal analysis, Y.S.H.; investigation, Y.S.H. and H.T.; resources, Y.S.H.; data curation, Y.S.H. and H.T.; writing—original draft preparation, Y.S.H., H.T., and M.F.; writing—review and editing, Y.S.H., H.T., M.F., and A.A.; visualization, Y.S.H.; supervision, A.A., M.A.H.T., and M.B.A.; project administration, Y.S.H, A.A., M.A.H.T., and M.B.A.; funding acquisition, H.T. All authors have read and agreed to the published version of the manuscript.

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The authors declare no conflicts of interest.

Data Availability Statement

All the generated data are included in this research paper.

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