agronomy

Review

A Bibliometric Analysis of Research on Apple Snails (Ampullariidae)

Fucheng Yao [1,2], Yingtong Chen [1,2], Jimin Liu [1,2], Zhong Qin [1,2,3,4,*], Zhaoji Shi [1,2], Qi Chen [1,2] and Jiaen Zhang [1,2,3,4,*]

1 College of Natural Resources and Environment, South China Agricultural University, Guangzhou 510642, China; yaofuch@163.com (F.Y.); yingtongchenchn@163.com (Y.C.); liujimin1213@163.com (J.L.); shizhaojiyyy@gmail.com (Z.S.); qiqichen0913@163.com (Q.C.)
2 Guangdong Laboratory for Lingnan Modern Agriculture, South China Agricultural University, Guangzhou 510642, China
3 Guangdong Engineering Technology Research Centre of Modern Eco-Agriculture and Circular Agriculture, South China Agricultural University, Guangzhou 510642, China
4 Key Laboratory of Agro-Environment in the Tropics, Ministry of Agriculture and Rural Affairs, South China Agricultural University, Guangzhou 510642, China
* Correspondence: q_breeze@scau.edu.cn (Z.Q.); jeanzh@scau.edu.cn (J.Z.)

Abstract: Apple snails (ASs), the freshwater snails of the family Ampullariidae, are widely spread in tropical and subtropical regions. Owing to their strong invasiveness and harmful effects on agricultural production and ecosystems, they have attracted considerable attention. However, less research has been conducted on the whole picture of the current research status and development trends in the ASs field. For this purpose, we conducted a bibliometric analysis based on a total of 1028 publications regarding ASs published between 1900 and 2021 using VOSviewer 1.6.18 and CiteSpace 6.1.R3 software. The results suggest that ASs research has received increasing attention in recent years. The most productive country has been the USA, while the institution with the most publications was Consejo Nacional de Investigaciones Científicas y Técnicas Conicet. "Zoology" was the category of the most popular subject, *Journal of Molluscan Studies* was the primary journal, and P.R. Martin was the most outstanding author in ASs field. Invasive alien species, alarm response, copper (Cu) exposure, taxonomy and phylogenetic analysis, *Angiostrongylus cantonensis* (parasite), control (including molluscicidal activity), growth and reproduction, and feeding preferences were the main research hotspots. Further, "*Pomacea maculata*", "Evolution", "Biology", "Digestive gland", "Phylogeny", "Identification", "*Pomacea canaliculata* caenogastropoda", "Diversity", and "Nonnative apple snail" have been emerging active topics in recent years. These findings can help researchers in this area to better understand the direction and advances of ASs research and are valuable for future research and agricultural practice of apple snail control.

Keywords: apple snails; invasive alien species; bibliometrics; VOSviewer; CiteSpace; visualization analysis

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1. Introduction

In recent decades, the proliferation of invasive species has emerged as a significant environmental and economic issue on a global scale [1]. Invasive species, which are non-native species introduced into an ecosystem, have the potential to cause harm to native biodiversity and ecosystem function [2]. Their impact can be significant, including ecological, economic, and social consequences such as the extinction of native species, disruption of ecosystem services, and loss of livelihoods for local communities [3]. Therefore, it is imperative to prioritize the study of invasive species and explore strategies to control and manage their spread.

Apple snails (ASs, Ampullariidae) are freshwater snails originally from South America, which have spread to other parts of the world, including Africa, Asia, and non-native regions of the Americas [4,5]. Among the 10 genera in the Ampullariidae family, *Pomacea* has the highest number of species and has received the most attention [6]. *Pomacea* species have caused serious damage to local ecosystems and agriculture [7] since they have spread to tropical and subtropical regions in the world. This occurs mainly for *Pomacea canaliculata* and *Pomacea maculata*, which are the two most invasive and destructive species of ASs [8,9]. In fact, *P. canaliculata* is considered one of the 100 world's worst invasive alien species [10]. Consequently, these two *Pomacea* species have attracted significant attention in the ASs research field and are the primary focus of most studies in this area. It should be noted that studies in ASs field have mainly focused on *P. canaliculata*, but of course there is also some focus on *P. maculata*, so the results in this study overwhelmingly describe both.

Since *P. canaliculata* was defined as an invasive alien species, the field has been of increasing concern. To control the spread of ASs and mitigate their impacts, significant research efforts have been devoted to understanding their biology, ecology, and control strategies [11–13]. Researchers have studied various aspects of ASs, including their life cycles [14], reproductive behaviors [15], feeding habits [16], and habitat preferences [17]. This information is essential for developing effective management plans and controlling the spread of ASs in different environments and habitats. Taxonomy [18], genetics and evolution [19], parasites [20], resource utilization [21], and other cross-disciplines in this field have also attracted extensive attention from researchers. In addition, some researchers have reviewed some of the studies in the ASs field from multiple perspectives. For example, Hayes et al. [4] reviewed 184 publications on the taxonomy and distribution of *P. canaliculata* and *P. maculata*, elucidating the morphological differences and genetic characteristics as well as the geographical distribution of the two snails. Horgan [22] collected 162 publications in ASs field to review the ecology and physiology of ASs (especially *P. canaliculata* and *P. maculata*) and their impact on rice production systems. Panda et al. [23] reviewed 193 publications on ecotoxicity management methods for ASs, describing their feasibility as pollutant ecotoxic indicators.

Bibliometrics is a precise and objective approach that utilizes statistical and mathematical analysis to study extensive bodies of literature, enabling the extraction of measurable data to drive progress in knowledge [24]. It avoids the biases commonly found in traditional literature reviews. Bibliometric analysis is scalable and efficient, handling large volumes of literature to gain insights more effectively than traditional reviews. It involves the quantitative analysis of bibliographic data (i.e., authorship, country, institution, journal co-occurrence analysis as well as journal, author, and reference co-citation analysis) to identify key publications, influential authors, and emerging research topics [25]. Through reference co-citation analysis, researchers can identify clusters of closely related hot research topics to determine research hotspots and trends in specific fields [26].

ASs remain a hot spot for research on biological invasions as the number of concerns and publications continues to grow steadily. It is necessary and urgent to summarize the current research status, development trends, and research hotspots and advances in the ASs field. Here, we conducted a bibliometric analysis of the ASs research area. Specifically, CiteSpace was used for keyword co-occurrence analysis as well as author, country, institution, and keyword burst detection. Meanwhile, VOSviewer was used to perform country, institution, and author co-occurrence analysis as well as reference co-citation analysis. The findings are expected to help researchers to understand current research hotspots, trends, and emerging topics in the ASs field. This knowledge will enable them to stay updated and explore new avenues for further investigation.

