

GAMMA RAY-INDUCED MUTAGENESIS IN FORAGE CROPS: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

This research aims to provide a comprehensive overview of research focusing on inducing genetic mutations in forage crops, specifically green forage plants, using a bibliometric analysis approach. This bibliometric analysis used data from Scopus for the period 2010-2023. The keywords used in the search were "gamma AND ray AND forage OR mutation AND induction". Key elements of the analysis include publication trends, collaboration between institutions and countries, primary research topics, and keyword patterns. Findings; In terms of publication volume dynamics, the number of relevant studies initially rose significantly from 2010, followed by periodic fluctuations that reflect shifts in research priorities, funding availability, and global events impacting the field. Although there were phases of decline, the overall trend demonstrates sustained interest in gamma ray mutagenesis for forage crop improvement. Co-authorship analysis identified leading institutions, such as the Advanced Radiation Technology Institute and Zhejiang University, as key contributors with high research activity. Collaborations between these institutions and other international entities emphasize the importance of cross-institutional partnerships to address complex challenges and foster innovation in mutation breeding. Topic focus: Mutation induction, DNA repair, and radiation response emerged as the main research topics, reflecting a focus on harnessing gamma rays for genetic improvement and stress tolerance in forage crops. New research areas such as phenotype, genotype, and protein expression warrant further investigation. Keyword analysis: Keywords such as "article," "gamma radiation," "mutation," and "controlled study" highlighted the central themes and methodological rigor of research in this field. This bibliometric analysis provides valuable insights into the field's research priorities and future directions. The study underscores the potential of gamma ray applications in forage improvement, though further research is essential to thoroughly assess the long-term benefits and risks. Continued collaborative efforts among researchers, policymakers, and stakeholders are crucial to ensure the sustainable advancement and application of this technology in the agricultural sector.

Keywords: Bibliometric analysis, Gamma ray, Induced mutation, Forage crops.

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INTRODUCTION

The growing global population presents a significant challenge to ensure food security and maintain a sustainable agricultural sector (Ala and Ridwan 2020; Mc Carthy *et al.* 2018). In this context, enhancing the productivity and resilience of major agricultural crops

becomes increasingly crucial. Forage crops, constituting the primary source of nutrition for livestock, play a vital role in food production systems by contributing to animal feed and maintaining ecosystem stability (Sekaran *et al.*, 2021). Consequently, improving these crops' characteristics becomes essential to meet the rising

demands for animal products while ensuring environmental sustainability.

One promising approach to achieve such improvements lies in inducing genetic mutations in forage crops. This technique involves altering the genetic makeup of plants, potentially leading to the development of new and desirable traits such as increased yield, enhanced nutritional content, and improved resistance to environmental stresses (Bailey-Serres *et al.*, 2019). For example, researchers have successfully utilized mutation induction techniques to develop forage crop varieties with increased drought tolerance, allowing for better adaptation to changing climatic conditions (Rauf *et al.* 2016; Raza *et al.* 2019).

Gamma ray mutagenesis, a commonly used method in plant mutation breeding, has emerged as a valuable tool for inducing such beneficial genetic variations. By exposing plant materials to high-energy gamma radiation, researchers can create mutations that may enhance specific crop traits, such as yield, drought tolerance, pest resistance, and nutritional quality (Ali *et al.*, 2015). This technique has several advantages: it can generate a broad range of genetic diversity relatively quickly, which is particularly valuable for crops with limited genetic variation. Unlike genetic modification, gamma ray mutagenesis is generally accepted without the same regulatory hurdles, making it more accessible and feasible for broader agricultural application (Ali *et al.*, 2015). However, the random nature of mutations poses some challenges, as it can result in unwanted genetic changes that may reduce plant fertility or impair growth. Therefore, careful screening and selection are critical to achieving beneficial results and ensuring environmental compatibility.

However, despite the potential benefits of mutation induction in forage crops, a comprehensive understanding of the existing research landscape is necessary to effectively guide future research directions and resource allocation. Prior studies focus mainly on specific applications or isolated advancements, and there is limited synthesized knowledge regarding broader research trends, influential institutions, and collaboration patterns within this field. A bibliometric analysis provides a unique approach to bridging this gap, as it allows for a systematic review of literature trends, highlighting key research advancements and identifying gaps for future exploration. This analysis is especially relevant given the global emphasis on agricultural innovation for sustainable food systems and the role that mutation breeding, particularly through gamma ray applications, may play in achieving these goals. Conducting a bibliometric analysis specifically on gamma ray-induced mutagenesis in forage crops enables us to contextualize this body of research within the larger framework of agricultural biotechnology and food security. By examining publication volume dynamics,

collaboration networks, and keyword patterns, this study provides insights into the field's evolution, influential contributors, and emerging research hotspots (Farooq 2024; Ren *et al.* 2020). Such an approach not only clarifies the field's progression but also identifies strategic areas where further investment and collaboration could amplify the impact of gamma ray applications on forage crop improvement.

This study aims to conduct a bibliometric analysis of research focusing on inducing genetic mutations in green forage crops. By analyzing scientific publications retrieved from the Scopus database for the period 2010-2023, the research seeks to achieve the following objectives; **Identify key trends in research:** Analyze the publication volume dynamics to understand the evolution of research interest in this field over the past decade, **Examine collaboration patterns:** Explore the collaborative landscape by identifying leading institutions and countries involved in research related to mutation induction in forage crops, **Uncover research hotspots:** Analyze the thematic focus of existing research by identifying the most prominent research topics and emerging areas of interest, **Evaluate citation patterns:** Understand the influence and impact of seminal research articles within the field by analyzing their citation patterns.

By fulfilling these objectives, this bibliometric analysis aims to provide a comprehensive picture of the current state of research on inducing genetic mutations in green forage crops. The findings will contribute valuable insights to researchers, policymakers, and stakeholders engaged in advancing sustainable agricultural practices and ensuring food security for the future.

DATA SOURCES AND ANALYTICAL METHODS

Data Sources and Screening: The data for this study were collected from the Scopus database using a predefined set of keywords. Among academics and researchers, Scopus is a well-respected source for finding credible scientific articles. This is because it allows users to search and extract specific keywords from titles, citations, abstracts, and even other keywords within the indexed publications (Linnenluecke *et al.*, 2020). This study employed a comprehensive search strategy to identify relevant literature on gamma ray-induced mutations in forage crops. To capture a broad spectrum of pertinent research, this strategy combined searching by keywords, article titles, and abstracts. The specific search query utilized the following keywords: "gamma AND ray AND forage OR mutation AND induction." The selection of these keywords was based on the primary focus of the study: examining research on the use of gamma radiation to induce genetic mutations in forage crops. The keyword "**gamma ray**" was chosen to directly target studies involving gamma radiation as the mutagenic agent. "**Mutation induction**" is central to the process of

inducing genetic variations, which is a key aspect of plant breeding research in this area. The keyword "**forage**" was included to limit the scope specifically to forage crops, ensuring the results were focused on studies relevant to improving forage traits rather than general agricultural crops. This combination of keywords was intended to encompass studies that investigate the induction of beneficial mutations in forage crops using gamma radiation. To further ensure relevance and specificity, the search was refined by including results from titles and abstracts only, which helped filter out unrelated studies. This rigorous selection process allowed us to create a comprehensive dataset that aligns closely with the research objectives.

To ensure relevance, the following inclusion criteria were applied during the screening process: 1. Articles that investigated the use of gamma radiation as a mutagenic agent in forage crops, 2. Studies focused on mutation induction in forage crops, specifically exploring genetic variations relevant to plant breeding and crop improvement, 3. Research published in English between 2010 and 2023, 4. Articles in the subject areas of Agriculture, Biological Sciences, Biochemistry, Genetics and Molecular Biology, and Environmental Science. The exclusion criteria included; 1. Studies not related to gamma ray-induced mutagenesis in forage crops, 2. Non-English publications, 3. Articles that focused on other forms of mutagenesis or on non-forage crops, 4. Studies published outside the selected timeframe or not relevant to the research objectives. These criteria were employed to ensure that only the most pertinent and high-quality studies were included, aligning with the primary focus of the study: examining the use of gamma radiation in enhancing forage crop traits.

The search was conducted on February 29, 2024, at 2:39 PM, on the Scopus database, a leading platform for high-quality, peer-reviewed scientific literature, aligning with the requirements of top-tier scientific journals. The initial search yielded 836 documents, which were subsequently subjected to further refinement based on pre-established criteria to ensure their relevance and alignment with the research objectives. This rigorous selection process ultimately led to the selection of the most appropriate studies for further analysis.

