EGYPTIAN ACADEMIC JOURNAL OF
BIOLOGICAL SCIENCES
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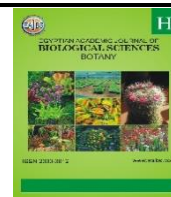
Wheat-Rust Interactions: A Comprehensive Study of Past 32 Years Using Bibliometric Analysis

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ABSTRACT

Wheat (*Triticum aestivum* L.) has been recognized as a major staple crop worldwide since the Green Revolution. It contributes to about 40% of the world's feeding requirements. However, several factors significantly reduce wheat productivity: for example, insects, rusts, foliar diseases, etc. Rust can form some new strains and can cause damage to resistant varieties; leaf, stem, and stripe are the most reported so far. The current study describes a comprehensive overview of leaf, stem, and stripe rust diseases and performs a bibliometric analysis. We used the WoSCC, and our keywords were "wheat" AND "Rust resistance" From the topics. The timespan was limited from 1990 to 2022. A total of 476 sources have published 5199 documents, with an annual growth of 7.27%. A total of 10457 authors contributed globally, and 154 papers were single-authored. A total of 9599 terms were used in the "Titles" of these documents, among which "wheat" appeared 1174 times, "resistance" 939 times, and "gene" was the primary third occurred term with a frequency of 404. A total of 106 countries have participated. The USA stood at the top, followed by Australia. A similar study is suggested using other databases like Scopus.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important food crops grown worldwide since the Green Revolution, as it contributes to about 40% of the world's feeding requirements (Yuan *et al.*, 2021). Wheat growth has increased enormously to ensure food security in developing countries; therefore, its production has made it possible to feed a large population (Arslan *et al.*, 2007). Due to its high demand for food markets, it has been noticed that wheat growth has been affected severely, resulting in substantial losses in its production, sometimes approaching more than 50% (Riaz and Wong, 2017). Some factors significantly reduce wheat productivity; for example, different stresses like drought and heat and insect diseases also play a significant part (Hussain *et al.*, 2017). Some other diseases also contributed considerably, such as bunts, ruts, and foliar diseases, to the reduction of wheat crop growth and yield (Soliman *et al.*, 2012). A report has proven that rust diseases are the most economically severe fungal diseases in some other cereals worldwide and are distributed in wheat-growing regions (Wellings, 2011). Rust can form some new strains and can cause damage to resistant varieties; these diseases can spread long distances with the help of windborne spores and develop faster under favorable weather conditions (Ghimire *et al.*, 2020). Leaf, stem, and stripe are the most commonly reported rust disease. Among them, leaf rust is the most common and fatal disease regularly occurring compared to stem

and strip (Cuddy *et al.*, 2016). Stem rust is not widespread compared to other diseases, as a wide range of wheat varieties i.e. showed resistance against it (Ayliffe *et al.*, 2008). Eight wheat genotypes (Misr-3, Misr-4, Giza-171, Gemmeiza-12, Lr34/Yr18, Lr37/Yr17, Lr46/Yr29, and Lr67/Yr46) were resistant to stripe and leaf rusts at seedling and adult stages (Omara *et al.*, 2021). With some newly reported outbreaks, stripe rust disease is also getting great at significant for its severance.

Leaf rust is a fungal disease caused by *Puccinia triticina* Eriks (*Pt*); it spreads aerially, damages wheat leaves, and ultimately affects photosynthetic activity badly. When *Pt* spores in incredible amounts break through the wheat leaf surface, they cause severe damage to the wheat by reducing the water intake, thus affecting wheat productivity and ultimately producing a significant loss in grain production (Gao *et al.*, 2019). It causes a 40% loss in wheat production, which is too high in susceptible wheat varieties, and is considered one of the leading fatal wheat diseases worldwide (Khan *et al.*, 2013). These losses are due to fewer kernels and their lower weights. *Pt* is now considered a severe pathogen in wheat-producing regions, which causes significant losses on a large scale (Kolmer and Hughes, 2014).

Puccinia striiformis Westend. (*Ps*), causes stripe or (yellow) rust and is known to be a destructive wheat disease in the present time (Wellings, 2007). It has been described that its occurrence took place a long time before wheat was grown, it was first reported in the year 1877 in Europe and has been found in more than 60 countries around the world with a severe consequence to wheat production due to which serious economic losses took place even in some developed countries in the world (Zeng and Luo, 2006). This disease affects the quality and quantity of grain and other cereals. The crops damaged by stripe have very low emergence at the seedling stage. The disease becomes so severe if it is not controlled in the early stage of its development; in some cases, it could cause 100% yield losses in developing countries due to the severity of its infection (Chen, 2005). This disease has caused damage to crop yield as well as its quality. According to some recently reported findings, about 20-40 % of wheat grain losses happened in susceptible wheat varieties due to stripe rust (Sharma *et al.*, 2016).

