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Global bibliometry on three decades of methyl jasmonate-induced plant defense research reveals growth of a specialty area in biology

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ABSTRACT

Methyl jasmonate (MeJA), a naturally existing plant hormone, acts as a vital defense and signaling molecule. Although this hormone has been discovered recently, published reports spanning the last several decades have shown the pleiotropic effects of the hormone raising numerous questions about its regulation, biogenesis, and mode of action. In this work, we explore the complete scientific research on MeJa from its discovery in 1992, spanning research conducted over three decades, through a complex network analysis of 2,542 documents authored by about 9,000 individuals. Several indicators of research progress were evaluated, including co-authorship networks, keyword thematic maps, indices of national and international collaboration, annual scientific production, and most productive affiliations. These indices not only enabled us to evaluate the importance of a specialty discipline in literature but also the place of nations in determining research directionality and the significance of quality of work. Overall, this bibliometric analysis identifies current research trends in a specialty area in biology and we hope that our work would pave the way for greater international collaborations among researchers and a better understanding of research gaps and future scope of work in the actively expanding field of MeJA induced plant defense, stress, and developmental processes.

1. INTRODUCTION

Methyl jasmonate (MeJA) is a naturally existing plant hormone that protects plants against biotic and abiotic stresses. The first jasmonic acid (JA) compound isolated was the methyl ester of JA abbreviated as MeJA discovered as an odorant from *Jasminium grandiflorum* flowers [1]. Its physiological role as a growth retardant was detected after two decades in *Vicia faba* [2]. Jasmonates act as signal molecules during signal transduction whenever plants are subjected to environmental stresses such as UV radiation, osmotic shock, and heat. MeJA also acts as a vital signaling molecule that influences the concentration of antioxidants such as phenolic compounds and their derivatives, primarily involved in defense responses [3]. MeJA has the potential to enhance gene expression of defense-related metabolites and thus can improve plant's tolerance against various biotic and abiotic stresses [4]. Plants that are exposed to a severely stressful environment tend to accumulate a greater concentration of jasmonates (JAs) than those thriving in a conducive environment. For instance, during the germination of tomato seeds, the concentration of jasmonates sharply increased in response to a non-favorable condition of high salt concentration [5]. Exogenous application of MeJA has been quite effective in the upregulation of genes involved in the production of antioxidants. MeJA can reduce the severity of stress by inducing various pathways. Exogenously application of MeJA has resulted in the reduction of drought stress in wheat [6].

Several researchers have significantly advanced our knowledge by contributing to research on volatile organic compounds (VOCs) found in plants [7]. When a plant is infected by a pathogen or herbivore, it releases certain VOCs, including salicylic acid (SA) and airborne MeJA, a volatile form of JA, synthesized from its precursor, JA, through JA carboxyl methyltransferase enzyme [8]. MeJA is also involved in inter-plant signaling and found to increase the accumulation of defense metabolites in neighboring plants prior to the manifestation of infection [9]. It has been experimentally proven that SA jasmonate and its derivatives induce and enhance defense responses in plants [10,11]. In the past few years, researchers have reported that jasmonates exhibit anti-cancer activity both *in vitro* and *in vivo* and have cytotoxic effects on several types of cancer cells. However, there is a growing interest among researchers in recent times to study MeJA-induced plant defense responses against biotic and abiotic stresses [12,13]. This bibliometric study presents an analysis of 2,542 scientific publications in the field of MeJA-induced plant defense spanning from 1992 to 2021.

A bibliometric analysis is a statistical measure to assess and evaluate the scientific publications on a particular subject [14]. It

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is a scientometric tool to determine the influence of research and scientific activities [15]. Bibliometry can be used to study huge sets of scientific data quantitatively and trace their evolution over a period of time [16]. Various research indicators can be analyzed through this bibliometric analysis, such as annual scientific production, leading thematic, countries, authors, as well as the degree of collaboration within and among countries, and so on. The present investigation offers insights into the trends in research related to MeJA and plant defense towards gaining insights into past trends and foci of this active field of research in plant communication and stress biology, as well as for identifying gaps in research, where potential future efforts can be targeted.

2. METHODS

2.1. Data Collection

The keyword combination of " MeJA AND plant defense" was used to obtain published documents from the Clarivate™ WoS Core Collection database including but not limited to research articles, reviews, proceedings, and book chapters and the metadata for all documents was also recorded for this analysis, comprising titles, abstracts, keywords, and cited references. These articles were published between 1992 and 2021 and have been indexed in the WOS database. A complete list of analyzed articles and DOI numbers is available in Supplementary Data.

3. RESULTS

3.1. Annual Scientific Production

The keyword search described in methods returned a total of 2,542 scientific publications, indexed in Web of Science (WOS), published between 1992 and 2021. Various kinds of documents were extracted, including research articles, review articles, book chapters, proceedings papers, preprints, and so on, as shown in Table 1. As can be seen in this table, the documents are authored by 8,763 researchers, 99.3% of whom have contributed to multi-authored publications. Out of 2,542 articles, 2,307 are research articles followed by 174 research articles while there is hardly one chapter on MeJA. This trend clearly shows that research is being undertaken at a much faster pace on MeJA involved in plant defense.

Table 1. General information about the data retrieved from the WOS.

