

Mapping the Intellectual Structure and Emerging Themes of *Nigella sativa*-Mediated Green Nanoparticle Synthesis: Biomedical Applications and Toxicological Gaps

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Abstract

- Background: Research on the green synthesis of nanoparticles using *Nigella sativa* has gained increasing attention in recent years, reflecting the growing interest in medicinal plants as sustainable resources for nanotechnology and biomedical innovation.
- Objective: This study sought to examine the intellectual structure, major research trends, and emerging themes in *Nigella sativa*-mediated green nanoparticle synthesis, with particular attention to biomedical applications and existing toxicological gaps.
- Methodology: Bibliographic records were collected from the Scopus database and analyzed using Bibliometrix in R together with VOSviewer. Following screening and eligibility assessment, a final set of 87 articles was included in the bibliometric and thematic evaluation.
- Results: The analysis revealed a clear rise in publication output after 2021, highlighting the recent development of this research area. The field was primarily organized around green synthesis, *Nigella sativa*, silver nanoparticles, and antibacterial activity, while other recurrent themes included antioxidant, anti-inflammatory, anticancer, wound-healing, and environmental applications. The temporal evolution of keywords further indicated a gradual shift toward broader and more multifunctional applications, although toxicity-related topics remained relatively marginal.
- Conclusion: Overall, this field is growing rapidly, but its development is still largely driven by synthesis and biological efficacy rather than by comprehensive safety evaluation. The limited attention given to toxicological validation underscores the need for more standardized assessment strategies and stronger translational research frameworks.

Introduction

In recent years, nanotechnology has emerged as a rapidly expanding field with significant applications in biology and medicine. In particular, the development of sustainable and environmentally friendly synthesis approaches has become a major focus of current research, as conventional physicochemical methods often involve hazardous reagents and energy-intensive processes [1, 2].

Within this context, *Nigella sativa* L., commonly known as black cumin, is a medicinal plant that has attracted sustained scientific interest in the fields of nanobiotechnology, pharmacognosy, and toxicology. This growing attention is attributed to its rich phytochemical profile and the large spectrum of biological activities, such as antioxidant, anti-inflammatory, antimicrobial, and metabolic effects. Nevertheless, the translation of these biological effects into reproducible biomedical applications remains constrained by several well-known limitations associated with natural products. These limitations include the variability in phytochemical composition, extraction-dependent yield, and the limited physicochemical stability and bioavailability of certain key compounds [3, 4, 5].

In parallel, the green synthesis of nanoparticles (NPs) has emerged as an alternative to conventional physicochemical synthesis methods. Within this approach, plant-derived phytoconstituents act as reducing, stabilizing, and capping agents, thereby minimizing the use of toxic reagents while enabling the production of nanomaterials with biologically relevant surface properties. In this context, *Nigella sativa* has increasingly been explored as a biogenic resource for the synthesis of metallic and metal-oxide NPs intended for biomedical applications [4, 5, 6].

The present study aims to provide a comprehensive bibliometric analysis of global research on *Nigella sativa*-mediated green synthesis of NPs using data retrieved from Scopus data base. By employing the bibliometrix package in R and VOSviewer for scientific mapping and network visualization, this study explores major contributors, publication trends, thematic evolution, and the principal biomedical application domains. Particular attention is also given to identifying persistent gaps in toxicological assessment within this research area [7, 8, 9].

Materials and Methods

Bibliographic data were retrieved from Scopus, which is widely used in bibliometric studies due to its broad multidisciplinary coverage and advanced search capabilities. The search was conducted on 12 March 2026. The study followed standard bibliometric procedures commonly applied in scientific mapping and quantitative literature analysis [7, 9].

An initial search query was performed in the title, abstract, and keywords field using the expression: TITLE-ABS-KEY ("Nigella sativa" OR "black seed" OR "black cumin" OR "kalonji" OR "thymoquinone") AND TITLE-ABS-KEY ("nanoparticle*" OR "nano-particle*" OR "NP*" OR "nanomaterial*" OR nanostructure* OR nano*). This preliminary search yielded 793 records related to nanotechnology research involving *Nigella sativa*.

To specifically identify studies addressing the green synthesis of NPs, the search strategy was further refined by incorporating additional keywords associated with green synthesis approaches: TITLE-ABS-KEY ("green synthesis" OR "biosynthesis" OR "biogenic synthesis" OR "plant-mediated synthesis" OR "plant mediated synthesis" OR "plant extract mediated synthesis" OR phytosynthesis OR "eco-friendly synthesis"). This refinement resulted in 113 publications. Subsequently, additional inclusion criteria were applied to ensure data quality and consistency by restricting the dataset to peer-reviewed research articles written in English. After applying these filters, a final dataset of 93 articles was retained for the bibliometric analysis.

