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A global assessment of aflatoxin M_1 in raw milk and some milk products' research from 2010 to 2024: a bibliometric analysis

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Abstract
Aflatoxin M_1 (AFM_1), a toxic compound produced by fungi, frequently contaminates milk and milk products. Therefore, consuming food tainted with AFM_1 poses severe, even life-threatening, health risks. This bibliometric study analyzed publications related to AFM_1 retrieved from the Web of Science database, covering the period from January 1, 2010, to December 31, 2024. We examined articles based on various criteria, including publication year, citation counts, authors, research areas, countries, institutional affiliations, journals, and keywords to pinpoint emerging and trending topics. Biblioshiny (R-packages) was used to visualize global collaboration networks and research hotspots. We identified 844 relevant documents. Food Control emerged as the leading journal in AFM_1 research, with 122 publications. China was both the most productive country and demonstrated the highest level of institutional affiliation. Our study provides both quantitative and qualitative analyses of the top 25 journals, most-cited articles, leading authors, and frequently occurring title words in AFM_1-related literature. Notably, AFM_1 research has experienced significant global growth over the past fifteen years. Therefore, this bibliometric assessment offers valuable insight into the historical development and current trends in AFM_1 research. Our findings can guide future investigations and contribute to improved decision-making in healthcare, public policy, and dairy industry practices.

Introduction
Aflatoxin M_1 (AFM_1) is a hydroxylated metabolite of aflatoxin B_1 (AFB_1) (Naeimipour *et al.*, 2018). It is a toxic byproduct of the *Aspergillus* fungal species and is a significant contaminant in milk and dairy products (Abadura *et al.*, 2022; Akinmoladun et al., 2025). Some of the *Aspergillus* species responsible for AFB_1 production and consequently associated with AFM_1 contamination in milk are *Aspergillus flavus, Aspergillus parasiticus,* and *Aspergillus nomius* (Daou *et al.*, 2020). It forms when lactating animals ingest feed contaminated with AFB_1, which is then metabolized *via* the liver into AFM_1 and excreted in milk (Fallah, 2010; Gonçalves *et al.*, 2018; Sumon *et al.*, 2021). This poses a serious global public health concern due to AFM_1's hepatotoxic and carcinogenic properties. Hence, the International Agency for Research on Cancer (IARC) has classified AFM_1 as a Group 1 human carcinogen, highlighting the urgent need for stringent monitoring and control measures (IARC, 2012). Several studies have substantiated the correlation between aflatoxin exposure and the enhancement of cancer cell proliferation, metastasis, and overall tumor aggressiveness (Hundal and Shaffer, 2014; Koshiol *et al.*, 2017; Koshiol *et al.*, 2024). Investigations have revealed that many cancer patients are those who have previously been exposed to AFB_1 and AFM_1 (IRAC, 2012; Koshiol *et al.*, 2024). Rama *et al.* (2015), Assaf *et al.* (2018), and Xiong *et al.* (2022) all reported that even in tiny amounts, AFM_1 presents a serious global health hazard because it has been linked to both immediate and long-term harmful effects. Its continued presence in milk and dairy products, especially with prolonged consumption, significantly elevates the risk to food safety and public health. These have made researchers seek to clarify the mechanistic pathways through which these mycotoxins may contribute to oncogenesis, particularly to hepatocellular carcinoma and other toxin-related malignancies, by analyzing molecular and cellular responses. Pieces of literature have recorded that mitigating AFM_1 contamination in raw milk and milk products requires a dual approach (Ahmedsham *et al*., 2018; Tadasse et al., 2020; Hundal and Shaffer, 2014; Koshiol et al., 2024). This includes direct interventions and, more crucially, indirect preventive measures. Direct strategies focus on treating already contaminated milk, which can be done through techniques such as physical removal, chemical detoxification, or advanced filtration methods to lower AFM_1 concentrations. Because AFM_1 is a metabolite of AFB_1 consumed by dairy animals, improving feed quality is of great importance. Therefore, a sustainable and effective solution lies in indirect strategies that involve minimising AFB_1 in animal feed.
Aflatoxin contamination in milk originates primarily from the ingestion of feed contaminated with AFB_1, which is produced by toxigenic fungi such as *Aspergillus flavus* and *Aspergillus parasiticus*. Feed contamination typically occurs during crop growth, harvest, storage, and transportation, particularly under warm and humid conditions that favor fungal proliferation. Commonly

contaminated feedstuffs include maize, groundnuts, cottonseed cake, and other cereal-based concentrates widely used in dairy production systems. Poor post-harvest handling practices, inadequate drying, and suboptimal storage conditions significantly increase the risk of AFB1 accumulation in animal feeds (Milani, 2013; Daou *et al*., 2020; Zahra *et al.*, 2024).