The bibliometric analysis provides a detailed, multidisciplinary research methodology, which includes various software usage, database management and statistics, and nowadays scientists are progressively using it for investigation and assessment (Chen *et al.*, 2016; Halepoto *et al.*, 2022). In contrast to "meta-analysis" and "research reviews," bibliometric analysis offers numerous benefits, including the ability to visually analyze datasets pertaining to authors, journals, keywords, institutions, and other relevant information; quantitative and statistical analyses of the research trends and features of a particular subject (Lv *et al*. 2021); research into frontiers and hotspots; and the exchange of knowledge and interactions between various disciplines (Chen *et al*. 2014). In recent years, bibliometric analysis has become increasingly popular (Gallegos-Cedillo *et al.*, 2021; Xu *et al.*, 2022). On the other hand, no bibliometrically based studies on the area of wheat-rust interaction have been recorded so far which has given us an opportunity to design the current study and fill the gap. In the current study research articles on wheat-rust interaction published during the last 32 years were gathered from the Web of Science Core Collection (WOSCC). Software like CiteSpace and VOS viewer were used to evaluate the database. The aim and objectives of our study are: (i) Scientists have been paying more attention to research on wheat-rust interaction in recent years, and therefore a detailed study is required for gathering information related to wheat-rust interactions. (ii) Research hotspots have demonstrated heterogeneity in different years within the issue of wheat-rust interaction. Therefore it is important to find out who conducted the research, when, and where it was done on wheat-rust interaction to make it easy for researchers to find out specific areas around the globe. Other goals included identifying research gaps and trends.

Wheat-Rust Interactions: A Comprehensive Study

MATERIALS AND METHODS

Study Design:

A retrospective bibliometric and graphical analysis was performed.

Literature Search:

Several databases are available to collect scientific literature. Web of Science is the most extensively used database. We used the Web of Science database "Core Collection" (WoSCC) on September 22, 2022, to search the relevant scientific literature on the host-pathogen interaction between wheat and rust. We have selected the three editions of the WoSCC, which were SCI-EXPANDED, Conference Proceedings Citation Index-Science, and Book Citation Index-Science. Our search keywords were "wheat" AND "Rust Resistance" From the topics. The topics can access the key strings from the title, abstract, author keywords, and keywords plus. A total of 5,199 documents were available. The timespan was selected from 1990 to 2022. We have exported all these documents as "plain text files" and set the option of "Full records and cited references." We have used Origin version 2022b (OriginLab Corporation, Northampton, MA, USA), Bibliometrics (Aria and Cuccurullo, 2017), and VOSviewer (Waltman and Van Eck, 2012) tools to analyze the data. We have extracted information from the Bibliometrix R tool, "biblioshiny". Biblioshiny is preferred here as it allows users to perform relevant bibliometric and visual analyses on an interactive web interface, greatly reducing user information input intensity and usage threshold (Chen *et al.*, 2016; Aria and Cuccurullo, 2017).

RESULTS

Main Information:

The extracted data was imported to "biblioshiny," an R tool to visualize the data. We have pulled the primary information. The timespan was limited from 1990 to 2022. A total of 476 sources have published all these 5199 documents, with an annual growth of 7.27%. A total of 10457 authors contributed globally, and 154 documents were single-authored. A detailed description is provided in (Table 1).

Fields of Study:

The data was analyzed to extract the relative information. Several bibliometric parameters were used to evaluate the retrieved literature. The built-in tool of the WoS was used to identify the "WoS categories". We have used the "The Origin Tool" Version 'Origin 2024b (10.15)' to draw the histograms, and a total of 68 fields of WoS categories were identified. The top 25 categories are shown in (Fig 1). The Highest number of publications were published in plant science following agronomy category.

**Annual Production of the Documents and Citations/Year:**

Our data can be traced back to 1990. In 1990, a total of 29 articles were published. The production over time was not smooth. From 1990 to 2006, the output was zigzagged, but in 2007, there was a big leap, and a total of 174 documents were released. Onwards, the production over time was progressive and reached its peak in 2021; a total of 346 documents were released, as shown in (Fig. 2A). The average annual citations per year were analyzed. The citations were not smoothly progressive. In 2018, the whole number "4" was reached. A description is provided in (Fig. 2B).

Three-field Plot of Keywords:

We have plotted the information into three fields, i.e.; Right, Middle, and Left. In (Fig. 2C), to the left, Keywords were assigned, at the Middle, Sources were assigned and to the Right, Titles were assigned.