Description	Results
Timespan	1992–2021
Sources (Journals, books, etc.)	422
Documents (research articles, review articles, book chapters, proceedings papers, preprints, etc.)	2,542
• Research articles	2,307
• Articles (book chapters)	1
• Articles (early access)	10
• Articles (proceedings papers)	33
• Article (retracted publications)	2
• Editorial material	3
• Meeting abstract	3
• Review articles	174
• Review (book chapters)	8
• Review (early access)	1
Average years from publication	10.9
Average citations per document	58.7
Average citations per year per document	4.05
References	65,868
Keywords plus	5,090
Author's keywords	5,226
Authors	8,763
Authors of single-authored documents	56
Authors of multi-authored documents	8,707
Single-authored documents	65
Documents per author	0.29
Authors per document	3.45
Co-authors per document	5.46
Collaboration index	3.52

3.2. Growth and Trends of Research on MeJa

Figures 1 and 2 reveal the annual scientific production of articles in the field of MeJA. Figure 1 clearly shows that over the past 28 years, there has been a growing interest among researchers to work in the field of MeJA, as indicated by annual scientific production data. Figure 2 depicts the number of articles published from 1992 to 2022, with a linear regression and R^2 value of 0.8556.

3.3. Analysis of Country-Wise Data

In terms of the number of published documents, China leads research in this field with 624 documented articles, followed by the United States of America (414 publications) as shown in Table 2. Together these two nations account for over 40% of the total number of published articles. However, citations reveal that the impact of MeJa-based stress-related research done in the USA is greater with more than twice the number of total citations in comparison to China.

Interestingly, another parameter that can be considered to assess the impact of country-wise publications is the average number of citations received by an article, determined by dividing the total citations of a country by the number of articles published by that country. Switzerland, which accounts for only 1.3% of the total number of published articles on MeJa research, was found to rank highest on this parameter (with a value of over 150), followed by the United Kingdom and Belgium. The major insight gained through these researchers shows that despite the significance of jasmonates as regulators of plant development and stress, the molecular mechanism of their signaling routes are still not clearly understood. The genomics studies demonstrated that there is cross talk between ethylene and jasmonates, involving a number of gene loci belonging to two branches in the JA signaling pathway, antagonistically regulated by two different sets of stresses, namely pathogen attack, and wounding. It is imperative to understand the hormonal cross talk to elucidate how plants activate the correct set of genes to a particular stress.

3.4. Estimating the Role of Author Affiliations from Citation Trends

Although the bulk of articles in this area has been published by China and the USA as mentioned in the earlier sections, the Max Planck Institute of Chemical Ecology (Jena, Germany) outperformed

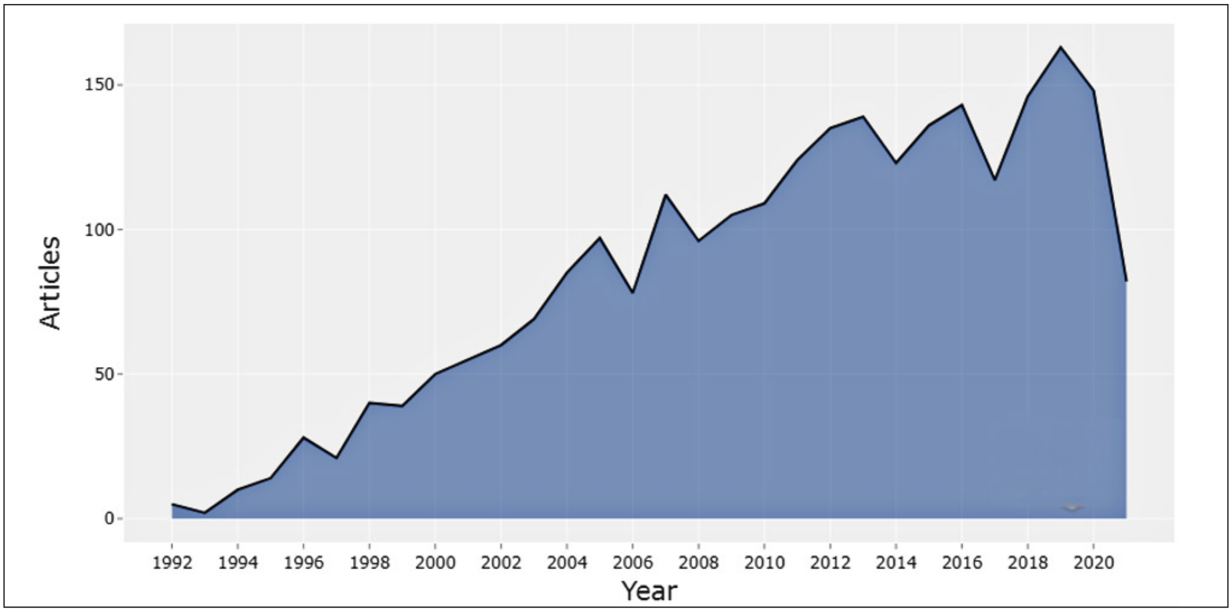

Figure 1. The expanding global research interest in the field of methyl jasmonate induced plant defence over the past 28 years represented by annual scientific production data.