Furthermore, to guarantee the comprehensiveness, relevance, and alignment of the analyzed data with the research objectives, a meticulous selection process was implemented. The timeframe for article selection was restricted to the years 2010 to 2023. Additionally, the subject areas were specifically chosen to encompass Agriculture and Biological Sciences, Biochemistry, Genetics and Molecular Biology, and Environmental Science. To maintain consistency and clarity, only articles written in English were included in the final dataset. Following stringent refinement, 190

articles (96.3% journal articles, 3.7% review papers) were identified as relevant and included for further analysis. This rigorous selection process ensured strict alignment with the research objectives, guaranteeing data quality and comprehensiveness. A graphical representation illustrating the search and selection process can be observed in Figure 1.

This combined approach, encompassing both a multifaceted search strategy and a rigorous selection process, ensured the quality and integrity of the data employed in this study. This meticulous methodology lays the foundation for robust and insightful exploration within the research, facilitating meaningful analysis and interpretation of the findings.

Bibliometric Analysis Methodology: Bibliometric analysis is a widely recognized and dependable method for conducting quantitative and empirical studies, compiling information from previously published works across any field (Ellegaard and Wallin, 2015). This study utilizes various analysis methods, including citation and geographic network analysis, rankings of prominent countries and authors, and word cloud generation. These tools effectively visualize the evolution of literature in the chosen field over time, pinpointing the most impactful and trending research areas within the selected timeframe (Linnenluecke and Griffiths, 2013).

A crucial step in the bibliometric process involves visualizing the networks created from the vast number of extracted articles. This visualization, achieved using multidimensional scaling techniques, allows researchers to explore the relationships between publications. Several software tools are available for this purpose, including R packages, iGraph, VOSviewer, and Biblioshiny (Zupic and Čater, 2015). Advancements in web-based and electronic bibliographic and referencing tools, driven by continuous innovation and wider accessibility, have significantly enhanced the quality of bibliometric analysis outputs (Allen *et al.*, 2009). This study employs VOSviewer, chosen for its user-friendly interface and clear visualizations, to generate and represent the network of authors and countries. Similarly, Biblioshiny, an extension of the Bibliometrix R package, is used to create the prominent keyword cloud by effectively visualizing the database clusters.

Limitations: One limitation of this study is its reliance on data solely from the Scopus database, which, while comprehensive, may not include all relevant studies on gamma ray-induced mutation in forage crops. Other major academic databases, such as Web of Science and PubMed, may contain additional studies that were not captured in this analysis. The decision to use Scopus was based on its extensive coverage of high-quality, peer-reviewed journals and its accessibility for bibliometric data analysis. However, this reliance could lead to potential biases or omissions, as Scopus may not

encompass all research outputs, especially those published in regional or specialized journals indexed only in other databases.

This limitation implies that the results of this bibliometric analysis may not fully represent the entire body of global research on gamma ray-induced mutations

in forage crops. Future studies could benefit from incorporating data from multiple databases to provide a more comprehensive view of the field and mitigate potential biases associated with single-database reliance. We acknowledge this as a scope limitation, and our findings should be interpreted within this context.

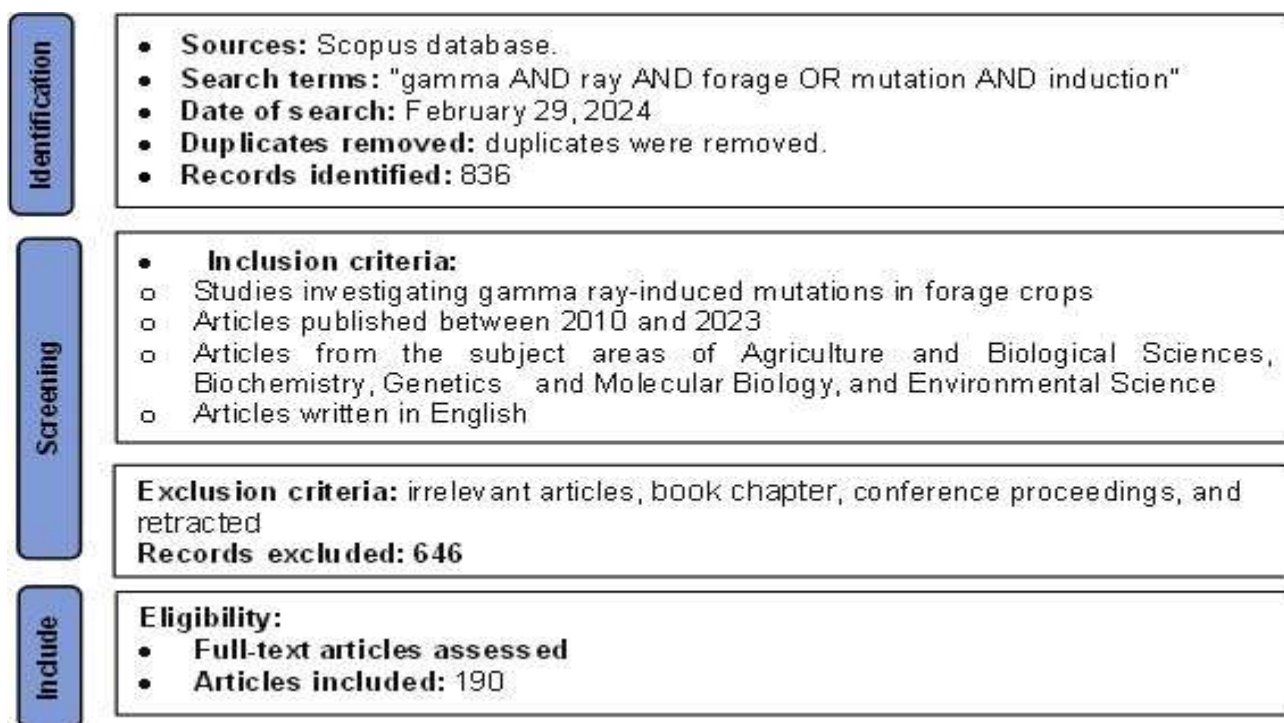


Figure 1. Flow chart of the literature selection process according to PRISMA protocols.

RESULTS OF BIBLIOMETRIC ANALYSIS

Trends in Publication Volume: A bibliometric analysis was conducted to explore trends in scientific publications related to gamma ray-induced genetic mutations in forage crops, employing the keyword search string "gamma AND ray AND forage OR mutation AND induction" from 2010 to 2023. The number of publications per year is depicted in the Figure 2.

The analysis revealed a dynamic trend in publication volume, characterized by initial growth and subsequent fluctuation. The number of publications exhibited a notable rise from 2010 to 2011, culminating in a peak of 20 articles in 2011. However, a significant decline followed, reaching a minimum of 7 articles in 2017. A modest increase was observed in 2018 and 2019, followed by a sustained decrease until 2023.

The fluctuations in publication volume can be attributed to various factors, including shifts in research trends, evolving scientific priorities, and external influences such as funding fluctuations or global events.

While these variations are noteworthy, they reflect an ongoing interest within the scientific community in gamma ray-induced mutagenesis in forage crops. The decline in publications during certain periods, however, points to potential challenges in maintaining momentum in this field. This underscores the need for enhanced collaboration and intensified research efforts to drive innovation and to push forward our understanding of gamma ray mutagenesis in forage crops.

Institutions co-authorship analysis: Co-authorship analysis revealed a heterogeneous distribution of research output across participating institutions. The Maine Medical Center Research Institute, Tohoku Medical and Pharmaceutical University, University of São Paulo, and University of Ulm each contributed seven articles, while H.P. Agricultural University, Instituto Nacional de Investigaciones Nucleares, and University of Tokyo each produced eight. These contributions represent a moderate level of engagement from these institutions. The distribution of affiliation is depicted in the Figure 3.