Following ingestion, AFB_1 is rapidly absorbed in the gastrointestinal tract of lactating animals and metabolized in the liver by cytochrome P450 enzymes into AFM_1, which is subsequently excreted into milk. The carry-over rate of AFB1 to AFM1 in milk typically ranges between 1–6%, although this value may increase depending on animal species, milk yield, health status, and dietary composition (Fallah, 2010; Gonçalves *et al*., 2018). High-producing dairy cows, for example, tend to exhibit higher AFM1 concentrations in milk due to increased feed intake and metabolic turnover.

Importantly, AFM_1 is chemically stable and resistant to common milk processing techniques such as pasteurisation, UHT treatment, and fermentation. As a result, AFM_1 can persist in processed dairy products, including cheese, yoghurt, butter, and infant formula, thereby posing a continuous risk to consumers, particularly infants and young children who consume large quantities of milk relative to body weight.

Over the past two decades, there has been a surge in research dedicated to understanding AFM1, focusing on its detection, prevalence, and mitigation (Assaf *et al.*, 2019; Zahra *et al.*, 2024). Researchers globally have extensively studied the occurrence, variability, and distribution of AFM_1 across a range of dairy products, including raw milk, cheese, yoghurt, buttermilk, Lassi, and Sour cream. These investigations have also addressed the associated health risks posed by AFM_1.

Bibliometric analyses have become crucial tools for mapping the scientific landscape and pinpointing knowledge gaps. It is a powerful quantitative tool that provides a systematic lens for understanding the evolution and trajectory of research within any given scientific field. Meticulously analyzing publication data allows us to paint a comprehensive picture of past and present research trends, pinpoint emerging areas of focus, and uncover the intricate networks of collaboration among researchers, institutions, and nations (Semerjian *et al.*, 2021; Adeniji *et al.*, 2022). This analytical approach does not just reveal the current state of a field and its key players; it also helps us anticipate where research is headed. Such insights are particularly invaluable for policymakers. They offer evidence-based guidance for identifying critical issues, formulating strategic plans, and efficiently allocating resources to both ongoing and future research endeavors. Ultimately, bibliometric analyses are instrumental in driving sustained progress and innovation within a discipline. Several reviews summarizing these findings have been published, notably by Iqbal *et al.* (2015), Malissiova *et al.* (2024), and Rigueto *et al.* (2024). However, only three bibliometric studies of AFM_1 identified in the literature to date were published by Altun *et al.* (2024), Roila *et al.* (2021), and Abadura *et al.* (2022). Two are localized within a region: Roila *et al.* (2021) and Abadura *et al.* (2022). The only one that is global did not address several critical bibliometric indicators (factorial analysis, author collaborations, most relevant sources, Sources of production over time, author's productivity through Lotka's law, most cited documents, most cited countries, co-citation network, co-occurrence network, thematic map, keywords, keywords plus, trend topics, and network collaborations among authors). Therefore, the present study is inevitable since it gives a comprehensive, up-to-date report on AFM_1 in milk and milk products, incorporating different bibliometric indicators that the previous authors did not address.

Key research areas such as Analytical methods for AFM_1 detection, Risk assessment of AFM1 contamination, and Strategies for reducing contamination in dairy products were identified in this study. Significant advancements have been made in analytical techniques for AFM_1 detection. High-performance liquid chromatography (HPLC) and enzyme-linked immunosorbent assay (ELISA) are widely used. Also, there are recent innovations, such as applying machine learning algorithms to predict contamination levels, thereby improving detection efficiency and accuracy. Furthermore, studies have begun to explore the alarming impact of climate change on AFM_1 prevalence, suggesting that rising temperatures and humidity could worsen fungal growth and toxin production. Despite these strides, several challenges remain. The lack of standardized detection methods and uniform global

regulatory limits for AFM_1 complicates international trade and jeopardizes consumer health. There is also a clear need for comprehensive research into the effectiveness of mitigation strategies, such as improved feed management and advanced processing techniques, to reduce AFM_1 contamination significantly.

This current study, therefore, employed a bibliometric analysis to comprehensively map the global research landscape of AFM_1 in milk and milk products from 2010 to 2020. Using data from the Web of Science (WoS) database, this investigation aimed to chart the evolution, scope, and intensity of scholarly output in this critical field, addressing a notable void in previous bibliometric assessments of AFM_1-related research.

The study was designed to illuminate emerging research themes, identify prevailing scientific trends, and highlight the key contributors to AFM_1 in dairy products research, including leading countries, institutions, authors, and journals. By focusing on the distribution and behaviors of AFM_1 in environmental media, such as raw milk, cheese, yoghurt, buttermilk, and other dairy products, the research also examined their implications for human health.

Ultimately, the findings from this study are intended to serve as a valuable roadmap for future research directions, enhance our understanding of recent scholarly emphases, and support the formulation of targeted policy and funding strategies. It offers a crucial reference framework for researchers, public health officials, environmental regulators, and policymakers dedicated to mitigating the risks associated with AFM_1 contamination and exposure.