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Table1. Main information extracted from the data about the publications on Wheat and Rust resistance

Description	Results
Timespan	1990:2022
Sources (Journals, Books, etc.)	476
Documents	5199
Annual Growth Rate %	7.27
Document Average Age	10.7
Average citations per doc	22.45
References	78134
Document contents	
Keywords Plus (ID)	4903
Author's Keywords (DE)	5668
Authors	
Authors	10457
Authors of single-authored docs	154
Authors collaboration	
Single-authored docs	249
Co-Authors per Doc	6.16
International co-authorships %	30.87
Document types	
Article	4545
Article; book chapter	64
Article; early access	31
Article; proceedings paper	77
Correction	18
Editorial material	81
Letter	14
Meeting abstract	105
News item	8
Note	15
Proceedings paper	39
Retraction	1
Review	187
Review; book chapter	13
Review; early access	1
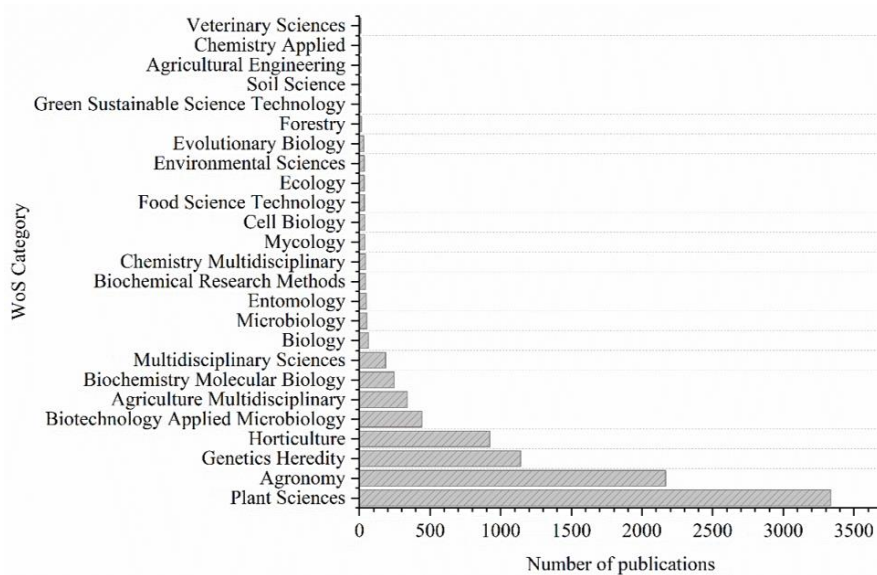
Fig. 1. A total of 25 (topmost) WoS categories are shown out of 68. Plant sciences has been on the top (3,336), followed by Agronomy (2,167). The graph was plotted in Origin 2022b.
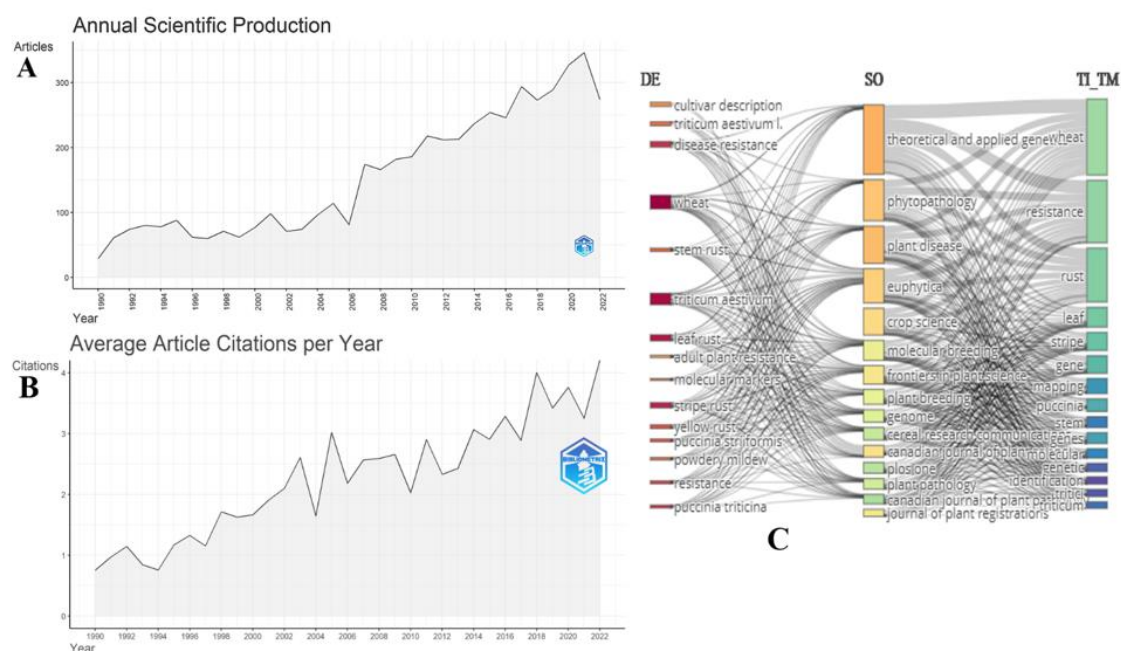
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Fig.2. A- Annual scientific production over time. The x-axis indicates years, while the y-axis indicates number of articles been published, **B-** Average article citation per year. The x-axis indicates the years, while the y-axis indicates the number average number of the citation, **C-** Three field plots. DE is keywords, SO is source, and TI_TM is the title.