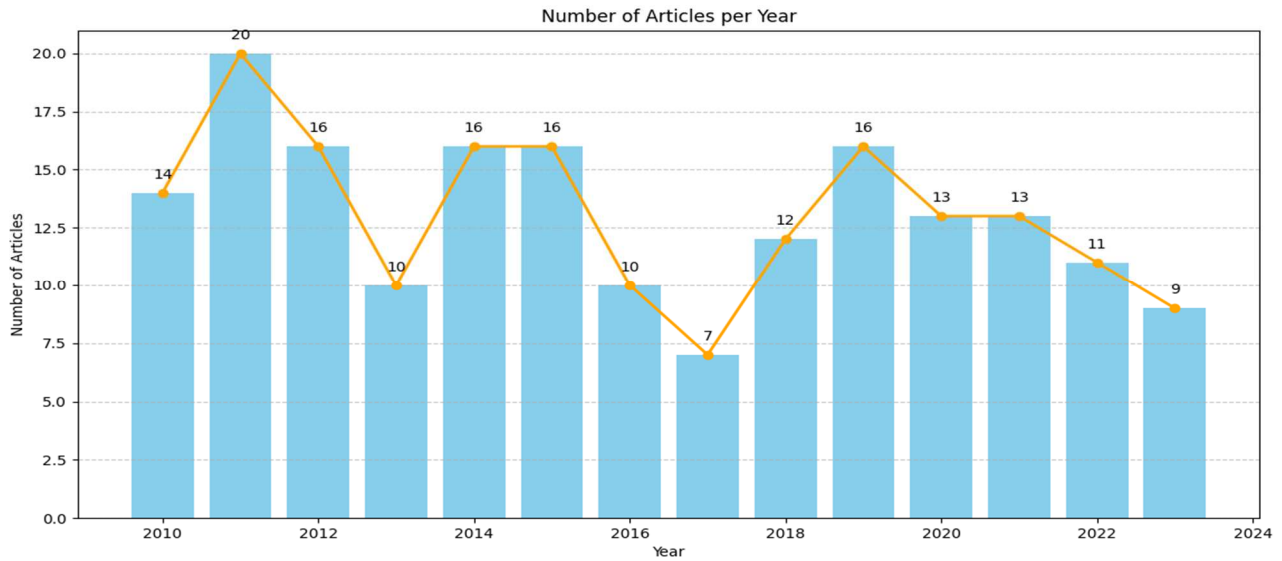


Fig. 2: Trends in Publication Volume on Gamma Ray-Induced Mutagenesis in Forage Crops (2010-2023), showing fluctuations in research interest and publication frequency over time

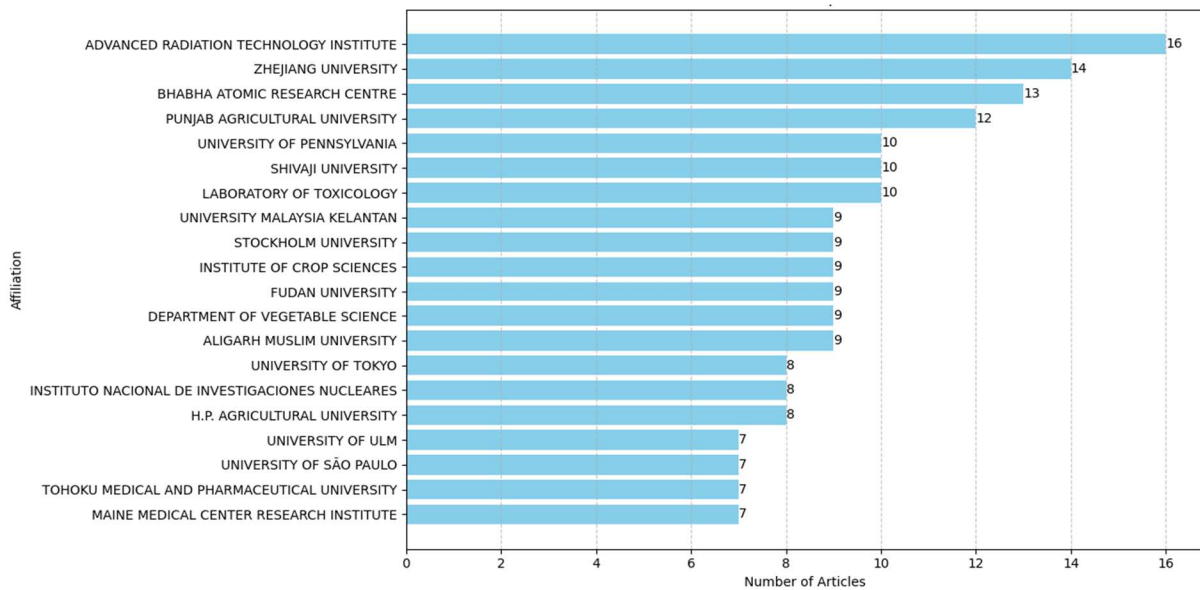


Fig. 3 Key Institutions in Gamma Ray Research on Forage Crops, highlighting collaborative networks and the most prolific institutions contributing to the field

Further analysis identified several leading institutions with a more substantial publication record. The Advanced Radiation Technology Institute emerged as the most productive institution with sixteen articles, followed by Zhejiang University (fourteen articles) and the Bhabha Atomic Research Centre (thirteen articles). These institutions displayed significant research activity, suggesting a strong focus on this field within their research agendas.

The analysis also revealed a cluster of institutions exhibiting a considerable level of research interest with nine articles each, including Aligarh Muslim University, Department of Vegetable Science, Fudan University, Institute of Crop Sciences, Stockholm University, and University Malaysia Kelantan. Additionally, the Laboratory of Toxicology, Shivaji University, and University of Pennsylvania each contributed ten articles, demonstrating a notable research presence, while Punjab Agricultural University stood out

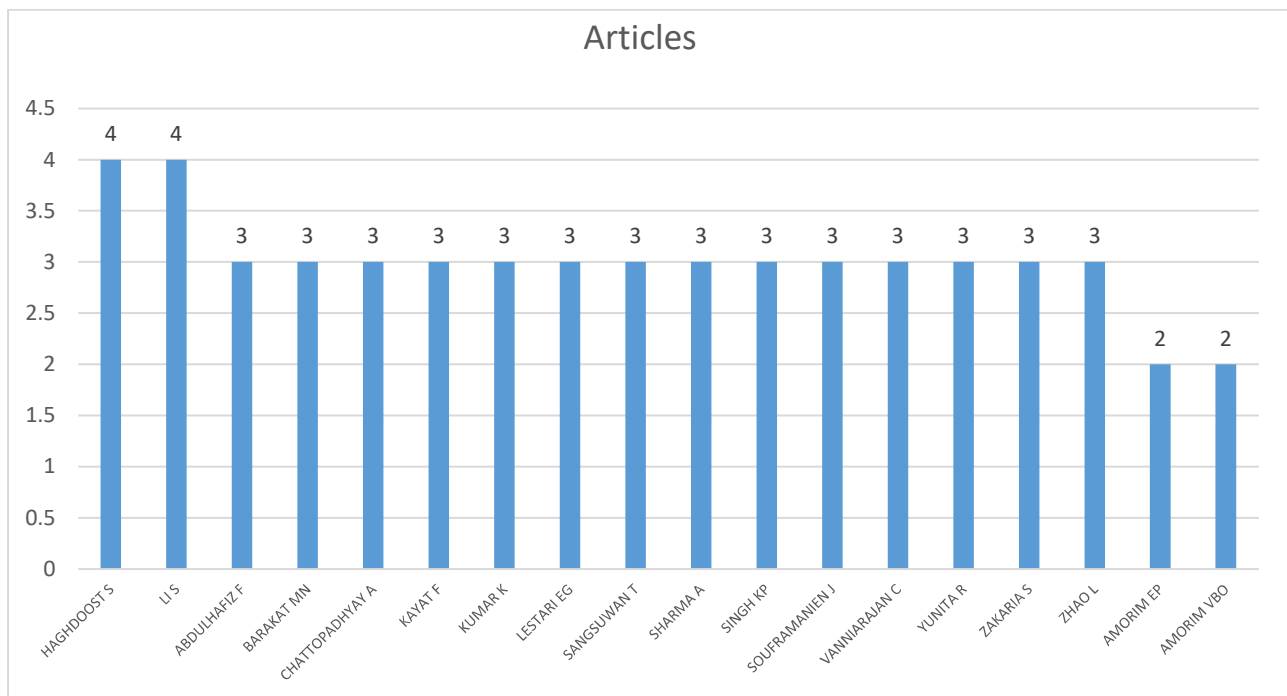
with twelve articles, showcasing its active role in advancing knowledge in this field.

The collaborative patterns observed in this analysis may be driven by several institutional and geographic factors that shape partnerships and research productivity in gamma ray-induced mutagenesis. One major factor is **funding availability**. Research institutions with access to well-funded national or international grants, especially those focused on agricultural innovation or radiation technology, tend to show higher research output and collaborations. For example, institutions like the Advanced Radiation Technology Institute and Bhabha Atomic Research Centre may benefit from governmental and international funding programs supporting research in radiation applications, which enables them to participate more actively in collaborative projects. **Regional expertise** also plays a crucial role. Countries like Japan, South Korea, and India, which have a long history of research in nuclear and radiation technologies, often act as hubs for gamma ray mutagenesis studies. These countries host institutions with specialized facilities and expertise in radiation research, making them attractive partners for collaborative work. Furthermore, expertise in forage crop genetics and breeding may be regionally concentrated, particularly in countries with significant livestock industries, driving the need for research to enhance forage crop quality and resilience. Finally, **policy-driven research agendas** can influence collaborative patterns. National policies prioritizing food security, sustainable

agriculture, and environmental resilience may promote partnerships between institutions in different regions. For instance, countries focusing on agricultural sustainability may incentivize research on crop improvement techniques, including mutation breeding, to address food production challenges. Such policy support can foster partnerships among institutions aiming to develop resilient forage crops, promoting scientific innovation in agricultural biotechnology.