2. Materials and Methods

2.1. Data Sources and Collection

The ASs-related literature was collected from the Science Citation Index Expanded (SCI-E) and the Social Sciences Citation Index (SSCI) in the Web of Science (WOS) Core Collection database of the Institute for Scientific Information (ISI) on 26 September 2022 [24,25]. The data source for the analysis was obtained by searching for subject words. TS stands for "Topic Subject" search in Web of Science search, which is a Boolean logic-based data search method that provides a way to quickly obtain a large amount of subject-related data. The search method is TS = ("*Pomacea canaliculata*" OR "Apple snail" OR "Apple snails" OR "Golden apple snail" "Ampullaria crossean" OR "Ampullaria gigas" OR "*Pomacea maculata*" OR "*Pomacea occulta*" OR "*Pomacea insularum*" OR "*Pomacea lineata*" OR "*Pomacea diffusa*" OR "*Pomacea bridgesii*" OR "*Pomacea doliodes*" OR "*Pomacea haustrum*" OR "*Pomacea paludosa*" OR "*Pomacea* spp." OR "Ampullariidae"), which includes the scientific and common names of ASs. The search spanned from 1900 to 2021. Finally, a total of 1028 records were obtained, including articles, meeting abstracts, reviews, proceedings papers, notes, and letters. These literature data were downloaded in two batches and exported as text-based files, including full records and cited references.

2.2. Research Methods

Bibliometrics is increasingly used to analyze the development and evolution of different disciplines [27–29]. Currently, bibliometric analysis typically utilizes software programs (e.g., VOSviewer, CiteSpace, etc.) to analyze literature data in a specific research area and visualize the results in a more intuitive way. CiteSpace is a visualization tool for scientific citation analysis developed by Prof. Chaomei Chen of the School of Computing and Informetrics at Drexel University; it is based on the Java language, with functions that mainly include co-occurrence analysis (author, institution, country, keyword, term, category), coupling analysis (reference, fund), and co-citation analysis (author, journal, reference) [30–32]. VOSviewer, on the other hand, is a software tool developed by the Centre for Science and Technology Studies at Leiden University in the Netherlands for bibliometric analysis applications [33]. Although VOSviewer and CiteSpace have similar functionalities, VOSviewer places more emphasis on graphical representations [34].

In this study, we utilized the bibliometric function in Web of Science (WOS) to analyze the type of literature, publication development trends (visualized by Origin 2022 software), major subject categories, countries and institutions, journals, and authors, which were presented in a tabular format. Additionally, we employed VOSviewer 1.6.18 to conduct co-occurrence analysis (Countries, Organizations, Authors) and co-citation analysis (Journals, Reference) of the ASs research domain. We combined the results with Scimago Graphica 1.0.25 software to visualize the results of the country co-occurrence analysis. VOSviewer parameter settings were: (1) Type of analysis for co-occurrence analysis selects Co-authorship, Unit of analysis = Authors, Organizations, Countries; (2) Type of analysis for co-citation analysis selects Co-citation, Unit of analysis = Cited references and Cited sources; (3) Counting method = Full counting, using text files to import into VOSviewer thesaurus file (optional) for synonym merging, word deletion, etc. The remaining parameters were set to default. Furthermore, we used CiteSpace 6.1.R3 to perform keyword network clustering analysis and burst detection (country, institution, author, and keyword) in the ASs research domain. This allowed us to explore the research hotspots and developments in the domain, as well as predict future trends. The CiteSpace parameter settings were: (1) The time slicing was from 1952 to 2021, years per slice = 1; (2) Node type = Country, Institution, Author, and Keyword; (3) Pruning = Pathfinder and Pruning sliced networks, Pruning the merged network. The other parameters were set to default. After running, the results of country, institution, author, and keyword burst detection were exported separately.

3. Results

3.1. Literature Types

The ASs research domain comprises nine types of documents (Figure 1), with articles being the most prevalent type of publication, accounting for 90.11% of the total type in the ASs literature. This indicates that articles are the primary medium of scholarly communication in this research domain. Meeting abstracts, reviews, and proceeding papers were also significant avenues of scholarly communication, representing 2.85%, 2.57%, and 2.19% of the total literature, respectively.

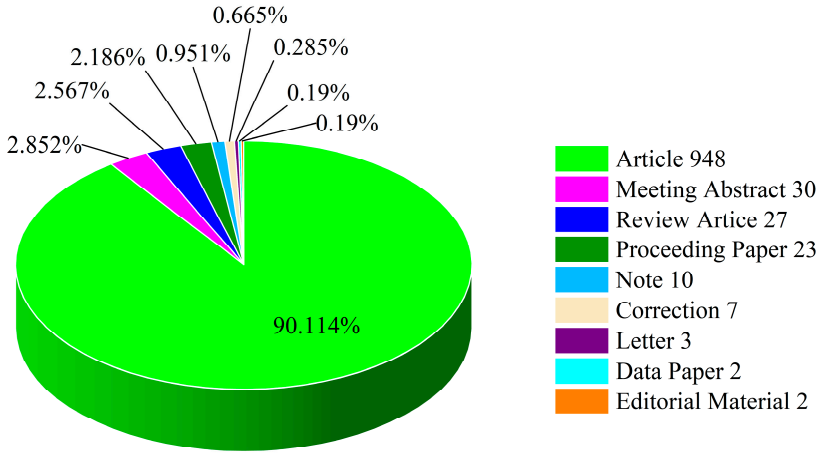


Figure 1. Literature types of the apple-snails-related publications from 1952 to 2021.

3.2. Publications Development Trends

The annual publication volume can reflect the development and level of attention provided to a particular field of study. In this study, a total of 1028 publications on ASs were retrieved from WOS between 1900 and 2021, with the first publication in 1952 *Nature Letter* [35]. Figure 2 shows that the number of annual publications on ASs is on an overall upward trend, with the highest number of publications (73) in 2018. This indicates an increasing interest in the field in recent years. However, compared with some other fields, the number of annual publications in ASs is still relatively low [24,25].

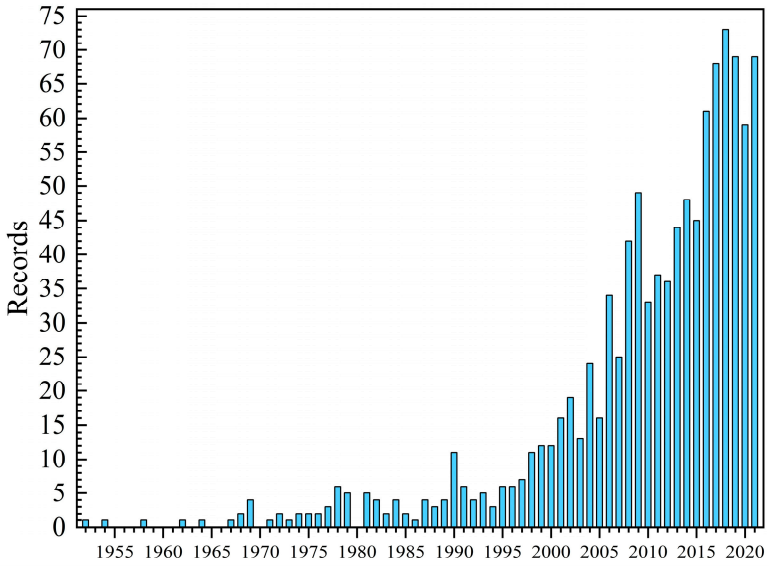


Figure 2. Records of annual publications in the apple-snails-related research field from 1952 to 2021.