Most Relevant Sources:

We have found that 476 sources were involved in the publication of the entire literature. We analyzed the data to find the top ten most relevant sources based on the number of publications, as shown in (Fig. 3A). A brief description of the Source's Local Impact with to 20 h-index is given in (Table 2).

Table 2. Brief description of the sources' local impact. The citation's list with the top 20 h-index

Element	h_index	g_index	m_index	TC	NP
Theoretical And Applied Genetics	70	105		18936	440
Euphytica	45	76	1.364	8283	262
Phytopathology	45	72	1.364	6936	278
Crop Science	42	65		5734	196
Plant Disease	40	66		6768	286
Genome	34	57	1.03	3819	108
Molecular Breeding	30	43	1.154	2711	128
Plant Pathology	29	49	0.879	2864	108
Plant Breeding	26	41	0.788	2284	114
Plos One	26	45	1.857	2313	87
Australian Journal Of Agricultural Research	24	44	0.727	2023	48
Frontiers In Plant Science	24	40	2.4	2331	157
Molecular Plant-Microbe Interactions	21	35	0.724	1328	35
New Phytologist	21	29		1086	29
Physiological And Molecular Plant Pathology	20	34	0.606	1177	46

Based on the number of publications, "THEORETICAL AND APPLIED GENETICS" Electronic ISSN: 1432-2242, Print ISSN: 0040-5752 with a total of 440 publications stood on the top. *Theoretical and Applied Genetics* publishes original research and review articles in all key areas of modern plant genetics, plant genomics, and plant biotechnology. The second topmost source identified was "PLANT DISEASE" which published 286 articles. *Plant Disease* published by *The American Phytopathological Society* ISSN: 0191-2917 e-ISSN: 1943-7692. *Plant Disease* is the primary worldwide publication for fast reporting on novel, developing, and established plant diseases. The journal covers translational and applied research on agricultural and horticultural crop disease diagnosis, development, and management.

Most Relevant Authors and Authors' Production over Time:

The most relevant authors were identified from the literature. *Xianming Chen,* with a total of 244 publications, remained at the top, (**Fig. 3B**) . He has published several research papers, review papers, and book chapters as well. He is primarily affiliated with the US Department of Agriculture – Agricultural Research Service and Department of Plant Pathology, Washington State University, Pullman, WA 99163, USA. Similarly, the authors' production over time was evaluated.

Most Relevant Institutions:

Several institutions were being involved in the research, as shown in (Fig. 3C). We found that Washington State Univ stands on the top with 551 articles. Northwest Aandf Univ comes in the second position with a total of 464 articles. The Corresponding author is the point of contact for the manuscript and related communications during the publication process, including final proofreading. We analyzed the data to find the most relevant corresponding authors based on the number of publications. We have found that the USA remained on the top with a total number of 1938 publications; out of which 741 were SCP (single author publications) while 297 were MCP (Multiple Country Publications), a brief description is provided in (Table 3).
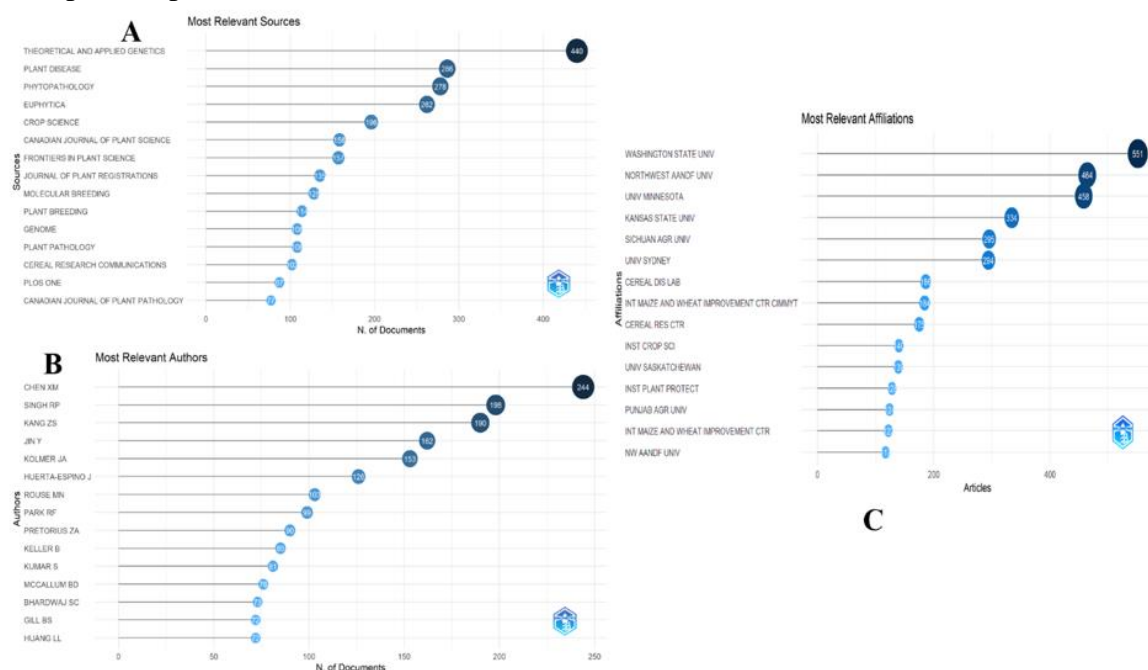

Fig. 3. A- Most relevant sources based on number of publications. The x-axis indicates the number of documents, the y-axis indicates the sources. Top 15 most relevant sources have been identified based on number of publications, **B-** Most relevant authors. Based on number of publications, the top 15 authors are shown. The x-axis indicates the author's name while the y-axis indicates the number of publications, **C-** Most relevant affiliations based on number of publications. The x-axis indicates the number of the articles while the y-axis indicates the name of the institutions.

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Table 3. Corresponding Author's Country

Country	Articles	SCP	MCP	Freq	MCP_Ratio
USA	1038	741	297	0.2	0.286
China	971	705	266	0.187	0.274
Canada	394	302	92	0.076	0.234
Australia	356	183	173	0.068	0.486
India	340	279	61	0.065	0.179
Mexico	153	76	77	0.029	0.503
Germany	141	93	48	0.027	0.34
United Kingdom	134	85	49	0.026	0.366
Pakistan	119	87	32	0.023	0.269
Russia	106	77	29	0.02	0.274
France	98	64	34	0.019	0.347
South Africa	97	67	30	0.019	0.309
Turkey	81	53	28	0.016	0.346
Brazil	74	60	14	0.014	0.189
Spain	62	43	19	0.012	0.306

Most Cited Countries:

Documents citations indicate its usefulness to the public and scientists. We have analyzed the data to extract the most cited countries, as shown in (Table 4). The USA, with a total of 31035 citations, scored first position, followed by China, with a total of 14560 citations.

Table 4. Most cited countries. The top 15 most cited countries are shown.

Country	Total Citations	Average Article Citations
USA	31035	29.90
China	14560	14.99
Australia	13958	39.21
Mexico	7204	47.08
Canada	6954	17.65
United Kingdom	5085	37.95
Germany	4147	29.41
India	3968	11.67
France	3574	36.47
Switzerland	3122	50.35
Denmark	2066	45.91
South Africa	1691	17.43
Israel	1514	30.90
Spain	1168	18.84
Netherlands	1015	26.71

The top 10 most cited documents are shown in (Table 5). The most cited article was "A Putative ABC Transporter Confers Durable Resistance to Multiple Fungal Pathogens in Wheat" which was published in "Science" and has earned a total of 788 citations (Krattinger *et al.*, 2009). A brief description of the top 15 most cited articles is provided in (Table 5).