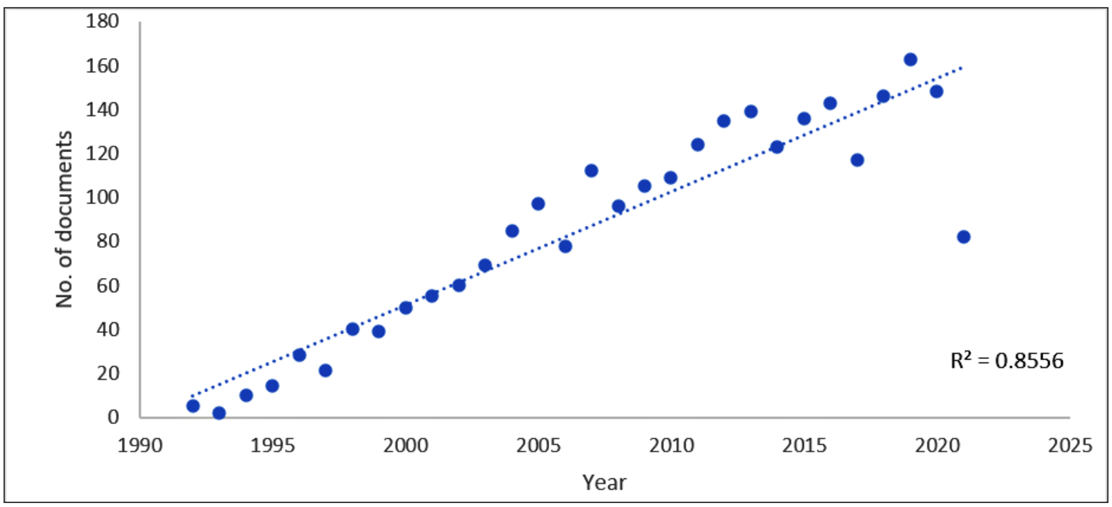

Figure 2. Graph depicting number of articles published per year from 1992 to 2021.

Table 2. Top ranking countries with more than hundred MeJa related articles and number of total citations.

Country	Articles	No. of citations
China	624	16,846
USA	414	39,714
Germany	161	11,423
Japan	117	6,281
Korea	113	4,134
Spain	113	10,021
Canada	100	6,759
India	100	2,385
France	61	2,882
Australia	53	6,354
United Kingdom	52	6,948

other global affiliations by publishing 110 articles (Fig. 3) and has international collaboration to maximizes the output as well as the impact of the publications. However, these affiliations are mainly between two countries with multiple authors rather than multiple country-authored research publications. Germany was the top ranker in this earlier also. Further evidence for this can be seen in the second most impactful and productive institute globally, which was identified to be the University of British Columbia, based in Canada, a single organization accounting for 81% of Canada's total publications.

3.5. International Collaborations and Bilateral Research Strengths

Multi-country publications (MCPs) ratio is often used as a parameter to assess the degree of collaboration between countries. The MCP ratio can be calculated by dividing the number of MCPs by the total publications of that country

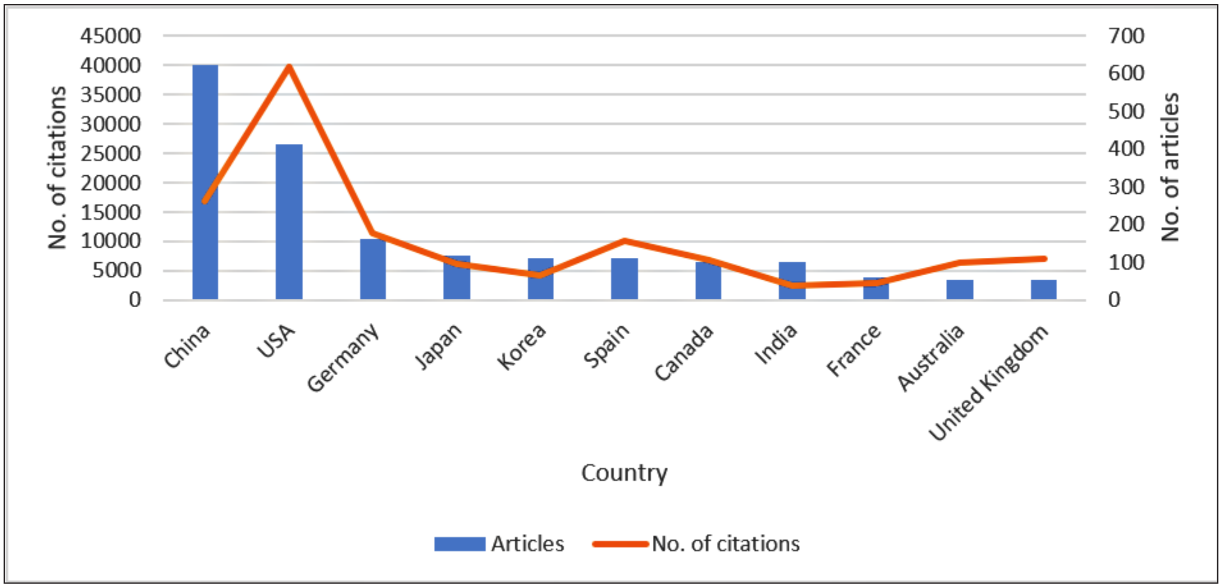

Figure 3. Top-ranking countries having more than 50 articles in our dataset along with total number of citations.