3.3. Major Subject Categories

The ASs literature obtained from the WOS search covered 92 subject categories. The top 10 subject categories in the ASs field are shown in Table 1. Among these categories, "zoology" is the most popular, accounting for 22.37% of the total publications with 230 articles. The second subject category is "Marine Freshwater Biology" with 185 publications (18.00% of the total literature). Other top 10 subject categories in this field include "Ecology", "Environmental Sciences", "Biochemistry Molecular Biology", "Biology", "Biodiversity Conservation", "Multidisciplinary Sciences", "Fisheries", and "Entomology", and "Parasitology". ASs, a freshwater mollusk natively from the Americas, were originally used in the production of freshwater fisheries. However, the presence of ASs outside of their native range leads to significant consumption of local aquatic crops, which results in a reduction in ecosystem diversity. Additionally, since ASs carry parasites, their population expansion increases the likelihood of parasitic disease occurrence. As a result, research in the ASs field has expanded to include disciplines such as "ecology", "environmental science", and "Parasitology", reflecting the need to understand the broader ecological and environmental impacts of ASs invasions and the associated health risks.

Table 1. Top 10 subject categories in the apple-snails-related research field.

No.	Subject Categories	Records	Percentage/%
1	Zoology	230	22.37
2	Marine Freshwater Biology	185	18.00
3	Ecology	127	12.35
4	Environmental Sciences	106	10.31
5	Biochemistry Molecular Biology	88	8.56
6	Biology	71	6.91
7	Biodiversity Conservation	67	6.52
8	Multidisciplinary Sciences	63	6.13
9	Fisheries	49	4.77
10	Entomology	47	4.57
10	Parasitology	47	4.57

3.4. Distribution and Cooperation of Countries and Institutions

3.4.1. Countries

The number of research results published by the researchers in each country reflects the degree of the country's contribution to a field. In this regard, we listed the top 10 countries with the highest number of ASs productivity (Table S1). The United States (232, 22.57%), China (206, 20.04%), and Argentina (189, 18.38%) were the three countries with the highest number of publications.

From 1952 to 2021, publications related to ASs research from 59 countries and regions (25.3% of the total number of countries and regions worldwide, Figure 3) worldwide have been included in the WOS Core Collection (SCI, SSCI). Using VOSviewer and Scimago Graphica, we analyzed the cooperation relationships between these countries as well as their external cooperation strength (total link strength, TLS) of the countries (Table S1, Figure 3). Among these countries and regions, 52 have foreign scientific cooperation, while 7 have none. The United States (USA), China, and Argentina played important and central roles in the cooperative network, as evidenced by their high TLSs (Table S1).

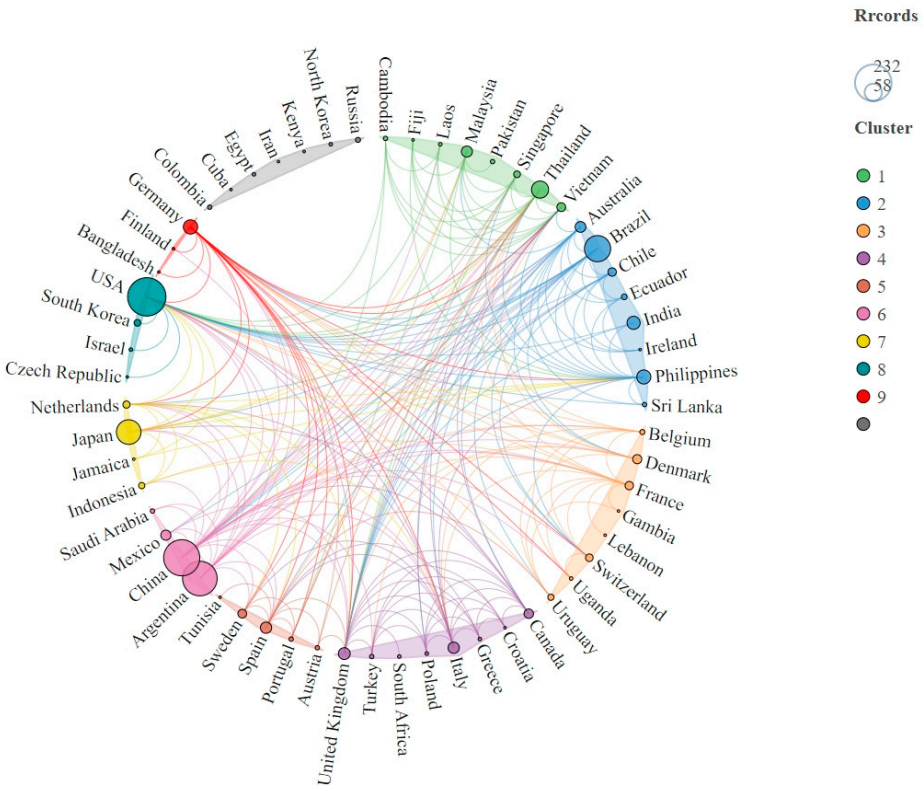


Figure 3. The network mapping of country cooperation in the apple-snails-related research field. Each node represents a country. The size of the node is proportional to the number of publications in the country. The set of the same dot color is a cluster, representing close cooperation between countries.

The publication time of the countries analyzed is useful for understanding the main periods of national contributions to a given field, which reflects the different countries' periods of high activity in the field. The ASs studies in these countries are mainly focused on the period 2010–2020 (Figure 4). The United States (USA) had a concentration of ASs studies in 2010–2011, while Brazil, Japan, the Philippines, Germany, Mexico, and India had concentrations in 2010. Argentina, the United Kingdom, and Sweden had concentrations in 2011–2012, and China, Thailand, France, and Canada in 2015–2016 (Figure 4).

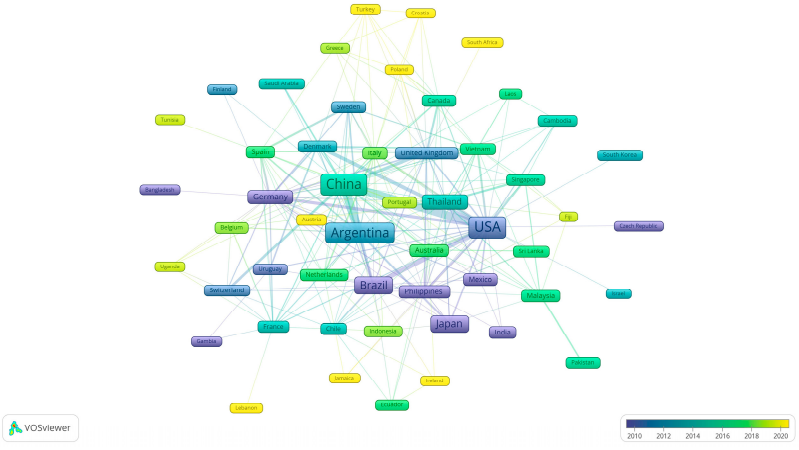


Figure 4. The main period in which the country conducted research in the field of the apple-snails-related research. Each square represents a country. The color of the squares indicates the time, and the thicker line between them means the closer the cooperation between countries.