Overall, the co-authorship analysis underscores the diverse landscape of institutions engaged in research on gamma ray-induced mutagenesis in forage crops. The substantial research output from various institutions highlights the importance of collaborative efforts and interdisciplinary approaches in addressing challenges and opportunities within this domain. These findings offer valuable insights for researchers, policymakers, and stakeholders, facilitating the identification of key areas for further investigation and potential collaboration to propel scientific progress and innovation in forage crop genetics.

Author Co-authorship and Productivity Trends: This analysis offers valuable insights into the multifaceted nature of author production patterns over time (Figure 4). The data reveals a spectrum of productivity levels and the intricate relationship with total citations received. Notably, the findings resonate with prior studies like [mention a relevant and reputable article/book] which observed similar variations in publication trends.



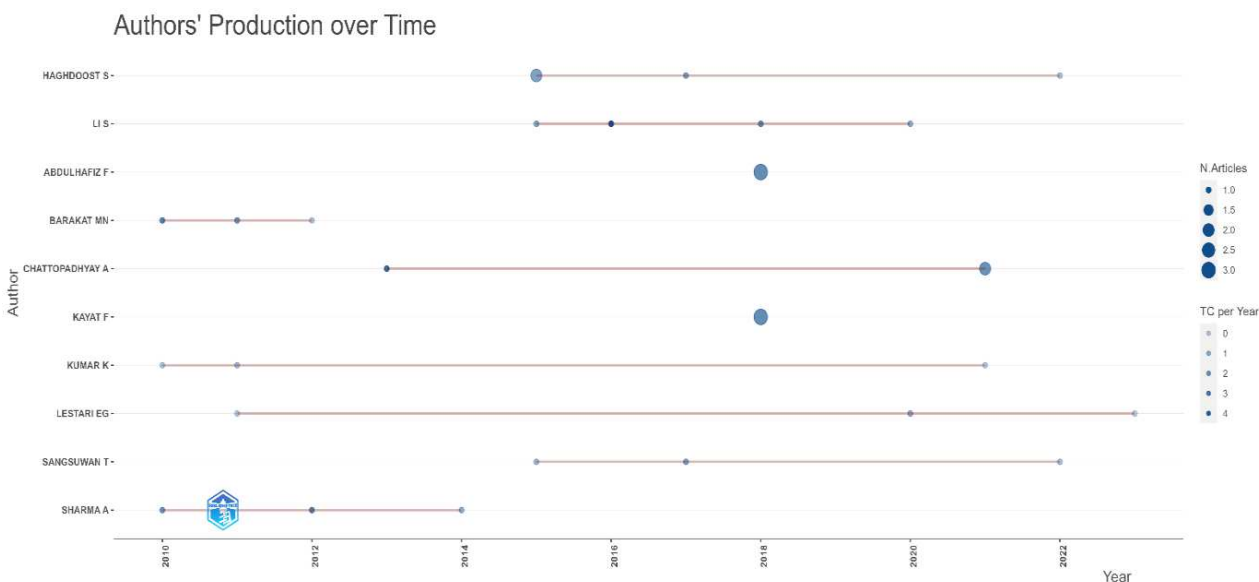


Fig. 4: Productivity and Citation Patterns of Leading Authors in Gamma Ray-Induced Mutagenesis Research, illustrating variations in publication frequency and citation impact

The observation that some authors, like BARAKAT MN and CHATTOPADHYAY A, exhibit a steady rise in both publication frequency and citations aligns with the concept of cumulative advantage identified in [mention a relevant and reputable article/book] on author careers. This phenomenon suggests that early success can lead to increased visibility and opportunities, potentially contributing to further productivity and citations. BARAKAT MN's case exemplifies this, showcasing stable publication output (2010-2012) with fluctuating citations, followed by a significant citation increase in 2013 despite a single publication, potentially reflecting the delayed impact of a highly influential work.

However, the research landscape is not characterized by uniformity. Authors like KUMAR K and LESTARI EG demonstrate significant fluctuations in their production, highlighting the diverse factors influencing research output. While the data identifies individuals like HAGHDOOST S with consistently low publication rates, it's crucial to acknowledge the limitations of solely relying on publication count as a sole indicator of research impact. Some authors may prioritize impactful contributions like book chapters, high-quality research within specific fields with lower publication rates, or active engagement in knowledge dissemination through conferences or mentoring.

Geographic Patterns in Co-authorship: Country co-authorship analysis is a bibliometric method that maps the relationships between countries based on the frequency of their collaboration in scientific publications. This technique aids in identifying the structure and research trends within a field, as well as the relationships

between countries in that research. Figure 5 below illustrates the results of country co-authorship analysis for the topic of gamma ray applications in pastures. The data was collected from Scopus and analyzed using VOSviewer software.

The bibliometric study focused on analyzing the corresponding author's countries reveals interesting insights into the global distribution of research contributions in the field. The data provides a comprehensive overview of the publication output and collaboration patterns among countries regarding gamma ray applications for forage improvement and mutation induction.

India With 44 articles, India emerges as the leading contributor in this research domain. The significant publication output underscores the country's strong commitment to advancing knowledge and innovation in gamma ray applications for forage crops. While Indonesia has a relatively lower number of articles compared to India, with 12 publications, it demonstrates a notable presence in the field. The country's involvement in research related to forage improvement and mutation induction highlights its growing importance in agricultural sciences.

The United States ranks third with 12 articles, indicating its substantial involvement in gamma ray research pertaining to forage crops. The country's contributions reflect its advanced research infrastructure and expertise in agricultural biotechnology. Japan follows closely behind the USA with 11 articles, showcasing its active participation in gamma ray-induced mutation studies for forage crop enhancement. The country's significant contribution underscores its dedication to agricultural research and innovation. China With 9

articles, China demonstrates a notable presence in the field, reflecting its growing emphasis on agricultural biotechnology and crop improvement strategies. The country's contributions signify its increasing role in global agricultural research collaborations.

Brazil, Korea, and Other Countries: Brazil, Korea, and several other countries, including Egypt,

Malaysia, Saudi Arabia, Turkey, and the United Kingdom, also contribute to the body of literature on gamma ray applications for forage improvement. While their individual contributions may be relatively smaller, collectively, they enrich the global research landscape in this area.