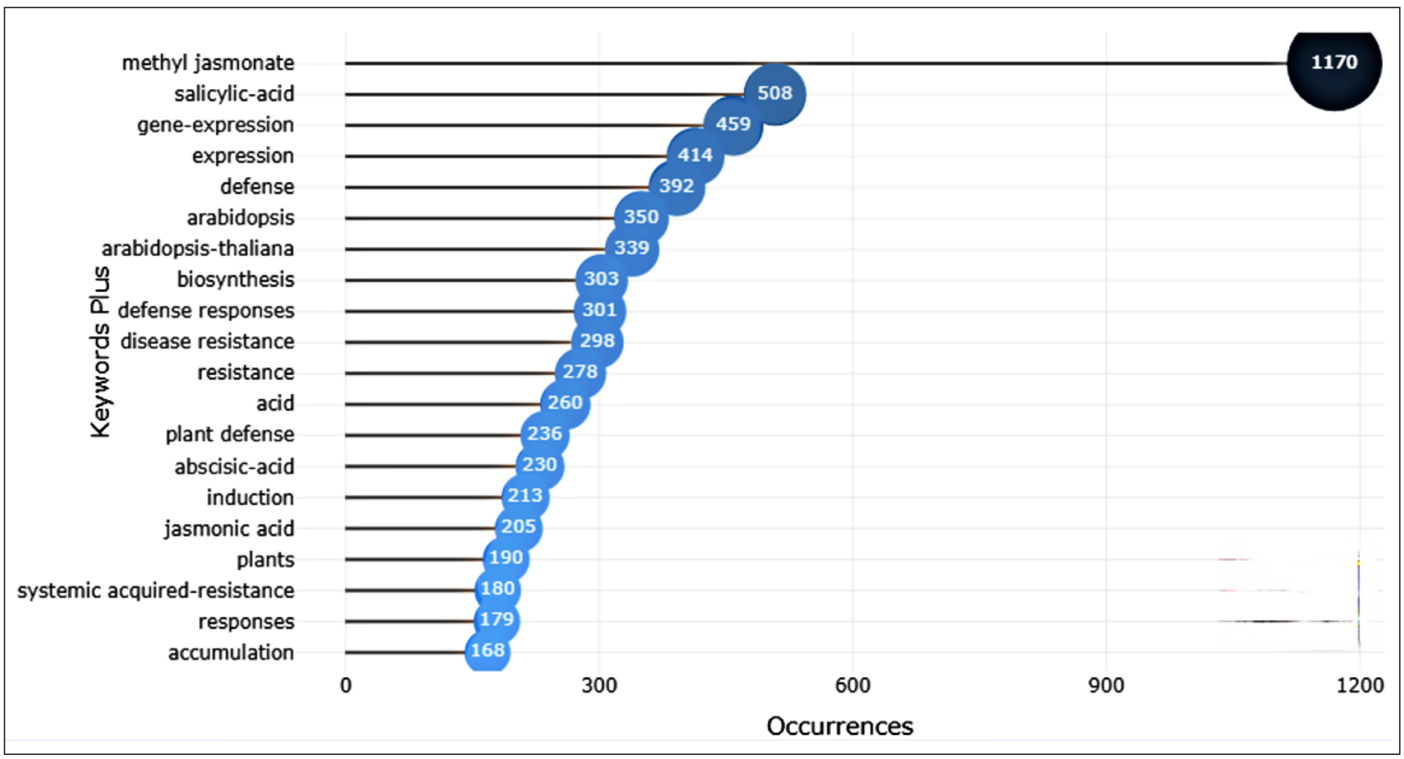

Figure 4. Thematic evolution of MeJa research over the time.

$$\text{MCP ratio of a country} = \frac{\text{No. of multi – country publications}}{\text{Total no. of publications by that country}}$$

For evaluating this parameter, we only considered countries with more than 100 articles in MeJa-based research on plant communication and stress biology. Out of the six countries that matched this filter, Germany showed the highest MCP ratio of 0.304, i.e., with over 30% of articles being authored by multi-country collaborators. In contrast, Japan showed the lowest MCP ratio of 0.145, i.e., with only 14% of all published articles having international authors.

3.6. Evaluating Author Impact and Citation Trends on Research

Besides being an apt parameter to study the contribution of sources/journals, H-index is used overwhelmingly to evaluate an individual researcher's impact and scientific productivity [17]. H-index of a researcher/author refers to the maximum number of documents published by the researcher, and each of which has been cited at least *h* times [18].

Among the leading researchers, Ian T. Baldwin, an American ecologist and Founding Director of Max Planck Institute for Chemical Ecology,

Figure 5. Tree map of thematic evolution of MeJa research.