3.4.2. Institutions

Analyzing the number of publications by institutions enables us to evaluate the research capacity and potential of institutions worldwide and facilitates the identification of the leading institutions in ASs research. Table S2 indicates that the Consejo Nacional de Investigaciones Científicas y Técnicas Conicet (Argentina) was the most productive institution, with 133 publications. The State University System of Florida (USA) ranked second with 71 publications, followed by institutions such as the National University of the South (Argentina), and the United States Department of the Interior (USA). Among these 10 institutions, five are from Argentina (South America), while Asia and United States (North America) had three and two institutions, respectively. Argentina stands out as a dominant pioneer in ASs research, with half of the top institutions located there.

From 1952 to 2021, a total of 1028 ASs-related studies were published by 906 institutions. To construct a collaborative network, we selected 66 institutions with at least five publications and visualized the network using VOSviewer (Figure 5). These institutions were grouped into 11 clusters, with strong academic collaboration between the institutions in each cluster. The institution with the most external academic cooperation was the Hong Kong Baptist University (China), with TLS (58) ranking first, followed by the South China Agricultural University (China), and the University of Florida (USA) (Table S2, Figure 5). Figure 5 illustrates the close academic cooperation between the Hong Kong Baptist University (China), National University of La Plata (Argentina), and Hong Kong University of Science & Technology (China).

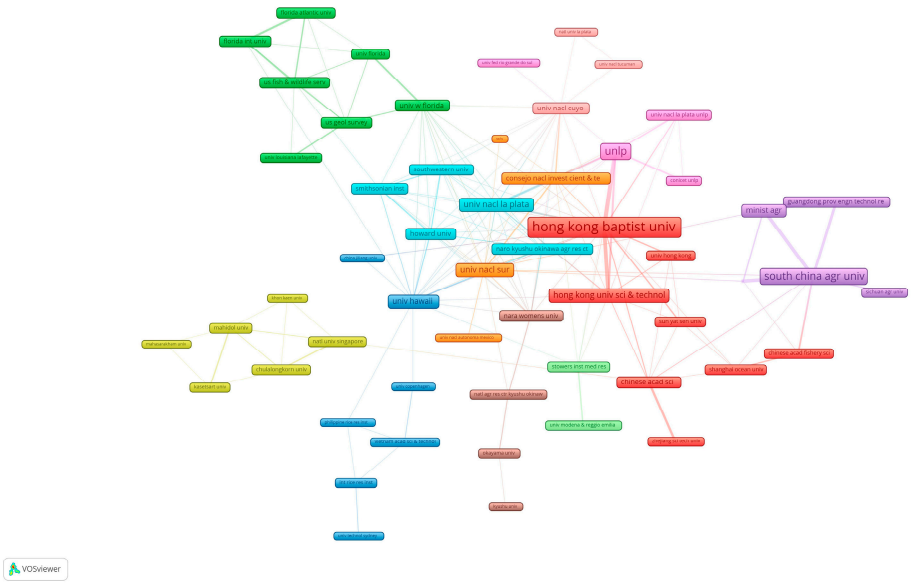


Figure 5. The network mapping of institutional cooperation in the apple-snails-related research field. Each square represents an institution. The width of the square is proportional to total link strength (TLS, indicating the strength of external cooperation). The same color represents a cluster (close cooperation), and the thicker line between them means the closer the cooperation between institutions.

3.5. Main Journals Source

Understanding the distribution of ASs-related publications across journals is important for researchers to identify the relevant journals for reading and submitting their work. We counted the top 10 journals in terms of the number of ASs publications (Table 2), with a cumulative total of 222 publications, representing 21.60% of the total publications, indicating a broad range of journals publishing ASs studies. In particular, the *Journal of Molluscan Studies* had the highest number of publications (43, or 4.18% of the total), followed by *Malacologia*, *Biological Invasions*, *PLoS ONE*, and *Biocell*, which had 31, 24, 21, and 20 publications, respectively (3.02%, 2.33%, 2.04%, and 1.95%, respectively). The top

10 journals spanned multiple subject areas, including Zoology, Marine Freshwater Biology, Entomology, Environmental Sciences, Fisheries, and Ecology, indicating the broad interest of researchers in studying ASs. This finding is consistent with the results presented in Table 1.

Table 2. Top 10 journals in terms of publication records in the apple-snails-related research filed.

No.	Journals	Records	Percentage/%
1	*Journal of Molluscan Studies*	43	4.18
2	*Malacologia*	31	3.02
3	*Biological Invasions*	24	2.33
4	*Plos One*	21	2.04
5	*Biocell*	20	1.95
6	*Hydrobiologia*	17	1.65
7	*Crop Protection*	15	1.46
8	*Freshwater Biology*	14	1.36
9	*Molluscan Research*	13	1.26
10	*Applied Entomology and Zoology*	12	1.17
10	*Journal of Shellfish Research*	12	1.17

3.6. Author's Contribution and Collaboration

The number of publications by authors is a visual indicator of their contribution to scientific research activities in the field. P.R. Martin (54 publications) was the most productive researcher, followed by H. Heras (44 publications) and A. Castro-Vazquez (38 publications). Other highly productive authors included I.A. Vega, J.E. Zhang, J.W. Qiu, M.S. Dreon, and Y. Yusa, all of whom had $\geq$30 publications in the ASs field (Table 3). Notably, half of the top 10 authors were from Argentina, reflecting the country's importance in the ASs field in terms of institutions, countries, and authors.

Table 3. Top 10 Authors in terms of publication records in the apple-snails-related research.

No.	Authors	Records	Percentage/%	Citations
1	P.R. Martin (Argentina)	54	5.25	1113
2	H. Heras (Argentina)	44	4.28	930
3	A. Castro-Vazquez (Argentina)	38	3.70	712
4	I.A. Vega (Argentina)	34	3.31	645
5	J.E. Zhang (China)	32	3.11	200
5	J.W. Qiu (China)	32	3.11	850
5	M.S. Dreon (Argentina)	32	3.11	664
5	Y. Yusa (Japan)	32	3.11	830
9	T. Wada (Japan)	25	2.43	795
10	P.C. Darby (USA)	20	1.95	532

Author collaboration networks provide insight into collaborative relationships between authors and highlight high-contribution collaborative teams in the field. A total of 2813 authors participated in ASs study during 1952–2021. We selected authors with $\geq$5 publications; 93 authors met this condition, and the largest collaborative network (59 authors) was constructed using VOSviewer (Figure 6). The collaboration network was divided into nine clusters, representing nine major research teams in the ASs field (Figure 6). Nine of the top ten authors were from six of the collaborative teams. M.S. Dreon and H. Heras were from one institution (UNLP), while I.A. Vega and A. Castro-Vazquez were from another institution (Consejo Nacional de Investigaciones Científicas y Técnicas Conicet). In addition, H. Heras had close collaborations with half of the top 10 authors, indicating a strong external collaboration. P.R. Martin, as the author with the most ASs publications, had collaborations with 3 of the top 10 authors.