Table 5. Top 15 most globally cited articles**.**

Paper	DOI	Total Citations	TC per Year	Normalized TC
Krattinger Sg, 2009, Science	10.1126/science.1166453	788	56.29	22.82
Chen Xm, 2005, Can J Plant Pathol	NA	711	39.50	13.86
Friebe B, 1996, Euphytica	10.1007/BF00035277	646	23.93	18.75
Song Qj, 2005, Theor Appl Genet	10.1007/s00122-004-1871-x	467	25.94	9.11
Fu Dl, 2009, Science	10.1126/science.1166289	454	32.43	13.14
Duplessis S, 2011, P Natl Acad Sci Usa	10.1073/pnas.1019315108	432	36.00	13.53
Draper J, 2001, Plant Physiol	10.1104/pp.127.4.1539	403	18.32	10.07
Singh, 2011, Annu Rev Phytopathol	10.1146/annurev-phyto-072910-095423	400	33.33	12.53
Hao, 2016, Plos One	10.1371/journal.pone.0150717	367	52.43	18.63
Watson A, 2018, Nat Plants	10.1038/s41477-017-0083-8	365	73.00	22.81
Borner A, 2002, Theor Appl Genet	10.1007/s00122-002-0994-1	355	16.90	8.46
Wellings Cr, 2011, Euphytica	10.1007/s10681-011-0360-y	348	29.00	10.90
Scofield Sr, 2005, Plant Physiol	10.1104/pp.105.061861	343	19.06	6.69
Feuillet C, 2003, P Natl Acad Sci Usa	10.1073/pnas.2435133100	322	16.10	6.51
Crossa J, 2007, Genetics	10.1534/genetics.107.078659	320	20.00	8.32

Most Frequent Words:

Extracting the most pertinent words from the data is crucial. As seen in (Fig. 4A), we have selected the best words from 4 distinct categories. "F-sp tritici" emerged as the most frequently occurring term among the keywords plus, with 955 occurrences, trailed by "leaf rust" with 839 frequencies (Fig.4B). According to the author's keywords, "wheat" emerged as the most often occurring term, occurring 888 times, and "Triticum aestivum" followed closely, occurring 571 times (Fig. 4B). The most pertinent term from the titles was "wheat," which occurred 3893 times, and "resistance," which occurred 2959 times (Fig. 4C). "Resistance" was the most often occurring phrase in the abstracts, appearing 15854 times, followed by "wheat" with 15041 appearances (Fig. 4D).

Co-Occurrence Map, the Linkage Among Countries and Organizations Based on Citations:

Term co-occurrence map, and "titles" terms were extracted, and "Binary" was selected as the counting technique. The minimum number of times each term appeared was set at 15. A total of 185 terms out of 9599 satisfied this requirement. As illustrated in (Fig. 5A), the most frequently occurring term was "wheat," which happened 1174 times, followed by "resistance," which appeared 939 times, and "gene," which was the third most frequently occurring term.

A total of countries 106 countries have participated, with a minimum of 10 documents, 52 countries met this threshold, USA stood on the top, with a total of 1440 documents that scored 42718 citations, followed by Australia with a total of 515 documents which scored 21874 citations, (Fig. 5B). VOSViewer was used to analyze the organization linkage based on citations; 2691 organizations in all took part. The minimum number of documents for an organization was set at 15, and out of the 129 that met this requirement, the University of Sydney was the highest with 270 documents totalling 12048 citations (Fig.5C).

Word Cloud:

The targeted "abstracts" were used to create the map of WordCloud. The top 50 most frequently terms are mapped which are shown in, as shown in (Fig. 5D).
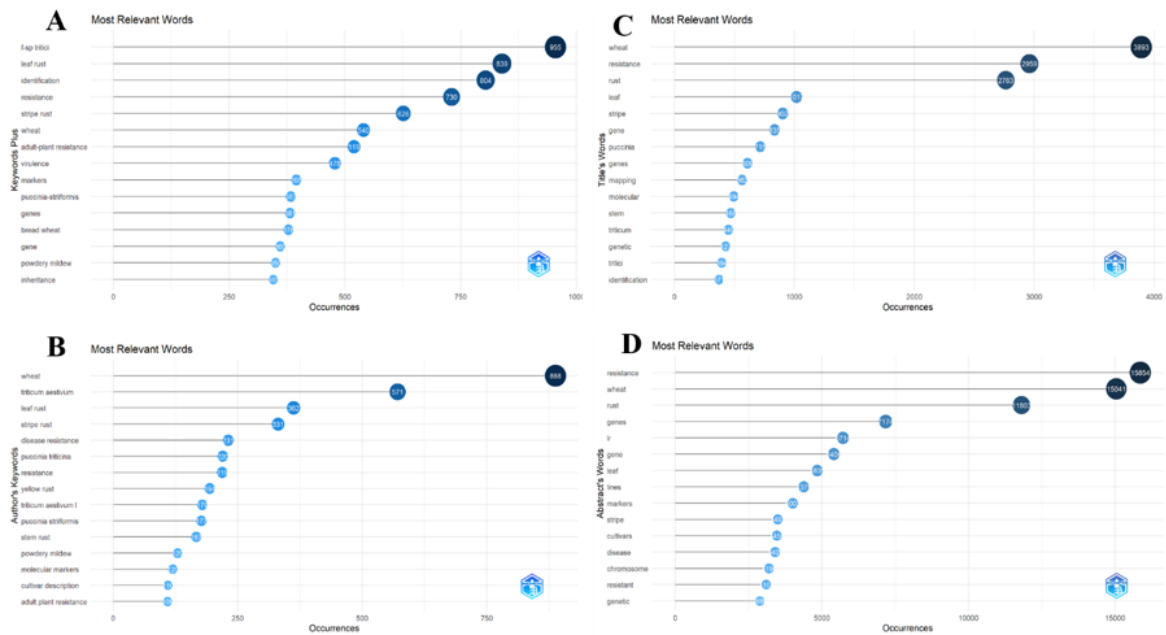
Fig. 4. A-Most frequent words extracted from the keywords plus. X-axis indicates the terms extracted from the keywords plus while the y-axis indicates the frequency. Top fifteen terms are mapped here, **B**- Most frequent words from the author's keywords. X-axis indicates the terms extracted from the author's keywords while the y-axis indicates the frequency. Top fifteen terms are mapped here, **C**- The most relevant terms extracted from the titles. X-axis indicates the terms extracted from the titles while the y-axis indicates the frequency. Top fifteen terms are mapped here, **D**- Most relevant terms extracted from abstracts. X-axis indicates the terms extracted from the abstracts while the y-axis indicates the frequency. Top fifteen terms are mapped here.
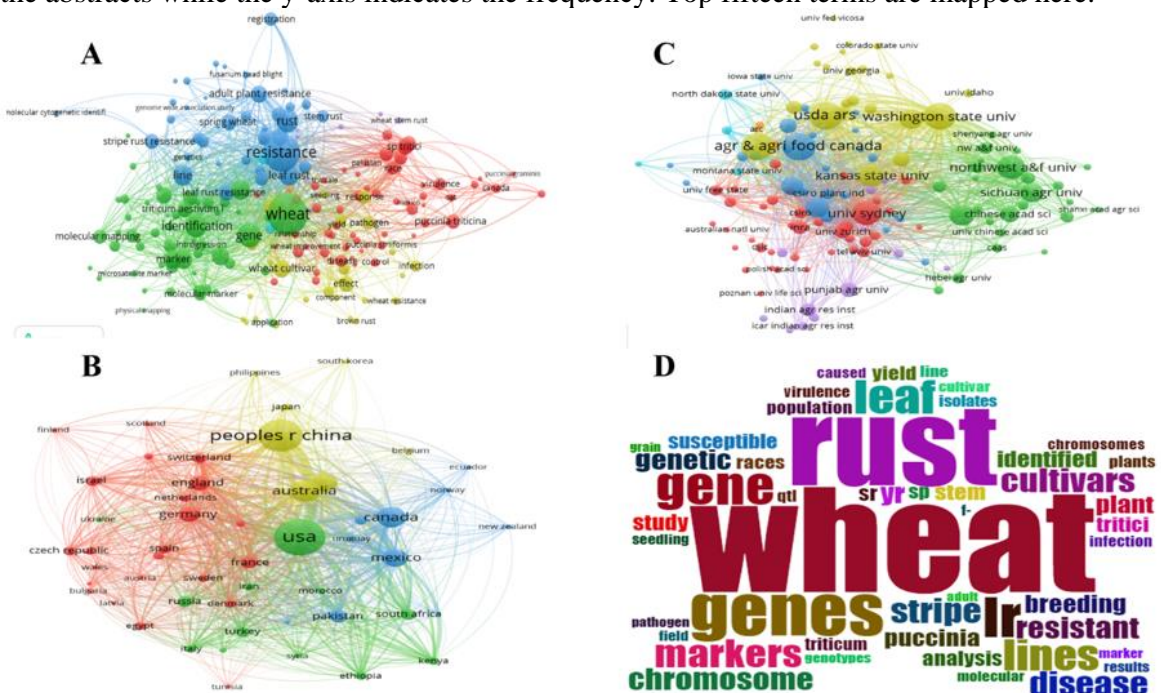

Fig. 5. A-Terms co-occurrence map. Wheat, and resistance were linked to most of the terms, **B-** Countries linkage based on citations. The country-to-country linkage was mapped using VOSviewer tool. USA is linked worldwide, **C**- Organizations linkage based on citations. The linkages between the institutions was mapped using the VOSviewer tool. Washington state university was linked to the institutions worldwide, **D**- The WordCloud of the most relevant words. The word cloud map was built using the R tool biblioshiny. Wheat appeared to be the most relevant word in this study followed by the "rust".