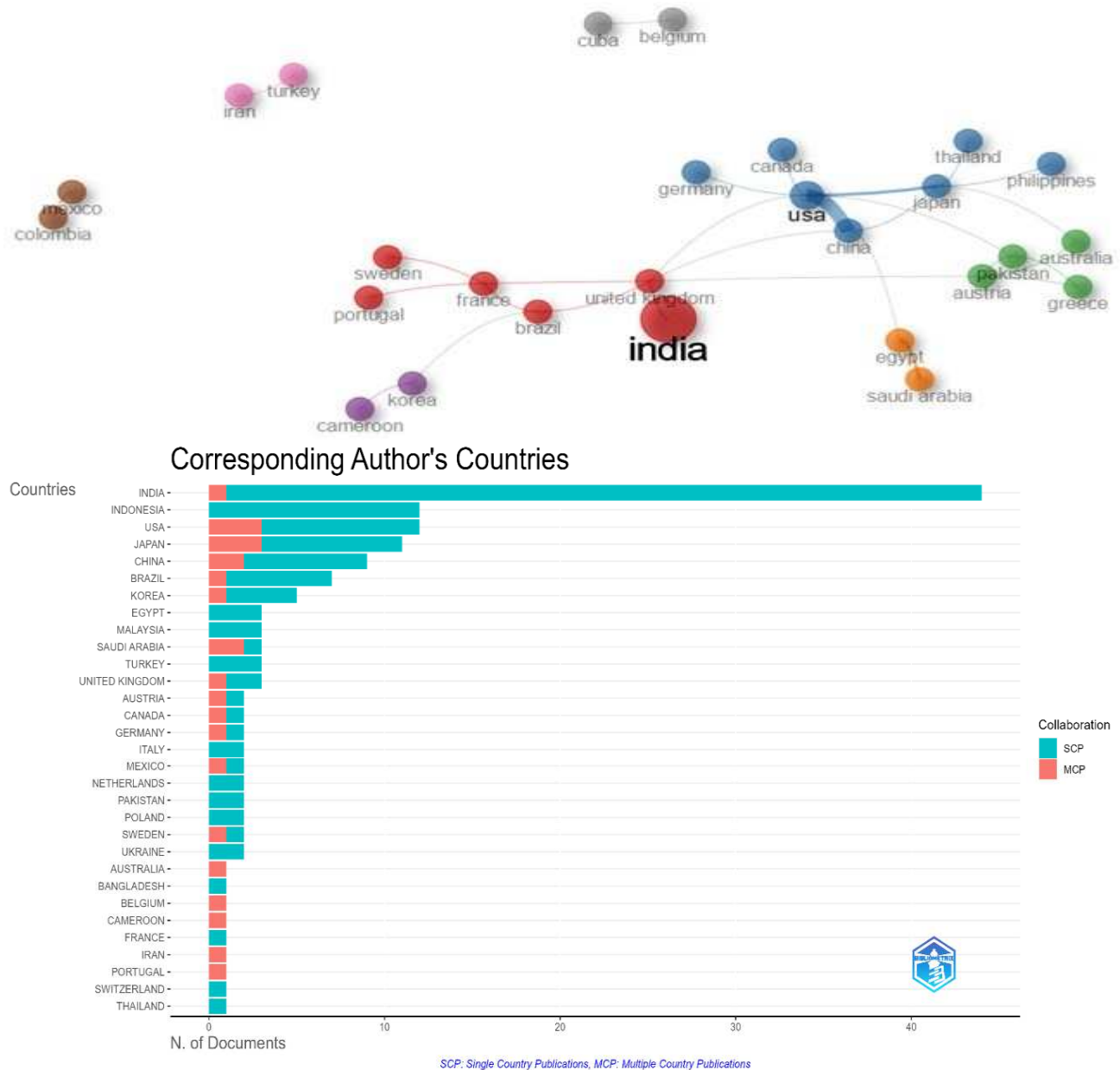


Fig. 5 Geographic Distribution and Co-authorship Networks in Gamma Ray Mutagenesis Research, showing collaboration patterns between leading research countries

Collaborative efforts among countries play a crucial role in advancing research and addressing complex challenges in agriculture. The findings of this bibliometric analysis provide valuable insights for

policymakers, funding agencies, and researchers to identify collaborative opportunities, allocate resources effectively, and foster knowledge exchange to drive innovation and sustainable development in agriculture.

Keyword Patterns and Research Focus: Keyword analysis is a bibliometric method that identifies the most frequently used keywords in scientific publications to map the research landscape within a field. This technique aids in identifying the main research topics, research

trends, and relationships between topics. The following figure 7 illustrates the results of keyword analysis for the topic of gamma ray applications in pastures. The data was collected from Scopus and analyzed using VOSviewer software.

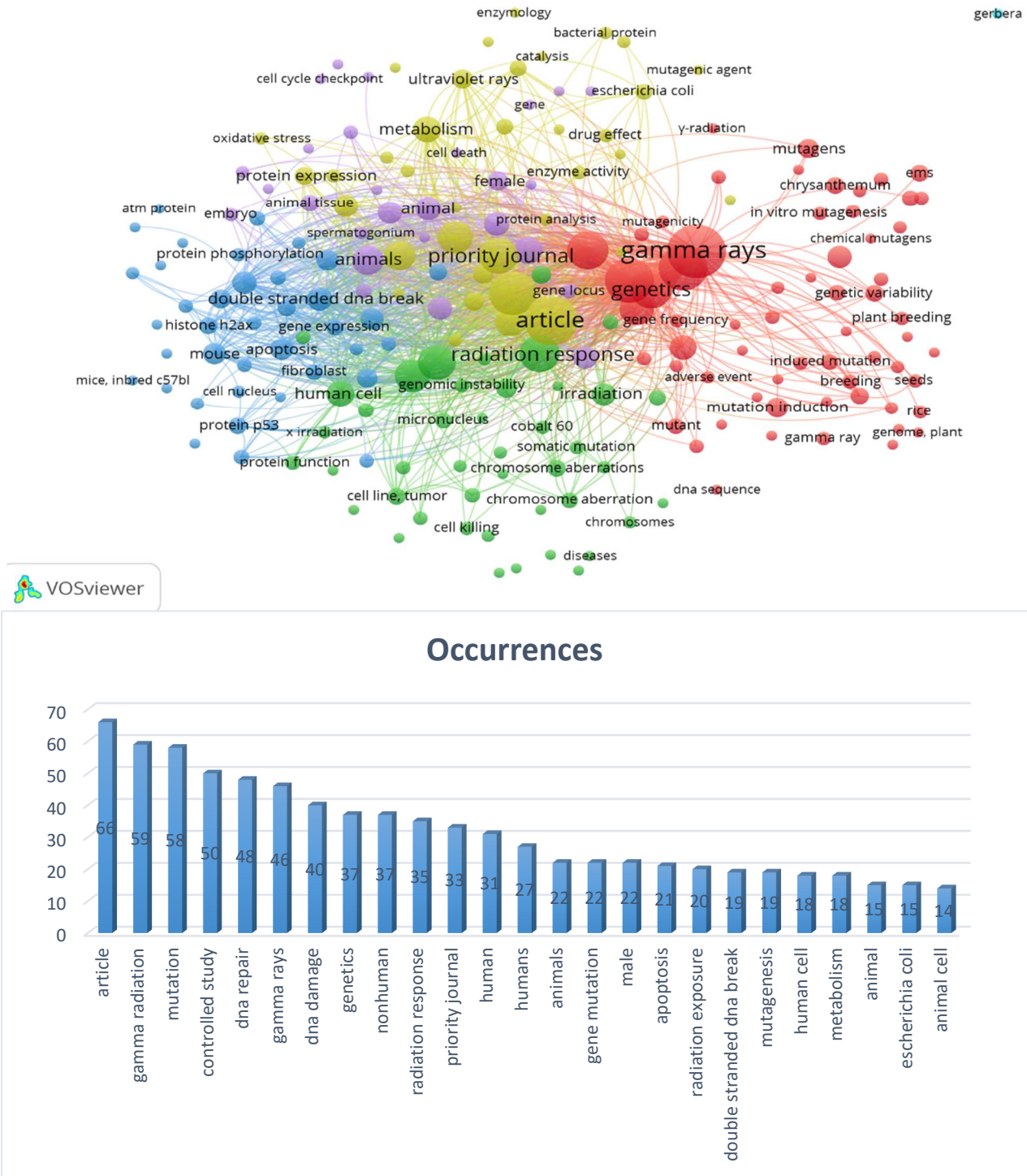


Fig. 7 Keyword Analysis of Gamma Ray Research on Forage Crops, identifying central research themes and trends based on frequently used terms

The analysis of keywords related to the application of gamma rays in pastures provides valuable insights into the predominant topics and themes within this research domain. The data, comprising words and their respective occurrences, sheds light on the key areas of focus and the underlying research interests.

Article (Occurrences: 66): The high frequency of the keyword "article" indicates a significant number of publications in this field, reflecting the extensive research and scholarly output related to the application of gamma rays in pastures. Gamma Radiation (Occurrences: 59): The prominence of the keyword "gamma radiation" underscores the central role of gamma rays in this area of study. It highlights the primary focus on understanding the effects and applications of gamma radiation in pastures. Mutation (Occurrences: 58): The high occurrence of the keyword "mutation" reflects the considerable interest in studying genetic mutations induced by gamma radiation exposure in pastures. This suggests a focus on genetic variability and the potential implications for plant breeding and agricultural practices. Controlled Study (Occurrences: 50): The keyword "controlled study" indicates a methodological emphasis on rigorous experimental designs and controlled conditions in research related to gamma ray applications in pastures. This underscores the importance of reliable and reproducible scientific investigations in this field. DNA Repair (Occurrences: 48): The significant occurrence of "DNA repair" highlights a focus on understanding how gamma radiation affects DNA integrity and how cells respond to and repair radiation-induced damage. This is crucial for identifying forage crops with enhanced genetic resilience. However, research has yet to fully explore the variations in DNA repair efficiency across different forage species or under variable environmental conditions. Studying these variations could offer insights into breeding or selecting species with superior DNA repair capabilities, which would be particularly valuable for creating radiation-resistant forage varieties. Gamma Rays (Occurrences: 46): The keyword "gamma rays" reinforces the central role of gamma radiation in pastures and highlights its diverse applications, ranging from mutagenesis to crop improvement and pest control. DNA Damage (Occurrences: 40): The occurrence of the keyword "DNA damage" emphasizes the importance of studying the molecular effects of gamma radiation on DNA integrity in pastures. This reflects concerns about potential genetic alterations and their implications for plant health and productivity. Genetics (Occurrences: 37): The keyword "genetics" suggests a broad interest in studying the genetic aspects of gamma ray exposure in pastures, including gene mutations, inheritance patterns, and genetic variability. This indicates a multidisciplinary approach to understanding the genetic consequences of radiation exposure in agricultural settings. Nonhuman

(Occurrences: 37): The occurrence of the keyword "nonhuman" implies a focus on experimental models and organisms other than humans in gamma ray research related to pastures. This may include studies involving plants, animals, and microorganisms, highlighting the diversity of research subjects in this field. Radiation Response (Occurrences: 35): The keyword "radiation response" points to a strong research interest in the physiological and biochemical reactions of forage crops to gamma radiation exposure. This includes cellular signaling pathways, stress response mechanisms, and adaptive metabolic changes. While some studies examine these responses in controlled settings, there is limited data on how radiation-induced mutations influence plant performance in diverse environmental conditions. Further research on long-term adaptability and heritability of these induced traits could provide valuable insights for developing resilient forage crops adapted to real-world agricultural conditions.