Germany, has been the most active and productive researcher with an H-index of 40 and a total of 63 publications in Meja research alone. He published his first article in 1994 and has been proactively researching on MeJA and plant defense. Using *Nicotiana* as a model system Baldwin studied signal transduction during herbivore attacks and an increase in the emission of volatiles which attracts predators as a result plant could reduce the number of herbivore attacks in a highly regulated manner and function as indirect defenses. Genes involved in plant-herbivore interactions analysis and regulation of plant metabolism showed a complex network of signals and regulatory components inducing the JA biosynthesis pathways. However, it is interesting to note that despite this outstanding performance, the most cited author in the past three decades of MeJa research is Gregg A Howe, a plant scientist at Michigan State University, with only 25 publications. He worked on tomato and *Arabidopsis* as model systems for identifying genes involved in jasmonates wound-inducible plant defense responses, jasmonate metabolism as a signaling molecule, and the mechanism of its perception. These studies established jasmonate as a central molecule acting as a regulator of plant defense against herbivores and other pests. Howe has received a total of 6,168 citations, followed by Clarence A. Ryan, a molecular plant scientist at Washington State University (23 publications; h-index 21) who is well known to be one of the early pioneers to carry out research in this field. He studied the regulation of synthesis of nearly 20 defensive proteins in plants when predator and pathogen attacks. The novel polypeptide signals were isolated viz., systemin, analogous to polypeptide signals in animals; oligouronide fragments from the plant cell wall, and JA (a prostaglandin analog). The application of this knowledge about polypeptides is used to improve crop production and to understand ecological systems.

3.7. Thematic Evolution of MeJa Research

As expected, the most frequently occurring combinations of words in 2,542 publications investigated in this study were "MeJA", followed by "*Arabidopsis thaliana"* indicating that much of the research in MeJa-induced plant defense has been performed using the model angiosperm Arabidopsis. This is further evident from Figure 4 depicting the top most relevant keywords where Arabidopsis is the only species term.

To understand the trend of research thematics over the years, a keyword analysis of over 5,000 terms was performed on the data, analyzed in terms of Keywords Plus, i.e., words or phrases extracted from the title of citations of an article [19]. Figure 5 (describe) depicts a Tree Map to understand these terms better.

The last decade/nineties were a time of evolution in molecular biological tools and emphasis was largely on gene expression as genomic approaches had not yet been discovered. Hence much of the initial research was focused on gene expression in model plants. Plant hormones such as abscisic acid, JA, and SA are important molecules in different signaling pathways of plant defense responses against disease, herbivore and pathogen attack, SA mediates the phenylpropanoid pathway, while JA mediates the octadecanoid pathway. SA is actively involved against pathogens, some insect pests, and abiotic stresses, while JA acts as a defense molecule against insect pests and some pathogens. SA regulates the components of its own signaling pathway as well as involved in cross-talk with other pathways mainly JA-regulated pathways. Figure 6 depicts bibliometric thematic evolution of keywords which is often used to highlight the evolution and development of new research trends over several years. A deeper analysis of keywords revealed that apart from the model organism *A. thaliana*, work has been done in *Nicotiana attenuata*, a wild species of tobacco as well as other species. Interestingly, plant pathogens *Botrytis cinerea* and *Pseudomonas syringae* also appeared in the list of most frequent words suggesting that research has been carried out using these two plant pathogens.

From 1992 to 2002, extensive research on MeJA-induced plant defense was carried out using wild tobacco, *N. attenuata*, to study plant-herbivore interactions. It is believed that *N. attenuate* has evolved several defense mechanisms against a specific herbivore *Manduca sexta*, which feeds upon the plant foliage [20]. Moreover, in *N. attenuata*, the synthesis of jasmonates sharply increased in response to insect herbivory and mechanical wounding [21].

In the next decade, at the turn of the millennium, another plant was brought under the ambit of research, Norway spruce, a coniferous gymnosperm, which is widespread in the European forest ecosystems and is threatened by the tree-killing European spruce bark beetle. The trees treated with MeJA induced up regulation of JA, SA, and ethylene biosynthesis and induced resistance against fungal attack in seedlings and mature Norway spruce. In recent times, in view of rapid climate change, there has been a greater emphasis on investigating the mechanisms opted by plants against the possible threat of