Materials and Methods

Bibliometric analysis has, in recent years, emerged as a potent instrument for evaluating diverse aspects of academic performance across a broad spectrum of scientific disciplines (Yang *et al.*, 2019; Fan *et al.*, 2020; Liu *et al.*, 2021). Leveraging this demonstrated efficacy, the current study employed bibliometric techniques to scrutinize the vast body of research on the global assessment of AFM_1 on milk and milk products from 2010 to 2024. This methodology allowed for a quantitative assessment of the field's research output and prevailing trends, illuminating its developmental trajectory and scholarly engagement throughout this period.

Source of data

The data for the current study were exclusively drawn from the Science Citation Index Expanded (SCI-Expanded), a part of the WoS database. This platform is widely recognized for its effectiveness in data retrieval and for providing a comprehensive overview of global scientific output (Wei *et al.*, 2020). To ensure the inclusion of highly relevant literature, a title-based search approach was employed, a method known for its reliability in achieving relevance and specificity in bibliometric analyses.

Protocol and search strategy

A systematic search was conducted on the WoS database. The search covered studies published between 1 January 2010 and 31 December 2024. The search string used is (“aflatoxin M1” OR “AFM1”) AND (“milk” OR “raw milk” OR “milk products” OR “dairy products” OR “cheese” OR “yoghurt”). This meticulous approach ensured comprehensive capture of all prominent dairy product matrices associated with AFM1. The data retrieval was specifically carried out on May 25, 2024, at 08:25 am.

Screening process

After sorting the results by literature type, the following categories were excluded from the analysis: revisions, books, short communications, congress papers, review articles, and letters. A total of 1352 articles were initially retrieved, filtered, and then underwent a rigorous cleaning and validation process to ensure that only publications directly relevant to the study's primary subject were retained. After which, only 844 articles were exported and saved in a Plain text file. The study then proceeded

to analyze several key aspects of the remaining publications, including their publication date, total citations, languages, research areas, contributing countries, affiliations, journals, keywords, and authors. All retrieved WoS publications were saved as Plain Text files and exported to RStudio for bibliometric analysis.

Analytical methods reported in the aflatoxin M_1 literature

Although this study did not generate experimental AFM1 data, an overview of the analytical methods commonly reported in the retrieved literature was conducted to contextualize research trends. Studies investigating AFM_1 in milk and dairy products typically employ a two-tier analytical approach, comprising screening methods followed by confirmatory or validated techniques.

ELISA remains the most widely reported screening method due to its rapidity, high throughput, and cost-effectiveness, particularly in large surveillance studies. However, ELISA is susceptible to cross-reactivity and matrix effects, necessitating confirmation using more selective analytical techniques.

Validated confirmatory methods frequently reported include HPLC coupled with fluorescence detection (FLD), liquid chromatography-tandem mass spectrometry (LC-MS/MS), and, to a lesser extent, thin-layer chromatography (TLC). Among these, LC-MS/MS is considered the gold standard due to its high sensitivity, specificity, and compliance with international regulatory requirements (European Commission, 2006; AOAC, 2019).

The bibliometric analysis revealed a growing preference for LC-MS/MS-based methods in recent years, reflecting increasing regulatory demands and advancements in analytical instrumentation.

Parameters and data analysis

A R-4.5.0 version of R Studio Software and Biblioshiny (5.0 version), an app version tool of Bibliometrix, was used for the analysis. Parameters calculated and derived through Biblioshiny in RStudio and presented in a Table, plot or network format are: factorial analysis, author collaborations, most relevant sources, Sources of production over time, author's productivity through Lotka's law, most cited documents, most cited countries, annual scientific production, country collaboration, average citation per year, co-citation network, co-occurrence network, thematic map, keywords, keywords plus, trend topics, and network collaborations among authors. Total link strength signifies the collective strength of a country's research collaborations with other nations. In the network visualization, a more intense color similarity between countries indicates stronger cooperation and shared attribution. Furthermore, each distinct color within the images represents a unique cluster or set of entities.

Results and Discussion

The general overview of the information in this study is shown in Table 1. The data, comprising 844 documents (all articles) from 231 sources, reveals several key characteristics. These documents had an average publication age of 6.93 years, with an average of 24.39 citations per document. The total number of references was 16272. The articles were authored by 3237 unique authors. A small portion, 16 authors, contributed to single-authored documents, while the co-author per document stands at 5.41. The author's keywords (DE) are 1506, while the keywords plus (ID) are 1123. International co-authorships % stand at 24.29.

In this current study, the WoS database search engine identified 844 documents related to AFM1 published between 2010 and 2024, including 832 articles, which was more than the 540-article report by [24] Altun *et al.* (2024) in their study of AFM_1, which covered the period from 1970 to 2022. This implies that awareness of the need to carry out research in this important area has increased greatly. This could be because in recent times, AFM_1 in milk and milk products has been linked to the reason why cancers occur in human beings. Unlike the report of Altun *et al*. (2024), who reported that the USA has the highest publications during their period of investigation, in this study, China has the highest research output (151 articles). This suggests that research on AFM_1 in milk has shifted from the USA to China in the last two years.