Therefore, all 93 retrieved records were exported from Scopus in CSV and BibTeX formats to remove duplicate documents and manually screen the titles and abstracts of each record. After this process, 87 articles were retained. Finally, bibliometric analysis and visualization were performed using the Bibliometrix package and VOSviewer software [7, 10] (Fig. 1).

Results

2.1. Annual scientific production

The first article published was by Fragoon et al. (2012), who synthesized pure gold NPs of various sizes and shapes using *Nigella Sativa* extract as a natural reducing agent [11]. Although the dataset includes 87 publications, this reflects the emerging nature of research on *Nigella sativa*-mediated NP synthesis.

The annual scientific production showed that research on *Nigella sativa*-mediated green NP synthesis remained very limited during the early years of the study period, with only sporadic publications between 2012 and 2020. A marked increase was observed from 2021 onward, with the number of documents rising sharply and continuing to grow through 2025, when the highest annual output was recorded (Fig. 2). This pattern indicates that the field has entered a phase of rapid expansion in recent years.

2.2. Most influential documents

The most influential documents in the field were identified using total citations, citations per year, and normalized citation scores (Table 1). These documents are mainly focused on the green synthesis, characterization, and beneficial biological applications of *Nigella sativa*-mediated NPs, particularly antimicrobial, antibiofilm, antioxidant, anticancer, and catalytic effects. Collectively, these highly cited studies indicate that the intellectual foundation of the field has been shaped primarily by efficacy-driven and proof-of-concept investigations, whereas detailed toxicological validation and long-term safety assessment remain comparatively underrepresented.

Table 1

Most influential documents in research on *Nigella sativa*-mediated green synthesis of NP, with digital object identifier (DOI), total citation count, annual citation rate (TC per Year), and normalized total citation impact (Normalized TC).

Paper	DOI	Total Citations	TC per Year	Normalized TC
AMOOAGHAIE R, 2015, ECOTOXICOL ENVIRON SAF [12]	10.1016/J.Ecoenv.2015.06.025	234	19,50	1,00
AL-SHABIB NA, 2016, SCI REP [13]	10.1038/Srep36761	158	14,36	1,00
ALKHALAF MI, 2020, SAUDI J BIOL SCI [14]	10.1016/J.Sjbs.2020.05.005	143	20,43	1,81
AWAN S, 2021, J SAUDI SOC AGRIC SCI [15]	10.1016/J.Jssas.2020.10.003	114	19,00	2,37
ROY A, 2021, CURR PHARM BIOTECHNOL [16]	10.2174/1389201021666201027155708	85	14,17	1,77
CHAND K, 2021, CHEM PHYS LETT [17]	10.1016/J.Cplett.2020.138218	76	12,67	1,58
AYGUN A, 2023, INT J HYDROGEN ENERGY[18]	10.1016/J.Ijhydene.2021.12.144	73	18,25	3,38
VIJAYAKUMAR S, 2021, J INORG ORGANOMET POLYM MATER [19]	10.1007/S10904-020-01713-4	68	11,33	1,41
BOUDIAF M, 2021, J PHYS CHEM SOLIDS [20]	10.1016/J.Jpcs.2021.110020	65	10,83	1,35
LIN J, 2022, FOOD CHEM TOXICOL [21]	10.1016/J.Fct.2022.112972	54	10,80	1,75

2.3. Most productive authors and countries

The authors' production over time analysis showed that the field is characterized by a limited number of recurrent contributors whose publication activity was concentrated mainly between 2021 and 2025 (Fig. 3). Most leading authors appeared within short publication windows, suggesting that authorship in this domain is recent and only moderately sustained over time. According to the bibliometrix

visualization framework, point size reflects the number of articles produced in a given year, whereas color intensity reflects total citations per year, indicating heterogeneity in both productivity and short-term citation visibility among the leading authors.

The analysis of corresponding author's countries (Fig. 4) revealed that India was the most productive contributor in the field, showing a substantially higher number of publications than all other countries. Pakistan ranked second, followed by Egypt, Saudi Arabia, and Algeria, which also showed notable research activity. The distribution of single-country publications (SCP) and multiple-country publications (MCP) further indicated heterogeneous collaboration patterns across countries, with some contributors relying more strongly on domestic output and others exhibiting greater levels of international co-authorship.