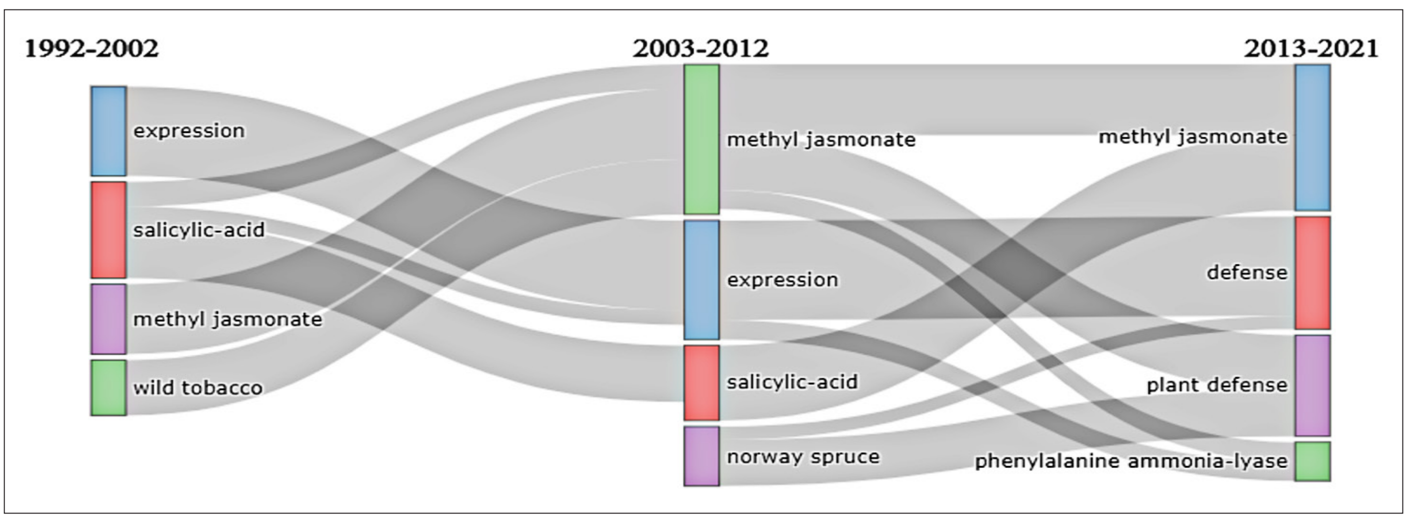

Figure 6. Temporal evolution of keywords in MeJa research.

environmental stress as well as more frequent pest outbreaks [22]. In the current decade (2013 onwards), focus of research has more emphatically been on plant defense, and the role of phenylalanine ammonia-lyase has been given significant attention. This enzyme is one of the critical enzymes involved in synthesizing phenolics, one of the primary plant defense metabolites. It has been experimentally suggested that exogenously applied MeJA can alleviate the expression of phenylalanine ammonia-lyase [23]. To better understand these trends and gaps in research, a network analysis was performed on the keywords, authors/affiliations, and countries in the bibliometric data as described in the next section.

4. DISCUSSION

MeJA influences the expression of genes involved in a plant defense response against biotic stress like pathogen attack and insect herbivory as well as abiotic stress, including drought, salinity, and extreme temperature [24]. MeJA induces various types of mechanisms to introduce plant resistance. Some of the mechanisms include proteinase inhibitors and anti-fungal compounds, and antioxidant systems more significant accumulation of defense metabolites such as phenolics [25,26]. The concentration of jasmonates tends to be greater in flowers than roots and leaves [27]. It has been experimentally demonstrated that exogenous application of MeJA significantly increases the accumulation of phenolic content in plant tissues [28]. Exogenous application of MeJA has been quite effective in inducing a protective mechanism known as systemic acquired resistance in plants, which helps the plant cope with stress [29]. However, detailed mechanisms are yet to be understood. Additionally, the potential role of MeJA as an inter-plant signaling compound is being researched extensively [30].

The first, horizontal, dimension separates keywords emphasizing defense responses, hormones linked to plant species (on the left) with 50.21% of variability, from those related to the genes and its expression (on the right) with 22.08% of variability (Fig. 7). A very important fact is evident from the conceptual map: two clusters represent two major areas of research. The blue cluster shows words as “tolerance”, “gene family”, “protein”, “stress responses”, “tomato”, “tobacco”. The red cluster shows words as “defense responses”, “signal transduction”, “abscisic acid”, “transcription factors”, words that show research. Conceptual structure maps reveal research gaps between understanding the defense response in plants however this is only limited in a few plant species and the future scope of work is actually induce defense responses in susceptible plants (Fig. 8).

The co-occurrence network of keywords in two clusters. The size of circles indicated keyword frequency, and thickness of lines indicated the strength of co-occurrence within and between clusters. As the figure shows, both clusters are interconnected, and there were strong relationships and high interdependence of different areas of research on MeJA and defense responses.

4.1. Co-Authorship Networks Elucidate Collaboration Patterns

The authors’ collaboration network is shown in Figure 9. In this, the nodes represent key players or author, and links that connect nodes reflect relationships. The bigger the size of the circle, wider is author’s collaboration network. Baldwin is the author with a maximum number of collaborating authors. As per the map Boland W. is the only author to collaborate between two research groups viz. Baldwin and Gershenzon. Overall, there were 34 authors, 11 clusters, and 30 links.

Institutions with larger networks of collaboration are bolded, as can be seen from the mapping of collaboration and social networks. The major institute involved in MeJa research is Max Planck Institute for chemical ecology. This institute is collaborating with seven other institutes. Pennsylvania State University and University of Florida are two Universities that have the smallest collaboration network, comprising of only these two. These institutes have not formed partnerships with other institutions to broaden their social network in the field of MeJA research, despite their active participation in it. This can be one of the reasons despite of so many researchers working on