Publication growth patterns related to aflatoxin M_1 in milk and milk products (2010-2024)

Supplementary Figure 1 shows the growth trends of articles published on AFM_1 in milk and milk products from 2010 to 2025 globally (top 25). The data indicates that the lowest number of articles was published in 2010 (34), while the peak output occurred in 2022 with 83 articles. Over the 15 years investigated in this study, there were fluctuations in the number of publications throughout the study period, totaling 844 articles, averaging 56.27 articles per year. This made the annual growth rate during this period negative (-6.71%). Though the research output grew steadily from 2020 to 2022, it sharply declined thereafter in 2023. The annual scientific production and the average citation per year also show the growth pattern of research on AFM_1 in milk and milk products during the period under investigation.

The growth of research on AFM_1 in milk and milk products in this study surpasses that reported in previous similar studies, suggesting that it garners significant global attention and support (Roila *et al.*, 2021). A total of 206 articles were published between 2010 and 2014, increasing to 276 between 2015 and 2019, and further rising to 350 from 2020 to 2024 among the top 25 articles. These trends highlight that AFM1 in milk and milk products attracts widespread scholarly interest worldwide.

Analysis of journal impacts

Research into AFM_1 in milk and dairy products has garnered significant global attention, with numerous findings appearing in prominent academic journals. Out of 231 journals analyzed, the top 25, detailed in Table 2, collectively published 55.7% of the articles published during the period under investigation. These articles accumulated 14,398 citations over this period, highlighting their considerable impact. Among the top 25 journals, Journal of Food Control published the highest number of articles in the study subject with 122 articles, followed by Toxins, while Journal of Food Science and Nutrition, produced the lowest of 7 articles during this period (2010-2024).

Three of these key journals began publishing on the subject in 2010, as shown in Table 3. The remaining journals started their coverage of AFM1 in dairy products in 2011 and 2013. Collectively, these three journals contributed 43.8% of all articles listed in Table 2 and garnered 6383 of the total citations attracted by all 25 journals.

The distributions of the top 25 journals that published research articles on the topic under consideration from 2010 to 2024 suggest a clear multidisciplinary research approach to AFM_1 contamination.

These top 25 journals can be categorized into five multidisciplinary groups. These include Food Safety and Regulation (Food Control, Food Additives & Contaminants, Journal of Food Safety); Toxicology and Exposure Assessment (Toxins, Food and Chemical Toxicology, Toxicon); Dairy Science (Journal of Dairy Science, Mljekarstvo); Analytical Chemistry (Talanta, Analytica Chimica Acta, Biosensors & Bioelectronics) and Food Science and Nutrition (Food Chemistry, Foods, Food Science & Nutrition). The issue of AFM_1 contamination in milk and milk products requires a multidisciplinary approach due to its complexity, involving aspects of food safety, public health, agricultural practices, analytical chemistry, toxicology, and regulatory science. Each discipline contributes unique expertise—agriculture provides insight into aflatoxin contamination at the feed level, analytical chemistry offers advanced detection methods, while toxicology and public health evaluate human exposure and risk. This convergence of knowledge is essential for developing effective monitoring, prevention, and control strategies (Milani, 2013). This distribution illustrates how AFM_1 research transcends traditional disciplinary boundaries, integrating methods and perspectives from toxicology, analytical chemistry, dairy production, and public health. Just as in this current study, bibliometric studies consistently show that multidisciplinary research leads to higher impact publications due to its broader applicability and innovation potential (Van Noorden, 2015).

Leading researchers in aflatoxin M_1 in milk and milk products studies

Our analysis of 844 articles revealed that 3237 authors contributed to their publication. Table 4 highlights the 25 most prominent authors among them, assessing their impact using metrics such as

h-index, g-index, m-index, total citations (TC), total papers (TP), citations per paper (TC/TP), and publication start year (PY_start). The 5 most impactful authors among the 25 top authors recorded in Table 4 are Wang JQ, Zheng N, Li SL, Gao YN and Corassin CH.

These 5 top authors contributed 14.2% of the total 901 articles published on AFM_1 in milk and milk products from 2010 to 2024. The h-index is a widely recognized metric for evaluating the quality of scientific output for researchers, journals, countries, or organizations, as it helps compare their contributions to scientific knowledge (Miao *et al.*, 2018; Huang *et al.*, 2019). In this study, the parameters varied, with ranges including 6-23, 6-35, 0.4-1.796, 105-1252, 6-40, and 2010-2020 for h-index, g-index,m-index, total citations, number of publications, and publication year start, respectively. Wang JQ has the highest H-index of 23, NP and TC of 40 and 1243, respectively, published in AFM1 in milk and milk products. However, he started publishing in 2013 in the niche area under consideration.

Application of Lotka's law of author productivity on aflatoxin M_1 in milk and milk products (2010-2024)

Supplementary Figure 2 shows Lotka's law of author productivity. The x-axis represents the number of documents written by individual authors, while the y-axis shows the percentage of authors producing that output. The solid line represents the observed distribution of author productivity within the dataset, while the dotted line represents the theoretical distribution according to Lotka's law. As shown, a large proportion of authors contributed only one document (~75-80%), while very few authors produced multiple publications, consistent with a power-law distribution in the study area during the period under investigation.