2.4 Keyword co-occurrence analysis

The keyword co-occurrence analysis revealed a research landscape structured around a dense central core dominated by "green synthesis, *Nigella sativa*, silver nanoparticles, and antibacterial activity", indicating that the field has been primarily driven by plant-mediated nanoparticle fabrication followed by antimicrobial validation. Beyond this core, the most relevant thematic clusters extended toward biomedical effects such as wound healing, antioxidant, anti-inflammatory, anticancer, antidiabetic, apoptosis, and cytotoxicity, while a second major branch gathered photocatalytic degradation, dye removal, adsorption, catalysis, and environmental remediation, highlighting the dual biomedical and environmental orientation of the literature. The clustering pattern further suggests that silver-based systems remain the dominant nanoplatform, whereas ZnO, NiO, iron oxide, gold, and copper nanoparticles appear as secondary but expanding materials associated with more specialized functions, including cytotoxic, magnetic, catalytic, or wound-healing applications (Fig. 5).

The overlay visualization showed that earlier studies were centered mainly on biosynthesis, plant extract-based reduction, and silver nanoparticles, whereas more recent keywords shifted toward catalysis, environmental remediation, wound healing, molecular docking, cytotoxicity, and broader multifunctional applications. Importantly, although cytotoxicity and oxidative-stress-related terms appeared in the network, they remained relatively peripheral compared with efficacy-oriented terms, suggesting that the thematic evolution of the field has favored application diversification more strongly than the development of a robust and autonomous toxicological research axis (Fig. 6).

Discussion

The rapid growth of publications, especially after 2021, reflects the increasing convergence between green nanotechnology and the biomedical valorization of medicinal plants, with *Nigella sativa* emerging as a promising source for biogenic NP synthesis due to its rich phytochemical composition and recognized pharmacological potential [3, 6, 22]. However, the field remains largely driven by proof-of-concept studies centered on NP synthesis, characterization, and efficacy-related bioactivities, whereas toxicological validation is still underrepresented despite its importance for biomedical translation [4, 23].

The productivity patterns of authors and countries further support the profile of a young and still consolidating research area, dominated by a limited number of recent contributors and led mainly by India and other countries where *Nigella sativa* is culturally and scientifically well-established [3, 22].

The keyword co-occurrence analysis indicates that research on *Nigella sativa*-mediated NP synthesis has been dominated by a core centered on green synthesis, silver NPs, and antibacterial activity, showing that the field has primarily evolved through plant-mediated fabrication followed by efficacy-oriented biological validation [4, 6]. This trend suggests that the literature has mainly prioritized rapid proof-of-concept applications, especially antimicrobial effects, while progressively expanding toward antioxidant, anti-inflammatory, anticancer, wound-healing, and antidiabetic activities, as well as some environmental applications such as catalysis, dye degradation, and remediation [3, 22].

At the same time, the thematic structure also reveals important gaps. First, silver-based systems remain predominant, whereas other nanoplatforms such as ZnO, iron oxide, NiO, gold, and copper nanoparticles appear less frequently and are still linked to more specialized or isolated applications, suggesting limited material diversification across the field [4, 5]. Second, although recent topics have shifted toward multifunctionality, cytotoxicity, molecular docking, wound healing, and environmental remediation, toxicity-related terms remain relatively peripheral, indicating that toxicological evaluation has not progressed at the same pace as efficacy-driven research [12, 23]. Overall, current research trends point to a fast-expanding but still immature field, where application diversification is evident, yet major gaps persist in standardized toxicity assessment, mechanistic safety studies, dose-response analysis, and translational validation under reproducible biological conditions [6, 12].

Conclusion

This bibliometric analysis shows that *Nigella sativa*-mediated green nanoparticle research is a rapidly emerging field shaped mainly by synthesis-driven and efficacy-oriented studies, particularly those involving silver nanoparticles and antimicrobial applications. Although the literature is progressively broadening toward multifunctional biomedical and environmental uses, toxicological assessment remains insufficiently developed relative to the pace of application-oriented research. The current knowledge structure therefore highlights a critical imbalance between biological promise and safety validation. Advancing this field toward genuine biomedical translation will require greater emphasis on methodological standardization, mechanistic toxicology, and robust evaluation of reproducibility and biosafety.

Study limitations

This study is subject to several limitations. The dataset was obtained only from Scopus and was restricted to English-language peer-reviewed articles, which may have excluded relevant publications indexed elsewhere or published in other languages and formats. In addition, the final corpus was relatively small (87 articles), reflecting the emerging nature of the field but limiting the robustness of

some network-based interpretations. The results also depend on the selected search terms, the date of data extraction (12 March 2026), and the consistency of author keywords, all of which may influence citation indicators, thematic clustering, and the apparent prominence of specific research topics.