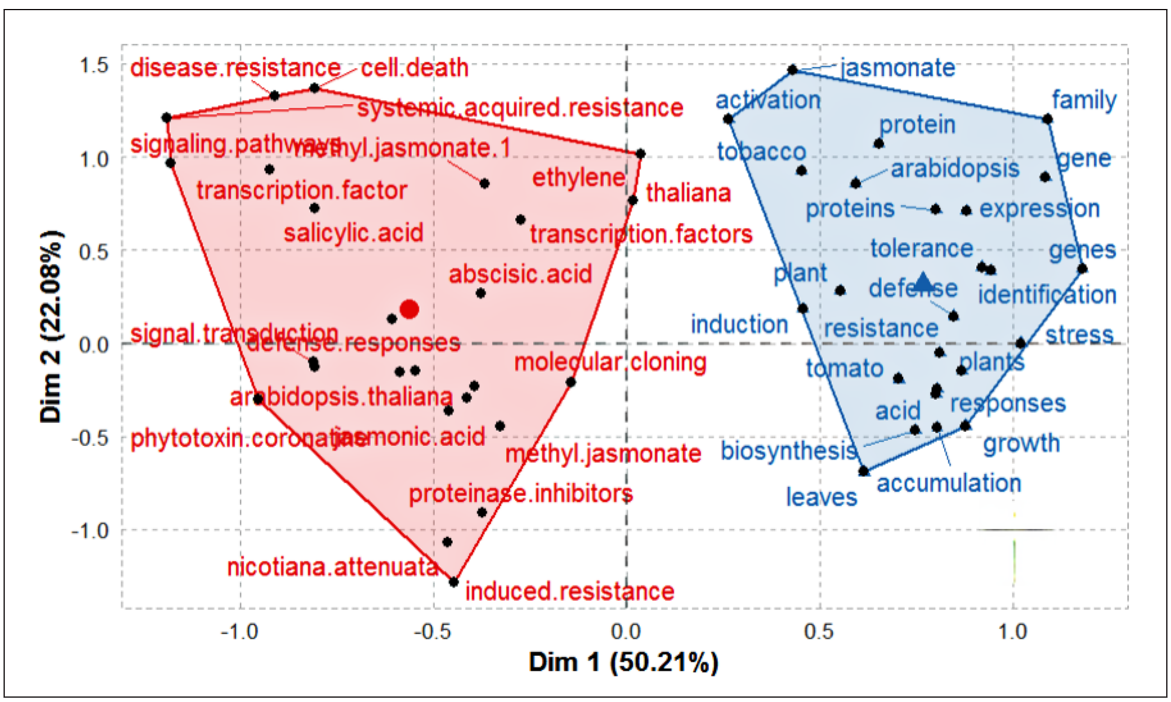

Figure 7. The conceptual map showing two major clusters with variability of 50.21% and 22.08%.

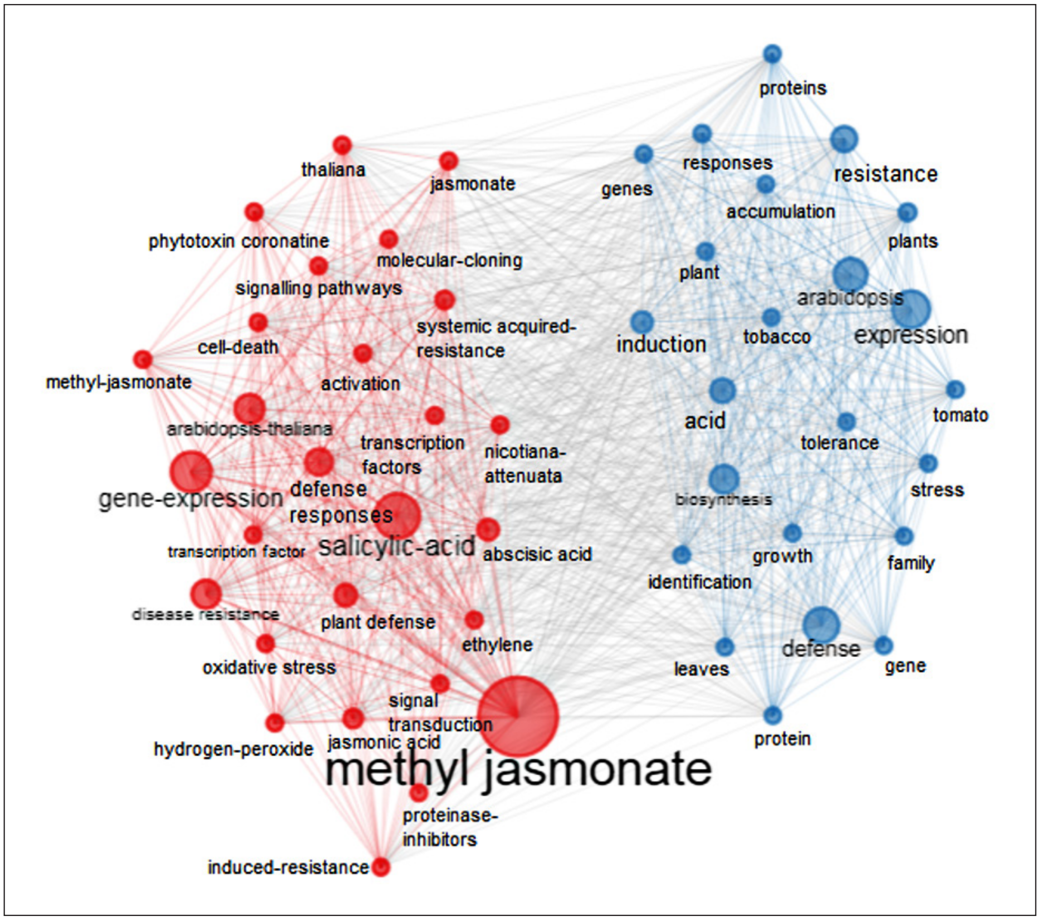

Figure 8. Co-occurrence network of keywords.