Lotka's law, formulated by Alfred J. Lotka in 1926, helps to understand author productivity and research evaluation by identifying patterns in author productivity. As shown in Figure 1, a large proportion of authors contributed only one document (~75-80%), while very few authors produced multiple publications, consistent with a power-law distribution in the study area during the period under investigation. This aligns with Lotka's law, which predicts that the number of authors publishing n papers is approximately $1/n^2$ of those publishing one paper. Figure 1 (Lotka's graph) showed that a few authors produced most of the articles published in the niche area from 2010 to 2024.

The results affirm that author productivity in the field of AFM_1 in milk and milk articles from 2010 to 2024 follows a highly skewed distribution, where a small core of prolific authors is responsible for a large portion of the literature. This is characteristic of many scientific domains, where a minority of researchers drive most of the scholarly output. The close fit between the observed and theoretical curves supports the validity of Lotka's law in this research area. This indicates a mature research structure, where a core group of experts has emerged and continues to contribute heavily to the field. This implies that high-output authors can inform collaborative networks, funding decisions, and the identification of thought leaders. Also, Institutions aiming to strengthen research capacity may focus on mentoring new scholars toward higher productivity to broaden the core group over time

Analysis of institutions relating to research on aflatoxin M_1 in milk and milk products from 2010 to 2024

As detailed in *Supplementary Table 1*, the top 25 institutions in this study—including their name, type, location, and article output—show a significant Chinese and Iranian presence, with 12 institutions equally shared by the two. This directly corresponds to China and Iran's high research output, as shown in *Supplementary Table 2*. Out of 859 articles published by these institutions over the past 15 years, 373 (43.4%) originated from China, while 20.4% were contributed by institutions from Iran.

Between 2010 and 2024, public research institutions, government bodies, and universities, predominantly from Asia and the Middle East, spearheaded AFM_1 research in milk and dairy products. China was the undeniable global leader, with its top three institutions—the Ministry of

Agriculture and Rural Affairs, the Chinese Academy of Agricultural Sciences (CAAS), and CAAS's Institute of Animal Science—collectively publishing hundreds of articles. This dominance underscores China's strategic emphasis on agricultural research and food safety, heavily influenced by national policy and funding to modernize its dairy industry and control aflatoxins. Iranian universities also made substantial contributions, reflecting a significant national focus on dietary aflatoxin exposure due to high dairy consumption and climatic factors conducive to mycotoxin growth (Daou *et al.*,2020).

Beyond these regions, the Egyptian Knowledge Bank and Brazil's University of São Paulo were notable contributors, indicating a rising awareness of foodborne toxins in Latin America.

The concentrated research output from China, Iran, and India points to regional needs for shared knowledge and enhanced capabilities. Yet, the global reach of dairy trade and aflatoxin contamination necessitates broader international cooperation with institutions in Africa, Latin America, and Europe. Such collaboration is vital for standardizing research methods, facilitating data exchange, and formulating unified policy recommendations.

Analysis of the contribution by countries and collaboration among their corresponding authors

Supplementary Tables 2 and 3 detail the top 25 countries in this domain, highlighting a clear distinction in their contributions. While China, Iran, Italy Turkey and Brazil, are dominant in sheer volume of publications (TP) and overall citations (TC)—accounting for 17.9%, 13.5%, 7%, 6.3%, and 5.9% of the 844 articles from these leading nations Also, China, Iran, Brazil, Italy and Turkey excel in average article citations-27.40,26.60,27.90, 23.30 and 18.90 respectively. Additionally, the results presented in Table 7 were derived by categorizing articles based on the country of origin of their first or corresponding author. This enabled the assessment of each country's influence within the research field, with the 25 most influential countries being identified based on the volume of articles published and their cumulative citations (Liu *et al.*, 2021). China remains the leading country and corresponding author in the investigating niche area from 2010 to 2024.

Analysis of the most globally cited papers in studies related to aflatoxin M_1 in milk and milk products (2010-2024)

A research paper's quality is typically judged by its citation count, which also indicates trending topics within a field. Older papers naturally have more citations than newer ones because it takes time to accumulate them (Liu *et al.*, 2021; Usman and Ho, 2020). *Supplementary Table 4* highlights the 25 most globally cited papers in this study; all published between 2010 and 2016. The highest and the lowest cited document among the top 25 articles considered were both published in the same year (2010), in the same journal (Food Chem Toxicol)- authored by Fallah and Gürbay with global citation of 72 and 38, respectively. The global citation count for a document on the WoS database indicates how often it was cited before its download. More than just a measure of fame, this term highlights an article's true impact and the quality of the researchers who cite it. Citations from highly influential papers can significantly boost a document's value, drawing the attention of other impactful authors and potentially leading to further citations (Sivankalai *et al.*, 2021). Of the top 25 most cited documents, the first on the list (*Supplementary Table 5*) was published in Food Chem Toxicol Journal, having a local citations/global citations (LC/GC) ratio % of 61.02, while the next four on the list were published in Food Control Journal with LC/GC ratio % of 47.41, 59.79,45.90 and 50.47 respectively. None of the first 10 articles on the Table has fewer than 50 global citations, highlighting their significant value and quality. According to Liu *et al.* (2021), the quality of a paper is significantly influenced by its content, independently of its publication year. All the articles in the table are experimental studies of AFM_1 in milk and milk products. The most cited document authored by Fallah in 2020 was conducted in Iran to determine the presence of AFM_1 in pasteurized milk and yoghurt milk using a competitive ELISA method. The result from this study shows that pasteurized and three samples (2.7%) of UHT milk had levels above the maximum tolerance limit of 500 ng/L AFM_1 in milk, as stated by the US FDA. The second most cited document, similar to the first one in method