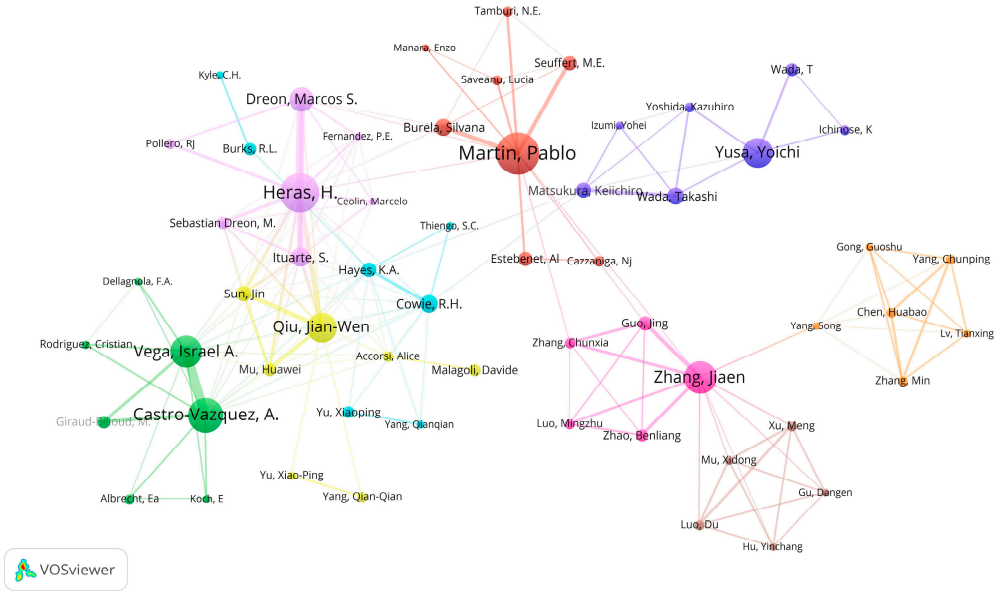


Figure 6. The network mapping of author cooperation in the apple-snails-related research field. Each circle represents an institution. The area of the circle is proportional to total link strength (TLS, indicating the strength of external cooperation). The same color represents a cluster (close cooperation), and the thicker line between them means the closer the cooperation between authors.

3.7. Research Hotspots

3.7.1. Keywords Co-Occurrence Analysis

Co-occurrence and cluster analyses of keywords group similar keywords generate clusters representing research topics in the field. To achieve more accurate results, we used the LLR method to label the ASs keyword clusters. Figure 7 presents the keyword co-occurrence network for the ASs field from 1952 to 2021, and we selected the top 10 keyword clusters and provided several indices (Size, Silhouette) related to them in Table 4. The clusters 0–9 are alien species, alarm response, invasive species, copper (copper exposure), *Pomacea canaliculata*, *Angiostrongylus cantonensis*, Ampullaria crossean, taxonomy, phylogenetic analysis, and molluscicidal activity, respectively (Figure 7, Table 4).

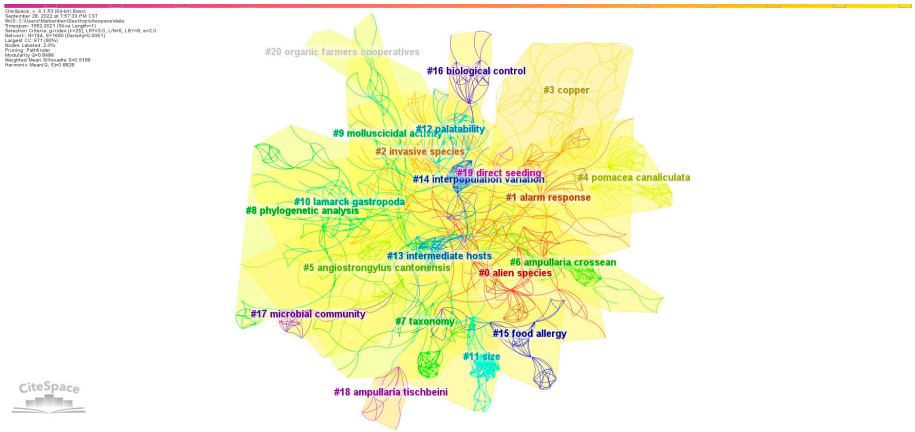


Figure 7. The keyword co-occurring network in the apple-snails-related research field from 1952 to 2021.

Table 4. The top 10 clusters and related feature information for apple-snails-related research.

Cluster ID	Size	Silhouette	Mean (Year)	Label (LLR)
0	56	0.934	2006	Alien species
1	56	0.896	2005	Alarm response
2	53	0.851	2010	Invasive species
3	45	0.907	2008	Copper (copper exposure)
4	41	0.971	1998	*Pomacea canaliculata*
5	41	0.948	2010	*Angiostrongylus cantonensis*
6	40	0.935	2007	Ampullaria crossean
7	39	0.876	2012	Taxonomy
8	35	0.955	2011	Phylogenetic analysis
9	34	0.808	2009	Molluscicidal activity

3.7.2. Co-Citation Analysis of References

The co-citation network of these 50 references (citations $\geq$ 35) was constructed using VOSviewer and Scimago Graphica, as depicted in Figure 8. These references were divided into four clusters, as indicated by their colors: orange (cluster 1, 16 references), blue (cluster 2, 15 references), green (cluster 3, 13 references), and purple (cluster 4, 6 references).

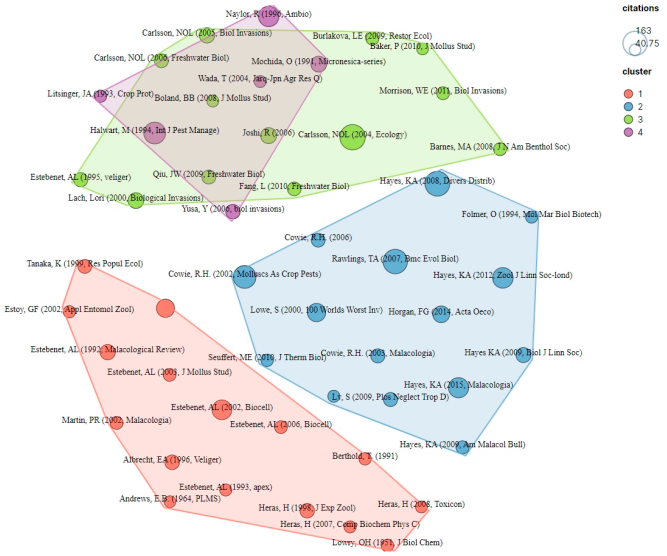


Figure 8. Co-citation network of cited references in the apple-snails-related research field. Each node represents a reference. The size of the node is proportional to the number of times referenced. The same color represents a cluster.