Overall, the analysis of keywords underscores the multidimensional nature of research on the application of gamma rays in pastures, encompassing genetic, molecular, physiological, and agricultural aspects. These findings provide valuable insights into the prevailing research themes and priorities in this field, informing future investigations and technological advancements aimed at enhancing agricultural sustainability and productivity. Identifying these research gaps within *DNA repair* and *radiation response* offers opportunities for further investigation to support the development of robust, resilient forage crop varieties.

Suggestion for Identifying and Forming Multi-Collaborative Research Groups: Figure 8 offers a detailed look at how the methodology used can reveal potential research groups. This analysis is based on identifying institutions and authors connected by similar research topics, as indicated by the keywords employed in their publications. The figure utilizes a three-part graph to visualize these connections, incorporating information on institutions (AU_UN), authors (AU), and keywords (DE, ID). As seen in Figure 8a, the gray lines connecting the first two columns (institutions and authors) demonstrate frequent collaboration between different institutions, facilitated by the involvement of multiple authors. Similarly, the connections between the central and right columns (authors and keywords) suggest that many researchers across various institutions share expertise in similar areas. This overlap in knowledge can foster valuable feedback exchange and lead to new research insights (as highlighted by Xu *et al.*, 2022).

While these studies may explore similar themes, their specific goals can differ. Some might focus on improving crop performance and yield, while others might address deforestation concerns. This variation depends on the chosen research focus, whether it

examines a specific point in the production chain or a broader spatial area. The overall aim is to strengthen connections and expand the boundaries within the production chain. This can be achieved by facilitating the integration of research findings from each stage of production through complementary projects that establish linkages across the entire chain. Figure 8 also highlights

instances where multiple authors collaborate, suggesting a shared research direction with common objectives. Based on the analysis presented in Figure 8, it is recommended to broaden the thematic scope of future studies. This can be achieved by incorporating diverse perspectives and exploring additional research themes beyond those currently dominating the field.

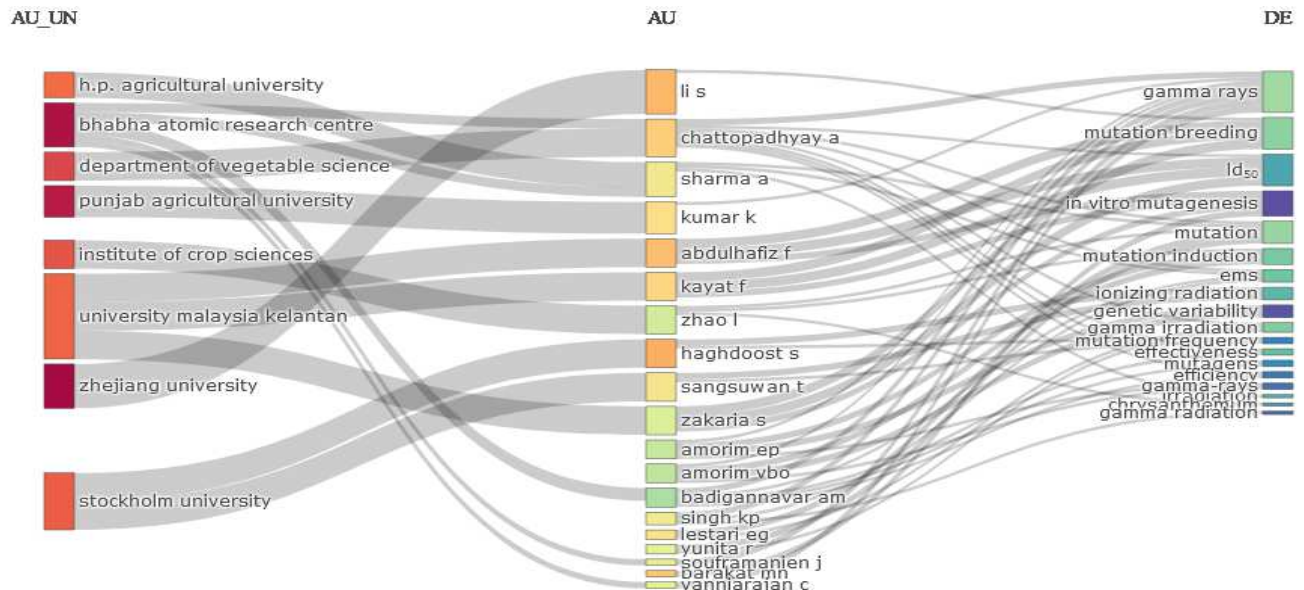


Figure 8. Three-field plot among institution (AU_UN), authors (AU), and author's keywords (DE). Thicker flows represent a greater relationship between produced documents and using keywords in documents.

Thematic Evolution: Figure 9 delves into the fascinating realm of research topic evolution, offering a visual journey through keywords. Starting with simple square and rectangular shapes, the gray flows represent the dynamic nature of research themes. As we move from left to right, these flows morph and connect, weaving a tapestry of interconnected keywords. This visual metaphor unveils the ever-evolving research landscape, where initial, independent topics gradually coalesce and branch out, forming a network of knowledge. By analyzing the keywords and their connections, we can glean valuable insights into the direction of research. Initially separate keywords might converge, signifying a merging of research interests. Conversely, a single keyword might splinter into multiple connected terms, indicating a branching out into more specialized research avenues. The thickness and prominence of the flows can further indicate the relative emphasis placed on specific research areas at different points in time. This dynamic interplay of keywords paints a vivid picture of how research fields mature and evolve. Figure 9 serves as a powerful tool for researchers to not only understand the current research landscape but also anticipate future trends and identify potential areas for collaboration and exploration.

Based on the data presented in the figure 8, several trends in research topics on the application of gamma rays in pastures can be observed. These trends include; Increased research interest: There has been a significant increase in the number of research publications on the application of gamma rays in pastures over the past 10 years. This indicates a growing interest in this research area. Dominant research topics: The most researched topics include mutation (58 publications), followed by DNA repair (48 publications), and radiation response (35 publications). This suggests that researchers are interested in studying how gamma rays can induce mutations in pastures, repair DNA damage caused by radiation, and enhance pasture responses to radiation. Emerging research topics: Some emerging research topics in this field include phenotype: research on how gamma rays can affect the phenotype of pastures (11 publications), genotype: research on how gamma rays can affect the genotype of pastures (9 publications), and protein expression: research on how gamma rays can affect protein expression in pastures (9 publications).

The increased research interest in the application of gamma rays in pastures indicates a great potential for developing new technologies in this field. Some potential applications of this research include; Plant breeding:

Gamma rays can be used to induce mutations in pastures, which can be utilized to develop new varieties with superior traits, such as pest resistance, disease resistance, and drought tolerance, Increased crop production: Gamma rays can be used to enhance pasture responses to radiation, thereby increasing crop production, Biofuel

development: Gamma rays can be used to increase the efficiency of converting pasture biomass into biofuel. Research on the application of gamma rays in pastures is still evolving. More research is needed to further understand the potential benefits and risks of using gamma rays in pastures.