used, was authored by several scientists in that field (Kos *et al.*, 2014), done in Serbia and investigated the occurrence of AFM1 in 150 cows, 10 goats, 5 donkeys, 10 breast milk, and 1 infant formula samples. These researchers reported that all age categories, especially children, face a significant risk of AFM_1 exposure through milk. It is worth noting that the second most cited was published six years earlier than the first most cited document. This could be due to the quality of the first-most-cited documents. Interestingly, also, the third and the fifth most cited documents on the Table were published both in Food Control Journal by the author of the first most cited document, but 9 and 10 years earlier than the most cited. This author used TLC in both the articles published in 2010 and 2011. This supports the reason for the quality work of the first-most-cited document after two early attempts.

Application of spectroscopy references in bibliometric analysis on aflatoxin M_1 in milk and milk products (2010-2024)

The spectroscopy references in *Supplementary Figure 3* show that papers considered in this study took the first references in a paper published in 1913 with 3 TC, and the peak of references was taken from a paper published in 2016 with 2020 TC.

A bibliometric analysis of spectroscopy literature from 2010 to 2024 reveals that references to early works by Alseburg (1913), Langmuir (1918), and Bigelow (1921) were the first three works to be cited in the field of study during the period under investigation. However, the work of Prandini (2009) in Food Chem Toxicol with TC 2006 and Campagnollo (2016) in Food Control with TC 2020 remains central, reflecting their foundational role in evaluating mechanisms by which AFM1 is affected by different processing methods and steps. Citation bursts for papers after 1998 suggest a growing emphasis on AFM1 in milk and milk products, and reach the peak in 2017, but decline thereafter.

Analysis of keywords on aflatoxin M_1 in milk and milk products from 2010 to 2024

Table 9 presents the top 25 author keywords identified in this study. Among the author keywords, the five most frequently occurring terms are: “milk” (383 occurrences), “mycotoxins” (321), “aflatoxin M1” (308), “M-1” (270), and “m-1” (220).

Emerging frontiers in a research field are often identified through the analysis of author keywords, which highlight priority areas within a specific time frame (Synnestvedt *et al.*, 2005). To facilitate rapid identification of core themes, authors are now typically required to provide a minimum of five keywords when submitting manuscripts for peer review (Okaiyeto and Oguntibeju, 2021). In this study, author-defined keywords (DE) were utilized to gain a comprehensive understanding of the evolving trends in research related to AFM_1 in milk and milk products from 2010 to 2024. The keyword analysis reveals insightful patterns in the thematic evolution and research priorities related to AFM_1 contamination in milk and dairy products from 2010 to 2024. The most frequently occurring keyword was “milk” (383 occurrences), affirming the central focus of the field. Closely following are “mycotoxins” (321) and “aflatoxin M1” (308), which underscore the persistent concern regarding the presence of toxic fungal metabolites in dairy-based food systems. However, the presence of multiple variants such as “M-1” (270), “aflatoxin M-1” (220), and “M1” (203) suggests inconsistency in keyword usage across publications, which could impact retrieval efficiency in databases. This highlights the need for standardization in terminologies to improve the discoverability and synthesis of relevant research. The frequent occurrence of “contamination” (178) and “exposure” (127) signals a strong emphasis on public health risk assessment and monitoring strategies. These themes align with global food safety objectives, especially given AFM_1’s carcinogenic classification and its stability during milk processing. Keywords such as “ELISA” and “HPLC” reflect the prominence of analytical techniques in AFM_1 detection. ELISA’s high frequency points to its widespread use in initial screening due to cost-effectiveness and rapid throughput, whereas the appearance of “HPLC” indicates reliance on more precise, confirmatory analytical tools, often required for regulatory compliance. The geographically indicative keywords like “province” imply a growing interest in spatial distribution and regional surveillance, potentially driven by differences in agricultural

practices, regulatory environments, and climatic conditions affecting aflatoxin prevalence. Finally, keyword distribution highlights a research landscape strongly anchored in detection methodologies, risk assessment, and product-level surveillance, with a modest yet growing emphasis on mitigation, source attribution, and regulatory impact. Future bibliometric-driven explorations could benefit from thematic clustering and longitudinal keyword trend analysis to map the transition from diagnostic focus to preventive and policy-oriented research. Moreover, the diversity in terminology (*e.g.*, "M1," "M-1," "aflatoxin M1") suggests that researchers and journal editors should encourage standardized vocabulary use to enhance metadata accuracy and bibliometric utility.