3.8. Burst Detection in ASs Research Area

3.8.1. Emerging Research Topics

We obtained some keywords with bursts in the past decade through CiteSpace (Table 5), and the red line indicates the time period of the burst. From Table 5, we found that studies related to "Caenogastropoda ampullariidae", "*Pomacea maculata*", "Evolution", "Biology", "Digestive gland", "Phylogeny", "Identification", "*Pomacea canaliculata* caenogastropoda", "Diversity", "Nonnative apple snail", and "Macrophyte" were the emerging topics of ASs in recent years.

Table 5. Top 11 Keywords in terms of publication records in the apple-snails-related research. Red line indicates the time period of the burst.

Keywords	Strength	Begin	End	2000–2021
Caenogastropoda ampullariidae	7.53	2016	2018	
Pomacea maculata	6.34	2016	2021	
Evolution	5.72	2018	2021	
Biology	5.66	2016	2018	
Digestive gland	4.77	2018	2021	
Phylogeny	4.75	2019	2021	
Identification	4.71	2018	2021	
Pomacea canaliculata caenogastropoda	4.70	2019	2021	
Diversity	4.41	2014	2019	
Nonnative apple snail	4.40	2010	2016	
Macrophyte	4.33	2013	2017	

3.8.2. Prominent Authors of Different Periods

Through the burst detection of authors, we identified authors who contributed prominently during different periods. We further grasped the latest research trends in the field of ASs by tracking the research of authors who have made outstanding contributions in recent years. We produced the outbreak of authors from 1952 to 2021 through CiteSpace, with results focused on 1967–2021 (Table 6). The results show that the author with the largest burst strength was J. E. Zhang, followed by Y. Yusa, J. Guo, and T. Wata, who are all from Asia. This means that the ASs invasion of Asia had attracted a lot of attention from researchers in the region. Surprisingly, authors of the top bursts in the last decade are all from China, reflecting the widespread interest in the dangers of ASs to Chinese agriculture and ecology, and the mechanisms of its invasion.

Table 6. Top 9 authors with the strongest citation bursts in the apple-snails-related research. Red line indicates the time period of the burst.

Authors	Strength	Begin	End	1967–2021
J. E. Zhang (China)	10.20	2014	2021	
Y. Yusa (Japan)	6.57	2002	2007	
J. Guo (China)	5.50	2016	2019	
T. Wada (Japan)	5.02	1999	2009	
A.L. Estebenet (Argentina)	4.70	1988	2005	
K. Swami (Scotland)	4.46	1967	1985	
P.C. Darby (USA)	4.38	1999	2008	
R.J. Pollero (Argentina)	4.29	1996	2006	
Q.Q. Yang (China)	4.27	2018	2021	

3.8.3. Active Countries and Institutions of Different Periods

The burst detection of countries and institutions allows us to understand the countries and institutions active in the ASs field at different periods of time. Tables S3 and S4 present the top 10 burst countries and institutions for the ASs study from 1952–2021, respectively.

As Table S3 shows, Japan had the strongest burst from early 1990 until 2009, and lasted for 20 years. However, among these burst countries, India and Brazil were the first to show vigor in the field of ASs, but they slowed down their ASs-related research after 1979 and 1997, respectively. In contrast, the bursts in the United States, China, and Chile were concentrated in two to three years, and all occurred after 2007, which may be related to the progressive prominence of ASs hazards. In the last 5 years, Australia has become the latest top burst country, which indicates that more and more countries are taking ASs-related research seriously.

The burst of institutions from 1998 to 2010 was associated with National Agricultural Research Center Kyushu Okinawa Regional (Japan), National University of La Plata (Argentina), Florida International University (USA), and Kyushu University (Japan). In the following period from 2013 to 2021, the bursts occurred at the South China Agricultural University (China), Universidad Nacional de La Plata (Argentina), Consejo Nacional de Investigaciones Científicas y Técnicas Conicet (Argentina), Key Laboratory of Agro-Environment in the Tropics sponsored by Ministry of Agriculture (China), Guangdong Engineering Technology Research Center of Modern Eco-agriculture (China), and Sichuan Agricultural University (China). This result indicates that those institutions in China and Argentina were dominant in ASs field. Among those institutions, four were from China, three from Argentina, two from Japan, and one from the United States. This result coincides with the contribution of institutions from the different countries mentioned above to the ASs field.

4. Discussion

4.1. Research Trends

We identified four temporal phases in the development of ASs research based on annual publication trends (Figure 2). The first phase (1952–1977) was a nascent period with an average of 0.97 publications per year, indicating that AS concerns were at a relatively low level. At this phase, the research emphasis was directed toward exploring biological properties, such as the study of yolk proteins (protein glands) in ASs [36]. The second phase (1978–1994) saw the field gradually gaining attention, with an average of 4.06 publications per year. The research during this phase focused mainly on the physiological and biochemical aspects of ASs [37,38]. However, during 1993–1994, studies emerged highlighting the harm caused by ASs to rice after its introduction into Asia, and the potential environmental consequences of farmers' excessive use of molluscicides [7,39]. The third phase (1995–2009) witnessed a rapid increase in the number of publications, from 6 in 1995 to 49 in 2009. As the spread of apple snails continues, their negative impacts are gradually becoming more apparent. The ASs were introduced to Asia (Taiwan province, China) in 1980 and, by 1990, the invasion had caused damage to Philippine rice agriculture, ranging from USD 425 to 1200 million [40]. During this period, studies on ASs control were also prevalent using chemical and phytogenic molluscicides [41,42], as well as research on its phylogeny [43] and the parasitic nematode *A. cantonensis* [44,45]. The fourth phase (from 2009 to present) showed stable and continuous growth, with an average of 53.5 publications per year and a maximum of 73 papers published in 2018.

4.2. Hotspot Research

4.2.1. Hotspot Research for Keywords Cluster

The analysis of keywords (co-occurrence analysis and cluster analysis) can help identify hot research topics in a specific field [46–48]. "Size" represents the number of keywords in the cluster. "Silhouette" indicates the homogeneity level of a cluster, and a value above

0.5 indicates highly reliable clustering results [49,50]. "Mean (year)" reflects the average year of each element in the cluster [49]. The top 10 ASs-related keyword clusters are concentrated between 1998 and 2012, and all the top 10 clusters have a "Silhouette" value above 0.8, which is considered reasonable (Table 4). However, we found that the topics of those clusters overlapped or had similar meanings. Therefore, we grouped similar clusters together for analysis. For example, Cluster IDs 0 and 2, and Cluster IDs 4, 6, 7, and 8.