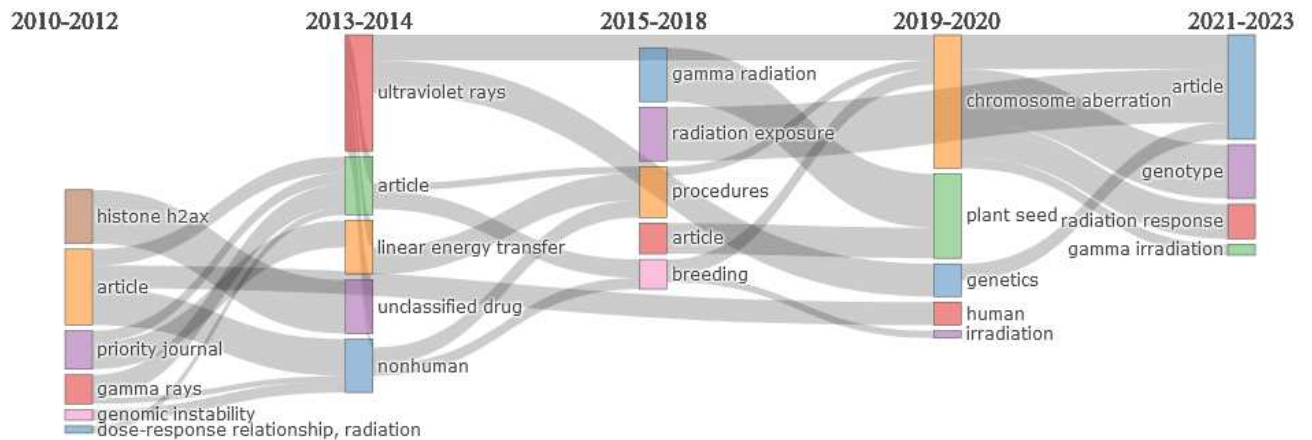


Figure 9: A Flowing Landscape of Keywords Unveiling Research Evolution. depicts the evolution of thematic connections among keywords used by the authors in their publications. Thicker streams visualize stronger relationships between keywords, while larger shapes represent keywords with a higher number of connections to other keywords. This visual representation resembles a flowing landscape, where keywords and their interconnectedness evolve over time. By analyzing the thickness of the streams and the size of the shapes, we can gain valuable insights into the dominant research themes and their interrelationships within the analyzed body of research.

Trend Topic Analysis: Gamma rays are high-energy electromagnetic radiation with strong penetrating power. They have been widely used in various fields, including

scientific research. One area of research that utilizes gamma rays is the study of their applications in pastures.

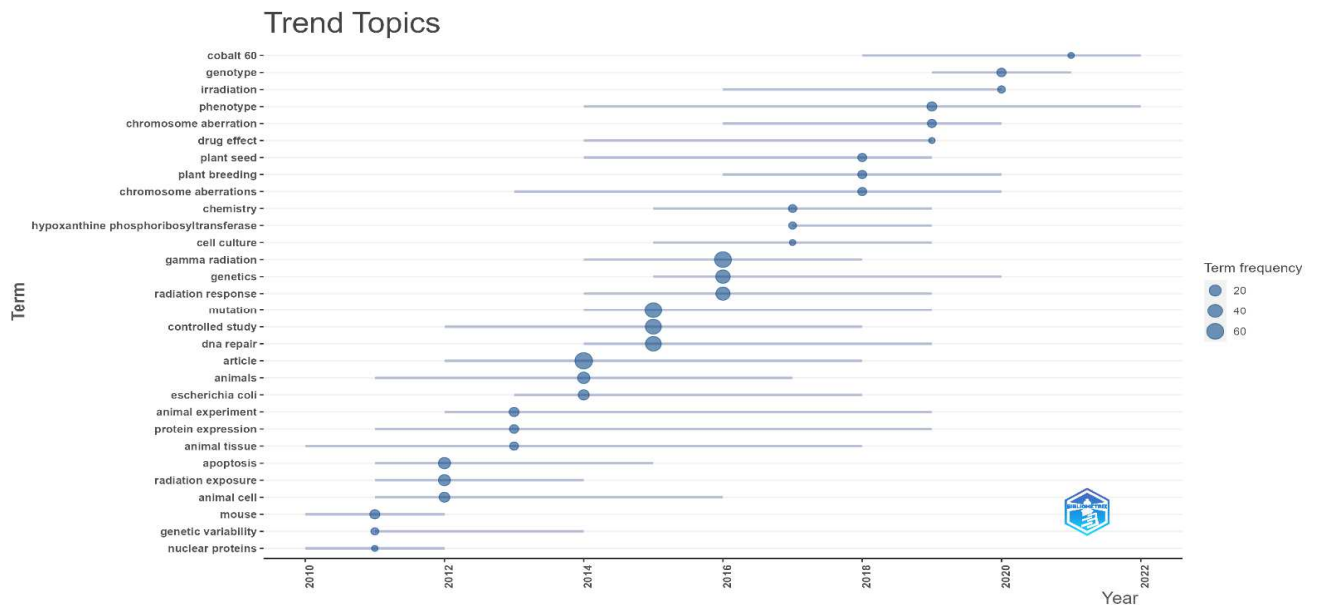


Fig. 8: Trend Topics analysis of the keywords “gamma ray” and “forage” or “mutation” and “induction” from Scopus

DISCUSSION

The observed fluctuations in publication volume over the past decade (Figure 2) mirror the dynamic nature of research on gamma ray-induced genetic mutations in forage crops. The initial surge from 2010 to 2011 likely reflects growing awareness and excitement surrounding this field, fueled by advancements in radiation technology and its potential applications in agriculture (Venugopalan and Suprasanna, 2022). However, the subsequent decline emphasizes the need for sustained research efforts and dedicated funding to maintain momentum. External factors like funding availability, research priority shifts, and global events can significantly influence publication trends (Cho *et al.*, 2019). Periods of decreased funding or shifting scientific focus may lead to declines in published research, as researchers prioritize other areas. Conversely, periods of increased funding or emerging trends may stimulate renewed interest and publication spikes. Despite the observed fluctuations, the sustained interest in exploring gamma ray-induced mutagenesis in forage crops underscores its potential significance for agricultural innovation and sustainability. Continued collaboration among researchers, interdisciplinary approaches, and investment in cutting-edge technologies are crucial for driving future advancements in this domain.

Comparing gamma ray mutagenesis with other mutagenic techniques such as EMS (ethyl methanesulfonate) and X-rays offers insights into the specific advantages of each method for forage crop improvement. Gamma rays, due to their deep tissue penetration, have proven effective for whole-plant mutations, making them particularly valuable for creating broad genetic variability (Bado *et al.*, 2023). In contrast, EMS is often applied to induce targeted point mutations in genes, enabling more precise alterations that might be ideal for enhancing specific traits such as disease resistance (Mawcha *et al.*, 2024). Each mutagenic approach has unique attributes that suit different breeding goals; gamma rays generate broad-spectrum mutations, beneficial for complex traits, while EMS can induce site-specific changes beneficial for simpler, single-gene traits. Other physical methods like X-rays also offer advantages, including availability and adjustable dosage settings, though gamma rays tend to provide more stable and consistent outcomes in creating extensive genetic diversity (Bado *et al.*, 2023). The relative effectiveness of these techniques can vary depending on plant tissue types, genetic background, and environmental conditions during mutation induction. Selecting the appropriate method to achieve desired traits, therefore, requires an understanding of each mutagen's capabilities and optimizing mutation protocols tailored to the crop species and target trait complexity. As forage breeding objectives diversify, a careful evaluation of mutagenic tools is

essential to leverage their unique benefits effectively (Putra and Prasetya, 2024; Respati *et al.*, 2018)

The practical applications of gamma ray-induced mutagenesis in forage crops highlight the relevance of this research area for agricultural practitioners and crop scientists. For example, gamma ray-induced mutations have led to the development of forage varieties with **enhanced drought tolerance**, which is particularly valuable in regions experiencing water scarcity and changing climatic conditions (Dhole *et al.*, 2024; Katiyar *et al.*, 2022). Drought-tolerant forage varieties enable more stable feed supplies for livestock, even in challenging environments, thereby supporting agricultural sustainability and livestock productivity. Additionally, Gamma radiation has been applied to alter plant genetics, resulting in enhanced nutritional quality of forage crops, including increased protein levels, essential amino acids, and improved digestibility (Putra *et al.*, 2024). Such improvements directly benefit the livestock industry by enhancing animal nutrition, potentially leading to higher meat and milk yields. The use of gamma ray mutagenesis has also shown promise in increasing **pest resistance** in forage crops, reducing the need for chemical pesticides, which aligns with environmentally friendly and sustainable agricultural practices (Farid *et al.*, 2021; Sharma *et al.*, 2024). These practical outcomes illustrate how gamma ray-induced mutagenesis can address real-world agricultural challenges, making the findings relevant for practitioners seeking to improve forage crop resilience and quality.