Declarations

Author Contribution

The authors work together to elaborate the research string, screen data, data visualisation and analysis of results.

Funding Declaration

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Figures

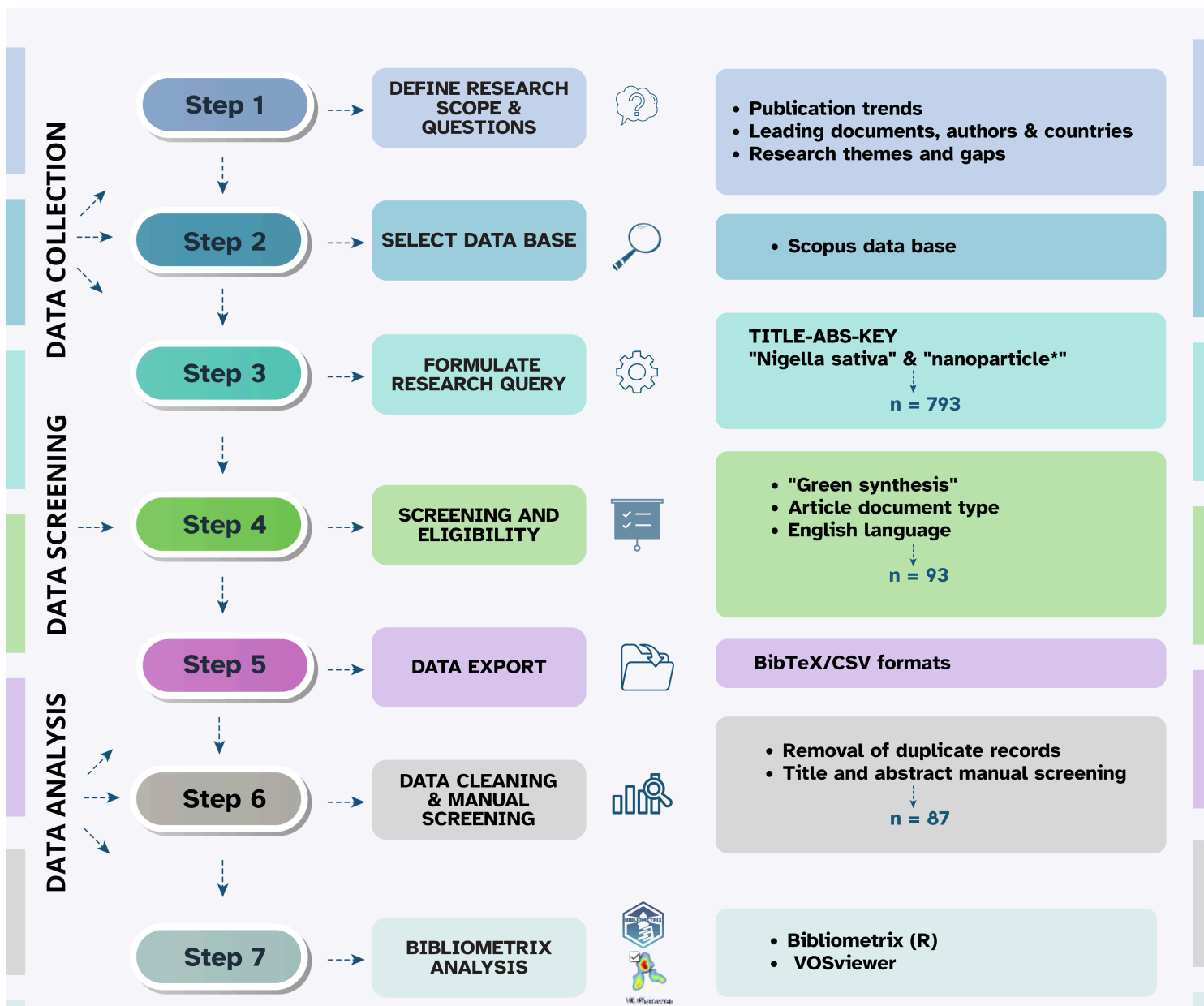


Figure 1

Methodological workflow of the bibliometric analysis following the PRISMA guidelines.