Analysis of collaborations among authors and countries

Supplementary Table 5 details the international collaborations in this research area. Of the top 25 countries, Brazil collaborated more than any other country, followed by two countries in Europe. Austria and Belgium. Of all these countries, Belgium collaborated with countries in Africa (Kenya, South Africa, and Tanzania) in the niche area and period under investigation. Additionally, as shown in *Supplementary Table 6*, the author collaboration network for publications on AFM_1 in milk and milk products from 2010 to 2024 reveals eight distinct clusters, each representing a collaborative subgroup. There is limited interconnectivity between most clusters, with many consisting of just two or three authors working in isolation. For example, Iqbal SZ and Asi MR (Cluster 1), and Sang YX and Wang XH (Cluster 2) show strong internal collaboration but no links to other researchers. Cluster 4 stands out as the most prominent and interconnected. Authors like Akhtar S, Riaz M, Ismail A, Corassin CH, and Rosim RE are central to this cluster. Notably, Ismail A plays a pivotal bridging role, connecting different subgroups within the broader network.

In this study, collaboration between countries was very low. Among the top 25 countries investigated in the study field during the period, collaborations were maximum with one nation and not with multiple nations, with low frequency. The collaborations of Belgium with four nations in Africa (Kenya, South Africa, Benin, and Tanzania) during this period of investigation are worth noting. Belgium, being a country with state-of-the-art equipment, will help in providing access to resources and funding to these limited-resourced nations, thereby improving research quality, visibility, impact, and Credibility in AFM_1 in milk and milk products. Though China, Iran, Italy, Turkey, and Brazil are the first five among the top 25 countries with the highest articles on AFM_1 from 2010 to 2024, none of them is among the top 25 countries that collaborate with another country. This suggests that all the research carried out during this period (2010-2024) may not have any global impact or address global challenges.

Collaboration plays a vital role in scientific research as it enhances productivity, promotes knowledge sharing and Innovation, and creates opportunities for mentoring early-career scholars, benefits that are difficult to achieve in the absence of collaborative efforts (Jeong *et al.*, 2011). Also, collaborations improve research quality and credibility and could help to address global challenges. Though China and Iran led in TP, they are very low in multiple country publications (MCP). This signified a very low level of collaboration with other countries. However, Belgium, France, and the USA have a lower number of publications compared to China and Iran, but a high MCP. These ratios represent the proportion of MCP to TP, as shown in *Supplementary Table 3*. With regard to collaboration among corresponding authors, all 25 countries listed in *Supplementary Table 3* demonstrated some level of international collaboration.

Concerning collaborations among authors, Wang JQ and Zheng NI have the highest collaborations in the study field during the period investigated. Each of them has a 0.083-page rank. This implies that among the top 25 authors listed in *Supplementary Table 6*, in the field of study for the period from 2010 to 2024, these two authors collaborate more than any other author in this study. Riaz M also contributes significantly to maintaining cohesion and information flow.

This overall decentralization highlights a need for greater integration among research groups. Strengthening these connections could lead to more robust research, interdisciplinary approaches,

better knowledge exchange, and improved strategies for detecting and mitigating AFM_1 contamination.

Factorial analysis of aflatoxin M_1 in milk and milk products from 2010 to 2024

The factorial analysis for this study is shown in *Supplementary Tables 7 and 8*. *Supplementary Table 7* shows the factorial analysis for keywords used by researchers in the field of study from 2010 to 2024, while *Supplementary Table 8* shows the factorial analysis of authors in the same field of study. Each word in the top 25 articles considered in this study has a word cluster and an article cluster of 1. Though the first article on *Supplementary Table 8* was published in 2020 and has a TC of 374 still has a cluster of 1.

In bibliometric analysis, factorial analysis helps to uncover and explain the underlying structure or thematic organization of a research field based on publication data (Iman *et al.*, 2023). In addition, it assists in identifying co-occurring patterns, such as clusters of keywords, authors, or documents, that represent research themes or conceptual groupings. Factorial analysis was employed to assess the proximity between keywords and the main topic, with the expectation that a strong relationship would be uncovered. In this study, a factorial analysis using the co-occurrence matrix of authors' keywords was performed in order to identify the thematic structure of AFM_1 in milk and milk products in articles published from 2010 to 2024. Factorial analysis of authors' keywords was considered. It is revealed that among the top 25 keywords used by all authors in the study area from 2010 to 2024, Factorial analysis of keyword co-occurrence shows a single dominant thematic cluster centered on dairy product contamination by mycotoxins. Dim1 separated general food-related terms (e.g., milk, ochratoxin) from geographically or contextually specific studies (e.g., Punjab, seasonal variation), while Dim2 distinguished between detection techniques (ELISA) and environmental or processing-related topics (cheese, stability). This suggests that recent research converges on contamination detection and regional variability in milk-based products. Also, all the keywords used by the researchers are closely related.