Cluster ID 0 (alien species) and Cluster ID 2 (invasive species). Invasive alien species (IAS) are those non-native species that threaten ecosystems, habitats, or species [1], and cause biological invasions as one of the main drivers of resulting global environmental changes [51]. In 2000, *P. canaliculata* was listed on the IUCN list of the world's 100 most serious invasive alien species, making them the only freshwater snail on the list [10]. The apple snails, native to South America, were first introduced to Asia (Taiwan province, China) for commercial use in 1980, then to the Philippines and Japan as a human food in 1981, and successively to Korea (1986), Indonesia (1987), Malaysia (1987), Vietnam (1988), Thailand (1990), and Laos (1992) [8,38,39]. In addition, *P. canaliculata* has been introduced to the southern United States (North America), Chile (South America), Spain (Europe), and Ecuador (South America) [52]. In their new habitats, apple snails lack natural enemies and reach sexual maturity much faster compared with their native habitat in Argentina [10]. This, combined with their high egg production and hatching rate [53], enables them to reproduce rapidly in their new environment. ASs also have some powerful features, such as their omnivorous nature (eating almost anything they can tear open and put in their mouths) and strong tolerance to environmental stresses (cold temperatures [54], drought [55], starvation [10], and water contamination [56]), which help them establish a foothold in new habitats. The invasion of ASs poses a significant threat to countries that heavily rely on rice cultivation, as it can result in a significant reduction in rice and aquatic crop yields, leading to substantial economic losses [39,40,43,57]. Additionally, ASs were a serious threat to the biodiversity and function of natural ecosystems (wetlands) [58–60]. For instance, the introduction of ASs can cause the transformation of macrophyte-dominated aquatic ecosystems into planktonic ones, resulting in a complete alteration of species composition [12,61].

Cluster ID 1 (alarm response). Many aquatic animals exhibit corresponding alarm responses (e.g., aquatic snails bury themselves in the soil or crawl out of the water when they are in danger, etc.) to chemical or physical cues from injured conspecifics or predators [62–64]. When apple snails detect danger, chemical signals from predators, or companions, they exhibit a series of alarming responses to reduce their own damage. Different sizes of apple snails show different alarm responses (snails measuring 2–3 and 8–10 mm and 35–40 mm will crawl to the surface and bottom, respectively) in the face of chemical signals from predators such as *Anabas testudineus* [65]. The spawning rate of ASs increases in response to predator signals to prevent population extinction, but this results in slower growth (due to investment in spawning) and reduces egg hatching rates in female ASs [11,66]. Additionally, ASs can recognize chemical signals from injured companions and exhibit an alarm response, but the occurrence of this response is generally lower in the field than in the laboratory [67]. ASs can also discern the size of injured companions by chemical signals (they exhibit an alarm response to danger signals emitted by companions that are similar in size or larger than themselves, but they do not respond to signals emitted by smaller companions) and thus anticipate whether the predator poses a threat to itself [68,69]. ASs were more fearful of chemical signals from injured companions than those from predators and showed a more intense alarm response [70]. Meanwhile, females exhibited more active alarm responses than males [71].

Cluster ID 3 (copper (copper exposure)). In the past, copper sulfate was commonly used in agricultural production as a fungicide, fertilizer, and even for apple snail control, but its extensive use resulted in copper contamination in water, sediment, and soil [72,73]. ASs (*P. canaliculata*) showed reduced feeding rates and slow growth in the short term (10 days) under the influence of copper (20–67.5 $\mu g\ L^{-1}$), but their growth and reproduction were

little impacted in the long term [74]. This may be related to ASs' detoxification capacity for accumulated copper [75]. Moreover, the toxicity of copper was found to be more pronounced in juvenile ASs (*Pomacea paludosa*) than in adults, and the extent of toxicity was influenced by the quality of water, including factors such as pH and DOC [76]. However, the effect of copper exposure on the F_0 generation of ASs did not seem to affect the survival, growth, or whole-body copper concentration of the subsequent F_1 generation [77]. Recent studies have revealed that copper accumulation in ASs (*P. paludosa*) can pose a significant risk to predators of Florida apple snails, such as the snail kite (*Rostrhamus sociabilis plumbeus*) [78–81]. In addition, ASs (*P. canaliculata*) showed significant pathological alterations in tissues in copper-rich environments, suggesting that ASs can serve as a biomonitor of copper contamination in freshwater environments [82,83].

Cluster ID 4 (*Pomacea canaliculata*), ID 6 (ampullaria crossean), ID 7 (taxonomy), and ID 8 (phylogenetic analysis). Apple snails are freshwater and amphibious gastropods from the family Ampullariidae (Gastropoda: Caenogastropoda). *P. maculata* and *P. canaliculata* are two of the most pervasive and destructive invasive apple snails, as well as being the focus of research in the field [9,84]. However, the two species were only distinguished after 2007 with the popularity of molecular techniques (using mitochondrial markers to resolve the taxonomic confusion in ASs) [18], which previously generally considered *P. maculata* to belong to *P. canaliculata* [4,85]. Similarly, *P. diffusa* was recognized from *P. bridgesii* using this technique [43]. In addition, apple snail species include *P. insularum*, *P. lineata*, *P. doliodes*, *P. haustrum*, *P. paludosa* [19], and *P. occulta* [86], etc. Various scientific names, including Ampullaria crosseana, Ampullaria gigas, and Pila gigas, have been used to denote ASs, which has caused a degree of confusion [87]. Hayes et al. [43] used mitochondrial DNA sequences to reveal the presence of four non-native apple snails in Asia, inferred to be caused by multiple introductions in their native regions. Meanwhile, Hayes et al. [88] revealed the global phylogeny of the apple snail, showing different nuclear DNA sequences between *P. canaliculata* from Argentina and *P. maculata* from Brazil. Keiichiro et al. [89] revealed the gene exchange between *P. canaliculata* and *P. maculata*, indicating that both are hybridized in the invasive site and origin.

Cluster ID 5 (*Angiostrongylus cantonensis*). *A. cantonensis*, the main cause of human eosinophilic meningitis, was first discovered in Guangzhou, China, in 1933 [90]. ASs were an intermediate host of *A. cantonensis*, which is generally more common in *P. canaliculata* [91,92]. In addition, the reports of *A. cantonensis* infections in humans through the intermediate host ASs are mainly concentrated in China [45,92]. From 1994 to 2003, there were 78 cases of angiostrongyliasis associated with ASs in China, mainly through close contact, and consumption of raw or undercooked ASs [93]. *A. cantonensis* infection from ASs occurs frequently in Asia, including Laos, Cambodia and Vietnam [20], and Thailand [94], with China reporting the highest frequency [92]. The overall prevalence of *A. cantonensis* infection with ASs in China was 7.6% [92], with prevalence generally below average in the Guangdong Province (1.5–6.50%) [95–97] and above average in the Hainan Province (12.36%) [98]. However, *A. cantonensis* infection of ASs was not found in two surveys in Brazil, but was present in other intermediate hosts (e.g., *Achatina fulica* and *Melanoides tuberculata*) [99,100].