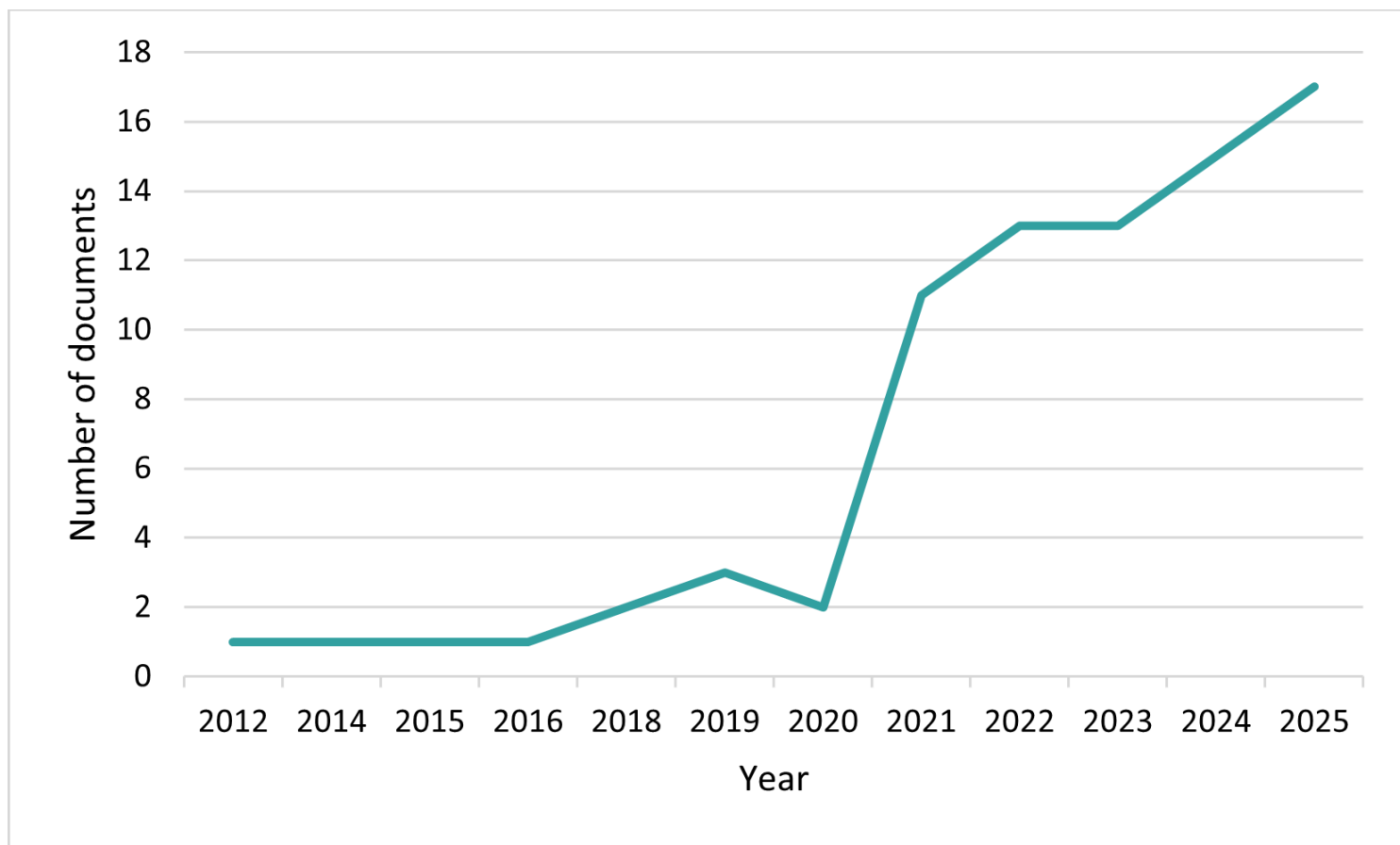


Figure 2

Annual scientific production on *Nigella sativa*-mediated green NP synthesis.