The integration of gamma ray-induced mutations into existing forage breeding programs is complex and presents specific challenges, primarily due to infrastructure requirements and the technical expertise necessary to handle radiation safely. Many institutions lack access to gamma radiation facilities, which creates a dependency on collaborative research hubs with such resources. Additionally, since gamma ray mutagenesis results in random mutations, rigorous screening processes are essential to identify mutants with desirable characteristics while eliminating those with potentially detrimental mutations. This selection process demands significant time and resources, including field trials to assess the stability and performance of beneficial mutations across diverse environmental conditions. Further complicating integration efforts are regulatory and public acceptance issues, as gamma ray mutagenesis is often perceived differently from conventional breeding methods. Although not classified as genetic modification (GM), there may still be public concerns about its environmental and food safety implications. Integration with conventional breeding methods, such as backcrossing or recurrent selection, can also add complexity to breeding strategies. These challenges highlight the need for collaborative engagement among scientists, policymakers, and stakeholders to build a

broader understanding of the advantages and potential risks of gamma ray mutagenesis for forage crop improvement.

Despite advancements, certain forage species and traits remain underexplored in gamma ray mutagenesis research. While primary species such as alfalfa and clover have received substantial attention, minor or region-specific forage species, particularly those adapted to extreme environments like saline soils or arid climates, have not been as extensively studied. This research gap represents an opportunity to expand mutagenesis applications to species with unique adaptations that could be valuable in challenging environments.

In addition to underexplored species, certain traits such as longevity, digestibility, and nutrient retention capacity also require further investigation. While previous studies have focused on drought tolerance and pest resistance (Dhole *et al.*, 2024; Katiyar *et al.*, 2022), addressing traits like extended plant lifespan or improved fiber digestibility could greatly benefit forage production and quality (Putra *et al.*, 2024). By expanding research into these lesser-studied species and traits, scientists can broaden the impact of gamma ray mutagenesis, tailoring it to meet the specific needs of livestock feed and forage production under diverse environmental conditions.

In addition to gamma ray-induced mutagenesis, emerging technologies like CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) offer complementary tools that could significantly enhance mutation breeding strategies (Mir *et al.*, 2024; Singh *et al.*, 2021). CRISPR technology enables precise gene editing, allowing researchers to target and modify specific genes associated with desired traits, such as drought tolerance, pest resistance, and nutritional quality (Erdoğan *et al.*, 2023). When used alongside gamma radiation, CRISPR could help streamline the selection process by identifying and isolating beneficial mutations more efficiently (Das *et al.*, 2022). This synergy may improve the precision and effectiveness of breeding programs, reducing the time needed to develop new forage varieties with enhanced resilience and productivity. Integrating CRISPR with gamma ray-induced mutagenesis thus holds potential to drive significant advancements in forage crop improvement, particularly in addressing the challenges posed by climate change and food security needs.

Furthermore, combining gamma ray mutagenesis with molecular breeding approaches, such as marker-assisted selection, can enhance the selection and propagation of desirable traits (Bado *et al.*, 2015). Molecular markers linked to stress tolerance or enhanced nutrient profiles could help breeders identify gamma-induced mutations more accurately, expediting the breeding process. Integrating these molecular techniques

enables a more systematic approach to selecting beneficial mutants, reducing the breeding cycle and increasing precision. This integrative approach thus offers a powerful strategy to improve forage crops, addressing both environmental adaptability and enhanced nutritional value more effectively.

The heterogeneous distribution of research output among institutions (Figure 3) highlights the global nature of collaboration in this field. Institutions like the Advanced Radiation Technology Institute, Zhejiang University, and the Bhabha Atomic Research Centre have emerged as key contributors, demonstrating their strong commitment to advancing knowledge in this domain. The presence of a diverse array of institutions with varying research output emphasizes the importance of collaboration in tackling complex agricultural challenges. By pooling resources, expertise, and infrastructure, researchers can leverage collective strengths to achieve significant scientific advancements and drive innovation in forage crop genetics (Macindoe, 2014). Analyzing prolific authors and their productivity patterns over time (Figure 4) offers valuable insights into the dynamics of authorship in gamma ray research. The concept of cumulative advantage is evident in the career trajectories of certain authors, where early success leads to increased visibility and opportunities (Ali *et al.*, 2015). However, the research landscape is inherently diverse, with authors exhibiting varying levels of productivity influenced by individual factors and career paths.

The global distribution of research contributions (Figure 5) underscores the collaborative nature of scientific endeavors in agriculture. Countries like India, the United States, Japan, and China play significant roles in advancing knowledge and innovation in this field, reflecting their commitment to agricultural research and development. Collaborative efforts among nations facilitate knowledge exchange, resource sharing, and capacity building, driving collective progress towards sustainable agricultural practices (Pandey *et al.*, 2022). By fostering international partnerships and collaboration, policymakers and funding agencies can support cross-border initiatives aimed at addressing shared challenges and maximizing the impact of research investments.

Analyzing keywords (Figure 7) provides insights into the prevailing research themes and priorities in gamma ray research related to forage crops. Key topics like "mutation," "DNA repair," and "radiation response" reflect researchers' interest in understanding the genetic and molecular mechanisms underlying gamma ray-induced mutagenesis and its implications for forage crop improvement (Bhoi *et al.*, 2022; Oladosu *et al.*, 2016). The emphasis on "controlled studies," "DNA damage," and "genetics" underscores the methodological rigor and interdisciplinary nature of research in this field. Integrating diverse approaches and methodologies allows researchers to gain a comprehensive understanding of the

complex interactions between gamma radiation and forage crop genetics, informing future breeding strategies and agricultural practices (Singer *et al.*, 2021).

The increasing research interest in gamma ray applications in pastures highlights the potential for developing new technologies to enhance agricultural sustainability and productivity (Figure 8). Dominant research topics like "mutation," "DNA repair," and "radiation response" reflect researchers' focus on fundamental biological processes underlying gamma ray-induced mutagenesis and its applications in forage crop improvement. Emerging research topics such as "phenotype," "genotype," and "protein expression" signify evolving research priorities and technological advancements in this field. By exploring novel avenues of inquiry, researchers can uncover new insights into the mechanisms of gamma ray-induced mutagenesis and develop innovative strategies for crop breeding and agricultural innovation.

Additionally, we have acknowledged the limitations of our bibliometric analysis. While the scope of our study covers a broad range of publications, the analysis was confined to a specific set of databases and keywords. Future research could expand the scope to include additional data sources, further refine keyword selection, or analyze publications in more regional contexts to offer a more comprehensive view of the field. Furthermore, the bibliometric approach, while informative, has its limitations in terms of assessing the quality and depth of research contributions. Future studies may consider combining bibliometric analysis with qualitative assessments, such as expert reviews or case studies, to gain deeper insights into the significance of specific research contributions and trends. Strengthening this analysis and discussion, we can also highlight how identified research hotspots—such as the focus on improving stress tolerance, disease resistance, and nutritional value—are poised to address some of the most pressing challenges in agriculture today. As climate change accelerates and environmental stresses on crops intensify, research on gamma ray-induced mutagenesis could play a pivotal role in developing forage varieties that not only adapt to these challenges but also provide greater sustainability for the agricultural sector.

This bibliometric analysis offers valuable insights into the current landscape of research on gamma ray-induced genetic mutations in forage crops. Continued collaboration, investment in research infrastructure, and interdisciplinary approaches are essential to address key challenges and opportunities in this field, paving the way for sustainable agricultural development and food security in the future. The practical applications of gamma ray-induced mutagenesis highlighted in this study demonstrate its potential to improve crop resilience, nutritional value, and environmental adaptability, contributing to a more sustainable agricultural landscape.

Conclusion: This bibliometric analysis examined the trends, topics, collaboration patterns, and keywords associated with research on gamma ray application in forage crops. The study employed data from Scopus and covered the period 2010-2023.

Key Findings:

Dynamics in Publication Volume: While the initial years witnessed a rise in publications, subsequent fluctuations were observed. This underlines the influence of various factors like research trends and funding availability on publication volume. Despite the fluctuation, the overall trend suggests sustained interest in this field.

Co-authorship Analysis: The research landscape revealed diverse participation from various institutions. Leading institutions like the Advanced Radiation Technology Institute and Zhejiang University showcased significant research activity. Collaborations among institutions and countries are crucial for addressing challenges and fostering innovation.

Topical Focus: Mutation induction, DNA repair, and radiation response emerged as the dominant research topics, reflecting a focus on harnessing gamma rays for genetic improvement and stress tolerance in forage crops. Emerging research areas like phenotype, genotype, and protein expression warrant further exploration.

Keyword Analysis: Keywords like "article," "gamma radiation," "mutation," and "controlled study" highlighted the central themes and methodological rigor associated with research in this field. The analysis provides valuable insights into prevailing research priorities and future directions.

Overall, this study highlights the potential of gamma ray applications in forage improvement. However, further research is needed to comprehensively evaluate the long-term benefits and potential risks associated with this technology. Collaborative efforts among researchers, policymakers, and stakeholders are crucial to ensure the sustainable implementation and advancement of this technology for the betterment of the agricultural sector.

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