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DISCUSSION

About 40% of the world's feeding requirements are fulfilled by Wheat (*Triticum aestivum* L.) (Yuan *et al.*, 2021). Wheat production has made it possible to feed a significant population since wheat growth has expanded significantly to assure food security in developing nations (Arslan *et al.*, 2007). It has been noticed that wheat growth has been affected severely, resulting in substantial losses in its production, sometimes approaching more than fifty percent (Riaz and Wong, 2017). Drought, heat, and pest diseases diminish wheat productivity (Hussain *et al.*, 2017). Some other diseases also contributed considerably, such as rust and foliar diseases (Soliman *et al.* 2012). It has been proven that rust diseases are the most economically severe fungal diseases globally. Rust can produce new strains and destroy even resistant varieties, spreading by windborne spores and developing faster under favorable weather conditions (Ghimire *et al.*, 2020). Leaf, stem, and stripe are the most commonly reported rust disease. Among them, leaves are the most common and fatal rust disease, regularly occurring compared to stem and stripe (Cuddy *et al.*, 2016).

Stem rust is not widespread compared to other diseases, as wide wheat varieties showed resistance against it (Ayliffe *et al.*, 2008). With newly reported outbreaks, stripe rust disease is also getting significant attention for its severe (Maqsood Qamar *et al.*, 2008). Wheat has been studied extensively on its genomics and molecular aspects (Gaurav *et al.* 2022), drought and heat tolerance, rust diseases (Kumar *et al.*, 2022), etc. This study analyzed and evaluated the available literature to investigate the most relevant authors, countries, institutions, keywords, and highly impactful research articles. We used the Web of Science database "Core Collection" (WoSCC) on September 22, 2022, to search the relevant scientific literature on the host-pathogen interaction between wheat and rust. Our search keywords were "wheat" AND "Rust Resistance" From the topics. A total of 5,199 documents were available. A total of 476 sources have published all these 5199 documents, with an annual growth of 7.27%. A total of 10457 authors contributed globally, and 154 papers were single-authored; a total of 68 fields of WoS categories were identified. The production of scientific literature over time was not smooth. From 1990 to 2006, the output was zigzagged, but in 2007, there was a big leap, and 174 documents were released in a single calendar year. Over time, the production was progressive and peaked in 2021; 346 papers were produced. Based on the number of publications, "Theoretical and Applied Genetics," with 440 publications, was the topmost publishing source.

Theoretical and Applied Genetics publishes original research and review articles in all critical areas of modern plant genetics, plant genomics, and plant biotechnology. "Plant Disease," which published 286 articles, was the second most relevant source. Plant *Disease,* published by The American Phytopathological Society. Plant Disease is the primary worldwide publication for fast reporting on novel, developing, and established plant diseases. *Xianming Chen,* with a total of 244 publications, was the most influential researcher in the field. He has published several high-impact research papers, review papers, and book chapters. He is primarily affiliated with the US Department of Agriculture – Agricultural Research Service and Department of Plant Pathology, Washington State University, Pullman, WA 99163, USA. Washington State Univ was identified as the leading institution in the field, with a total of 551 articles. Northwest Aandf Univ comes in position second with a total of 464 articles. Based on the number of publications, the USA remained on the top with a total number of 1938 publications, out of which 741 were SCP (single author publications) and 297 were MCP (Multiple Country Publications). Similarly, based on the number of publications, the USA was the leading country with a total of 31035 citations, followed by China with a total of 14560 citations. The most cited article was "A Putative ABC Transporter Confers Durable Resistance to Multiple Fungal Pathogens in

Wheat" which was published in "Science" and has earned a total of 788 citations (Krattinger *et al.*, 2009).

Conclusions

After providing a summary of wheat and rust resistance, this study does a bibliometric analysis of papers gathered between 1990 and 2022. Using the VOSViewer and bibliometrics tools, this study investigates several fundamental aspects of the recovered documents about publishing category, yearly publications, and publication sources. After that, the highly cited articles are reviewed and a map of the distribution of publications by country and region as well as collaboration networks is constructed.

Future Suggestions

Going forward, it is recommended that other bibliometric approaches be employed and that datasets other than WoS be added.

Declarations:

Ethical Approval: No animal model(s) or human subjects were recruited directly for the current study. Consequently, no ethical considerations are necessary.

Conflict of Interest: The author declares no conflict of interest.

Authors Contributions: Eman Abdullah Almuqri (E.A.A) designed the project, performed the analysis and wrote the manuscript

Funding: The author(s) received no specific funding for this work.

Availability of Data and Materials: All datasets analysed and described during the present study are available from the corresponding author upon reasonable request.

Acknowledgements: The authors represent their acknowledgement to Prof. Wagieh El-Saadawi for his precious advice, his work all over the past years on Egypt Bryoflora and for providing all references required to accomplish this work.

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