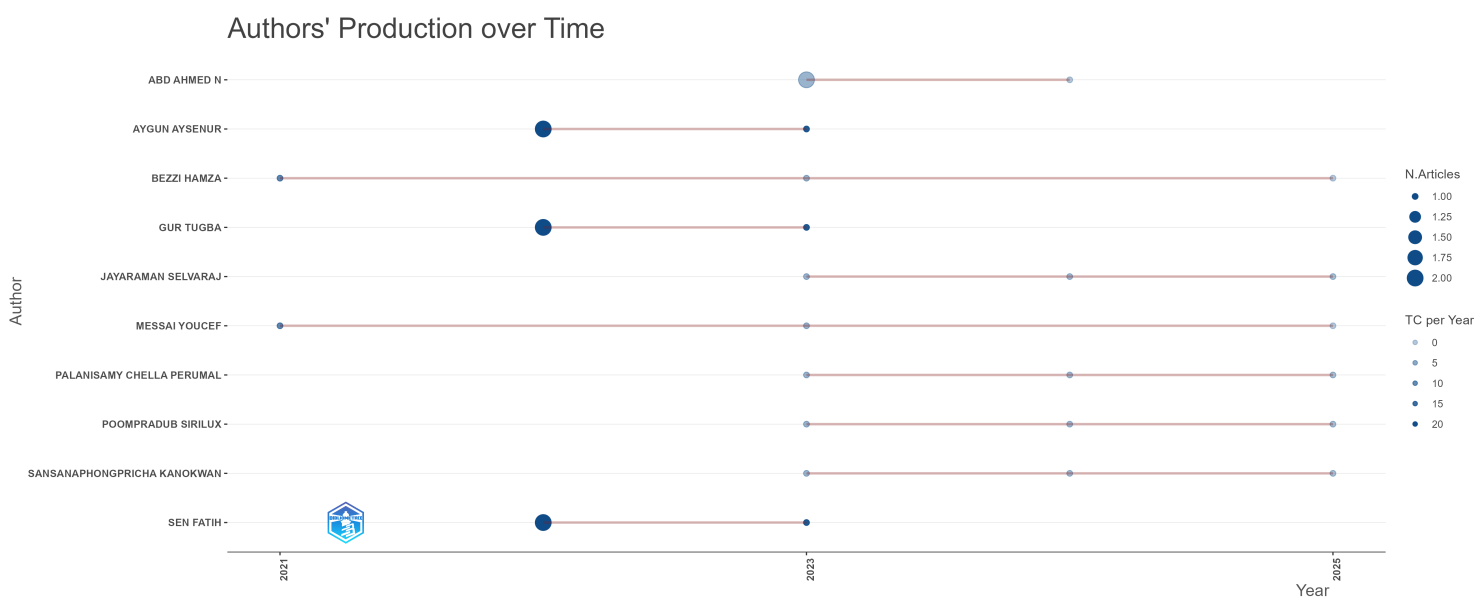


Figure 3

Temporal publication patterns of the most productive authors in research on *Nigella sativa*-mediated green synthesis of nanoparticles.