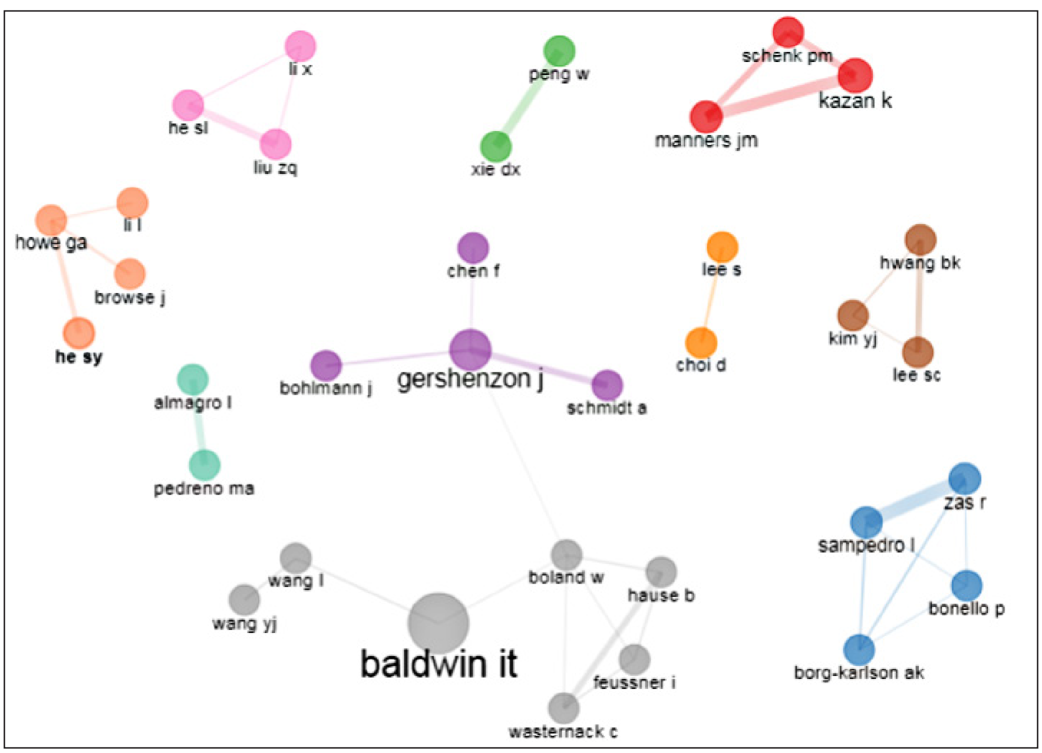

Figure 9. Bibliometric map based on the network of co-authorship relations among different authors.

MeJa it has yet not been exploited in a commercial scale on plant defense responses. In summary, networks maps of authors' and institutes reveal neither much collaboration between different groups nor between different institute universities.

5. CONCLUSION

The present analysis highlights the research involved in MeJa and plant defenses and shows an overview of evolutionary thematic directions and research trends; however, there are some limitations in putting the research into application. In the present study, 2,542 documents were analyzed to understand the scientific production, most productive countries and their citations, the thematic keywords, temporal evolution of keywords, co-occurrence of keywords, and authors and institutions collaborations. The first article on MeJA appeared in 1992 and maximum number of articles (more than 150) were published in 2019. Although China has published the maximum articles in the field, USA surpasses it many times in terms of citations. The analysis highlights the need for collaboration amongst the authors and the institutes.

There is a wide range of research and topics on scientific articles published in the past and indexed in WoS and other scientific databases such as Scopus and Google Scholar; however, in the present study, only WoS database has been used. Despite a significant rise in contributions on the plant defense responses there is still need to capture more comprehensive, diverse, and detailed research in this area from a holistic perspective, for utilizing in crop productivity. This study explored the methods of keywords analysis to get a panoramic view of thematic evolution and research of this domain. More number of key words can consolidate and broaden the bibliometric findings of studies and can act as a guidance for analyzing the knowledge based on this research fields. We estimated the qualitative and quantitative aspects of scientific output and research productivity in the field of MeJA-induced plant defense globally over 28 years. Our study outlined extensive information about the leading countries in terms of research, the extent of international collaboration among countries, best affiliations in this field of research, the contribution of various journals, the impact of researchers, the most frequent words in the title, and the evolving research trends via thematic evolution of Keywords Plus. This study may help researchers to identify the leading countries, authors, affiliations, and so on. Therefore, it could result in greater research collaboration among authors, countries, and institutes worldwide.

The software utilized for the analysis of the study had a technical flaw that prevented data from several databases from being combined. Because the study's sample was drawn from the WoS database, some pertinent data may have been excluded. This restriction ought to spur new research in which academics investigate methods of gathering data from several databases for a more thorough examination.

5.1. Data Analysis

All data analysis and network visualization were performed in biblioshiny 4.0 software which is a shiny app for bibliometrix version: 3.1.4. Bibliometrix is an R-package (R-studio version: 1.4.1717) which is used for comprehensive science mapping analysis [31]. The various bibliometric indices that were analyzed in this work include Annual scientific production, Country-wise production and performance, Authors' affiliations, International collaboration, Author's impact, Thematic evolution, Conceptual structure maps, and Collaboration networks.

6. AUTHOR CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agree to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

7. CONFLICT OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

8. FUNDING

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9. ETHICAL APPROVAL

This study does not involve experiments on animals or human subjects.

10. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

11. PUBLISHER'S NOTE

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12. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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