Cluster ID 9 (molluscicidal activity). ASs (e.g., *P. canaliculata*, *P. maculata*, etc.) are recognized as global agricultural pests that have been targeted with various control measures. Currently, the use of traditional chemical molluscicides (e.g., niclosamide, metaldehyde, etc.) is the most widely used measure to control ASs [101,102]. However, the use of such chemicals can have adverse effects on non-target aquatic organisms and is not sustainable [41,103]. Therefore, developing eco-friendly and effective molluscicides has become a priority for ASs control. Plant-derived molluscicides are a promising option, as they are natural compounds that can effectively kill snails without causing resistance and are biodegradable. For example, compounds with molluscicidal activity have been extracted from *Pueraria peduncularis*, *Ambrosia artemisiifolia*, and *Schima superba*, among others [104–106]. Alternatively, existing molluscicides can be improved, such as through the

introduction of a urea group and a substituent (Cl) into the benzene ring of nicotinanilide, resulting in a new molluscicide PBQ with high molluscicidal activity against ASs and low toxicity to non-target organisms [13,107].

4.2.2. Hotspot Research for References Co-Citation Analysis

The articles in the orange cluster primarily investigate the growth and reproduction of ASs. Habitat density can affect the growth and reproductive potential of ASs, because high densities may hinder these processes [108]. Additionally, ASs' shells exhibit variations across different habitats [109]. In terms of reproduction, ASs typically mate about 2.9 times per week, primarily during the day (82%), and lay eggs about 1.4 times per week, mostly at night (93%) [110]. Notably, the eggs of ASs contain protein neurotoxins that protect the reproductive abilities of their offspring [111].

The blue cluster in Figure 8 focuses on the taxonomy and phylogenetic analysis of ASs. Taxonomy and phylogenetic analysis have proven to be powerful tools for the identification and investigation of the spread and evolution of ASs [6]. For example, researchers have used the analysis to identify four AS species in Asia and trace their pathways of spread [43]. In 2007, five non-native ASs species were also discovered in the United States [85]. Furthermore, the two most invasive species of ASs have been completely distinguished from each other through the developments in this field [4].

The green cluster includes articles on the feeding preferences of ASs and their effects. The ASs demonstrate a certain level of discriminatory ability toward aquatic plants and selectively prey on those with weaker defense mechanisms [10,112]. For example, apple snails prefer to feed on water hyacinth first, followed by water lettuce and then water spinach [16]. Additionally, juvenile ASs have a higher relative foraging ability than adults [113].

The research in the purple cluster focuses on the control of ASs. The control of ASs can be achieved through various methods such as chemical, mechanical, biological, cultural, and resource utilization [39]. For instance, managing ASs populations can be achieved by performing crop rotation with upland rice, employing molluscicides, and introducing natural predators, such as leeches and carps [114].

4.3. Emerging Research

Keyword burst detection analysis reflects the trends of hot topics in a specific research area, while focusing on recently burst keywords enables picking out emerging research topics [49]. Emerging topics included "Caenogastropoda ampullariidae", "*Pomacea maculata*", "Evolution", "Biology", "Digestive gland", "Phylogeny", "Identification", "*Pomacea canaliculata* caenogastropoda", "Diversity", "Nonnative apple snail", and "Macrophyte". *P. canaliculata*, commonly known as the invasive apple snail, has been a focal point of research in the field for a considerable period of time. However, in recent years, another species, *P. maculata*, has gained increasing attention due to its expanding distribution and associated concerns. Therefore, both *P. canaliculata* and *P. maculata* are the focus of ASs research at this stage.

Advances in molecular biology have revolutionized the ability to differentiate among various species using molecular techniques. This has facilitated more precise studies on individual ASs species and provided researchers with additional tools to delve into aspects related to species evolution. Consequently, there has been a surge in research on apple snails, with a particular focus on areas such as species identification [115], evolutionary patterns [116], phylogenetics [117], and species diversity [118].

Moreover, the biological characteristics of invasive apple snails play a pivotal role in unraveling their invasion mechanisms. These characteristics, including their reproductive strategies, feeding behavior, and habitat preferences, contribute to their successful colonization and spread in new environments. Understanding the invasive traits of apple snails is crucial for developing effective management and control strategies to mitigate their ecological impact.

In terms of digestion and nutrient absorption, the digestive gland of apple snails assumes a vital role. Situated within the snail's visceral mass, this gland produces enzymes and secretes digestive juices that facilitate the breakdown of food particles [119]. The digestive gland also plays a significant role in the storage and distribution of nutrients, ensuring the fulfillment of the snail's energy requirements for growth and survival [120]. Additionally, the impact of apple snails on macrophytes (aquatic plants) has garnered increasing attention in recent years, as their feeding behavior can have profound effects on the ecological balance of aquatic ecosystems [121].

These recently emerging topics not only help us identify advances in the ASs research, but they also serve as a source of new trends. And these topics can lead to some new research questions, scientific hypotheses, and perspectives in future studies.

5. Conclusions

A bibliometric analysis revealed that the whole picture and research progress in ASs field can be divided into four periods: beginning (1952–1977), slow growth (1978–1994), rapid growth (1995–2009), and stable growth (2009–2021). ASs-related research is an interdisciplinary field that involves various areas such as zoology, marine freshwater biology, ecology, environmental sciences, and more. Half of the top 10 countries in terms of published articles in ASs area came from Asia, where close collaborations primarily occurred between Asian and American countries. The Consejo Nacional de Investigaciones Científicas y Técnicas Conicet, State University System of Florida, National University of the South, National University of La Plata, and Universidad Nacional Cuyo Mendoze are the top five most productive institutions. The *Journal of Molluscan Studies* has published the highest number of articles in the ASs field. Prof. P.R. Martin is the author with the highest number of publications and citations in this field. The research hot topics in AS research obtained from performing a co-occurrence analysis of keywords and co-citation analysis of the references included invasive alien species, alarm response, copper (Cu) exposure, taxonomy and phylogenetic analysis, *A. cantonensis* (parasite), control (including molluscicidal activity), growth and reproduction, and feeding preferences. The studies on the following topics have been the emerging active topics in recent years: "Caenogastropoda ampullariidae", "*Pomacea maculata*", "Evolution", "Biology", "Digestive gland", "Phylogeny", "Identification", "*Pomacea canaliculata* caenogastropoda", "Diversity", "Nonnative apple snail", and "Macrophyte". This study explores the literature information, co-occurrence analysis, and co-citation analysis in the ASs field in order to accurately understand the research overview, direction, and advances. It can help related researchers to better understand the development process and emerging research topics of the ASs field and provide new directions and ideas for their future research and control area.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13071671/s1, Table S1: Top 10 countries in terms of publication record and TLS in the apple snails-related research filed. Table S2: Top 10 Institutions in terms of publications record and TLS in the apple snails-related research filed. Table S3: Top 10 countries with the strongest citation bursts in the apple snails-related researches. Table S4: Top 10 institutions with the strongest citation bursts in the apple snails-related researches.

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