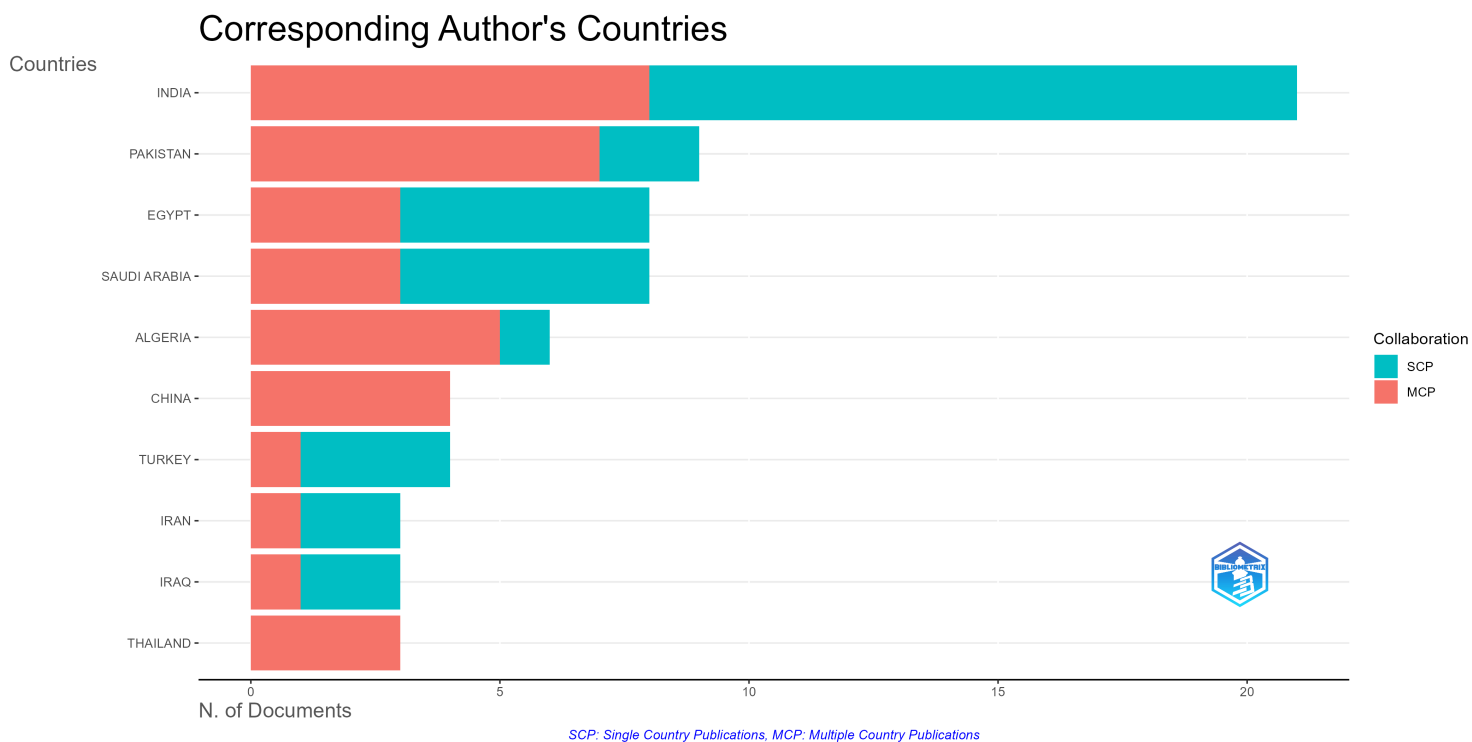


Figure 4

Geographical distribution of top ten corresponding authors' countries showing single and multiple-country publications.

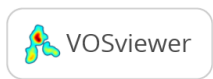
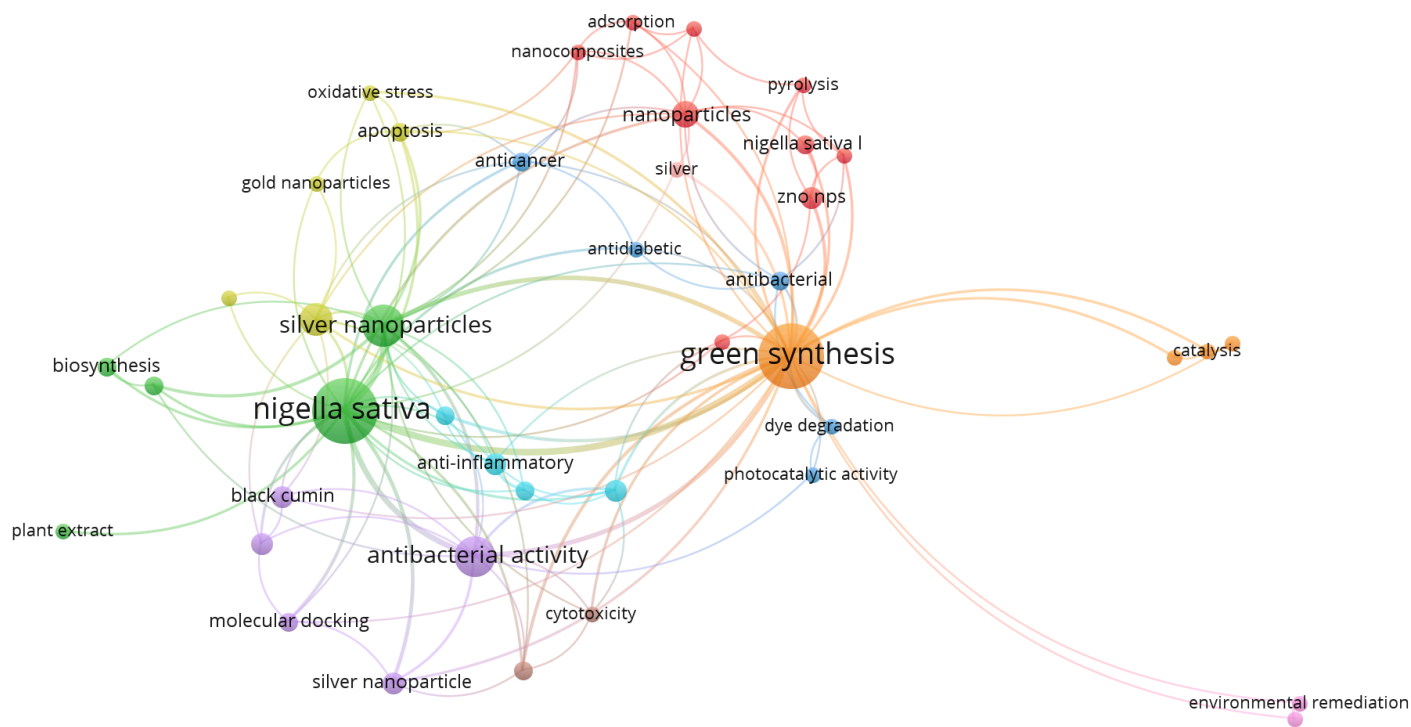


Figure 5

Keyword co-occurrence network showing the main research themes in *Nigella sativa*-mediated green synthesis of nanoparticles.

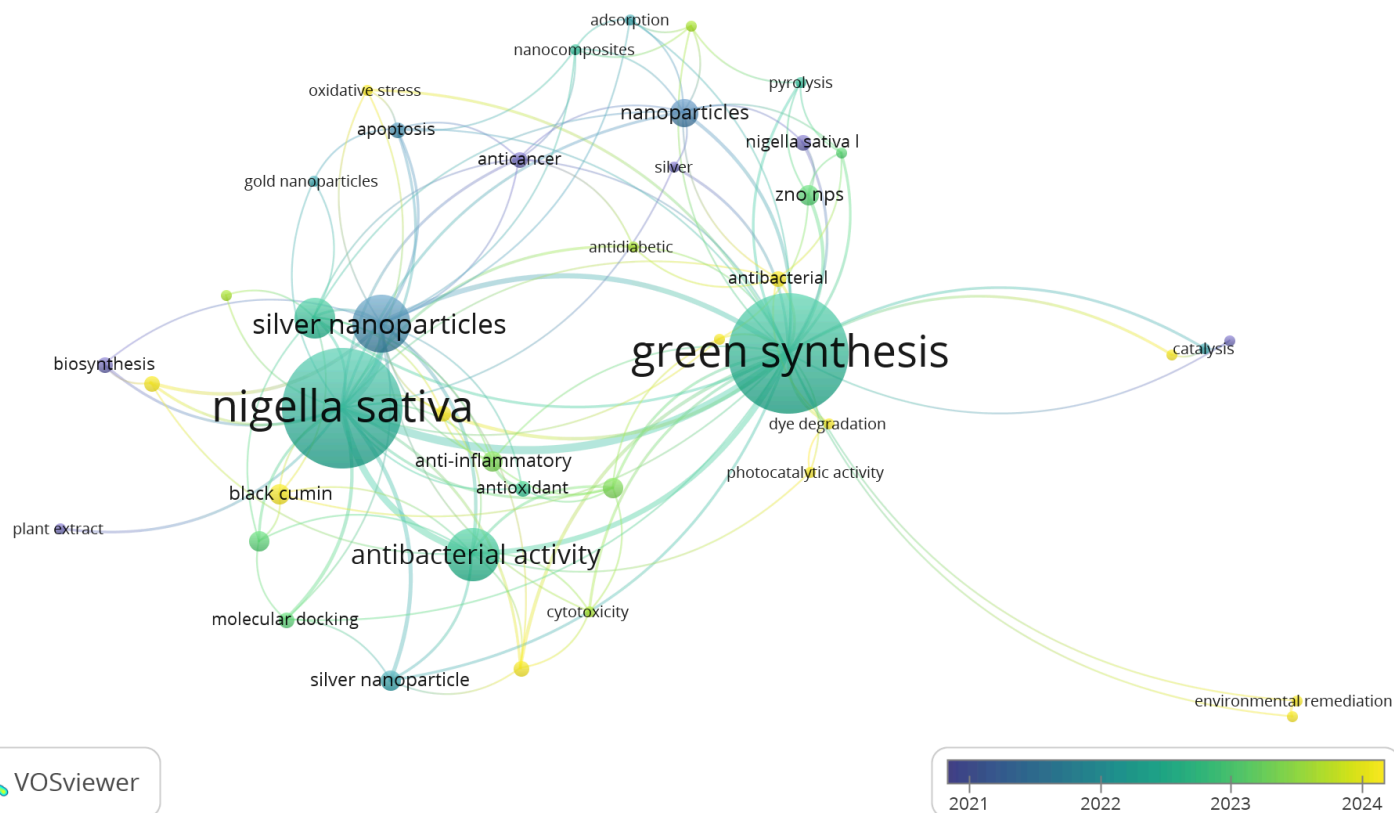


Figure 6

Temporal evolution of author keywords highlighting recent research directions and persistent toxicological gaps in *Nigella sativa*-mediated green NP synthesis.