Author clustering via bibliographic coupling

A bibliographic coupling analysis was performed to identify the intellectual structure of research on AFM_1 in milk and dairy products over the period 2010–2024. The resulting visualization (Figure 1) demonstrates the relationships between authors based on the number of shared references in their publications. Nodes represent individual authors, with node size reflecting publication volume or citation impact, and edge thickness denoting the strength of bibliographic coupling. The colors indicate distinct author clusters, each corresponding to thematic groupings within the research domain.

This bibliographic coupling forms a tripartite structure in AFM1 research. Firstly, the green colour, which stands for the technical core Green) This area is dominated by experimental and analytical chemistry work, which drives the development of detection tools, often setting the foundation for health and policy studies. This is the most densely interconnected and expansive cluster, reflecting a strong research focus on analytical methods, contamination levels, and risk assessment. Prominent authors in this cluster include Bilandžić N and Antošová M.

This is followed by red color, which represents impact-oriented research. This translates analytical results into toxicological frameworks and public health concerns. This cluster is tightly knit, focused on the toxicological effects, human exposure, and health outcomes of AFM_1 ingestion through milk, with Donkor (2017) and Taranum (2021) as major authors often cited for work on risk exposure modelling and toxicological reviews.

Lastly, the blue color connoting Policy and Regulation. Here are ways to institutionalize findings through food safety policy, acting as intermediaries between science and application. This cluster is less dense, but the authors here serve as bridges between toxicological and analytical domains with their research work focusing on regulatory comparisons across regions, policy implementation, and consumer protection. However, there is moderate connectivity between green and red clusters,

indicating a functional overlap. Analytical findings inform health risk models. Also, there are sparse but crucial links between blue and the other clusters, suggesting opportunities for stronger evidence-policy integration in future research.

Three-field plot (publications-authors- keywords)

Figure 2 shows a Sankey diagram of a threefold plot of core publications, authors, and keywords of articles published on AFM1 in milk and milk products from 2010 to 2024. The results revealed that Core Publications and Citation Trends in the bibliometric analysis highlight a set of core publications that have significantly shaped the landscape of AFM1 research in milk and dairy products. The research works of Iqbal (2015) and Pei (2009) have laid foundational methods and risk assessment frameworks, underscoring a persistent interest in analytical techniques and public health implications; hence, they were highly cited.

Also, Campagnollo (2016) and Bakirci (2001) remain among the most frequently cited, reflecting sustained relevance in contamination monitoring and regulation. These foundational articles often serve as citation anchors across the network, suggesting they offer methodological benchmarks or seminal data sets widely used by subsequent authors in the field of study. Analysis of the author (AU) node in the Sankey diagram identifies Wang JQ, Zheng N, and Iqbal SZ as key contributors, each demonstrating substantial publication activity and connectivity within the AFM_1 research network. Their scholarly output encompasses areas such as analytical method development, risk evaluation, and epidemiological assessments. Notably, the work of Wang and Zheng is frequently associated with the application of ELISA and LC-MS/MS techniques for the detection of AFM1 in milk and dairy products.

Moreover, the inclusion of authors from a broad range of geographic and institutional backgrounds such as El-Khoury A and Oliveira CAF reflects the field's growing trend toward international and interdisciplinary collaboration.

This increasing diversity signifies a collective recognition of AFM1 as a global public health concern, particularly in regions characterized by high dairy consumption and limited regulatory oversight.

The keywords cluster points to a stable research core focused on toxin quantification, exposure risk, and contamination pathways. More recent inclusion of keywords like "raw milk", "samples", and "feed" indicates a shift toward upstream risk factor analysis, specifically feed-to-milk transmission pathways and source attribution (*Supplementary Table 9*). The prominent association with keywords like "ELISA" and "samples" underscores the pivotal role of analytical methodologies within the existing literature. There is a clear emphasis on screening tools, particularly ELISA, which are widely favored for their efficiency in high-throughput diagnostics. These are typically supported by confirmatory techniques such as LC-MS/MS, highlighting the dual need for both practical applicability in routine testing and regulatory-grade precision in quantification.

However, despite substantial progress in AFM1 research, several critical gaps persist. Long-term surveillance studies tracking AFM1 contamination trends in developing countries remain limited. Additionally, the potential impact of climate change on aflatoxin occurrence within dairy supply chains has received minimal attention. Research on intervention strategies, including the use of feed additives or innovative detoxification approaches, is also relatively scarce. To address these shortcomings, future investigations should incorporate omics-based tools, machine learning algorithms for predictive risk modelling, and policy-oriented impact assessments. Such integrative approaches are essential to closing the translational gap between laboratory research and effective public health interventions.

Limitations of the study

While this study provides a comprehensive bibliometric overview of global research trends on AFM1 in raw milk and selected milk products from 2010 to 2024, several limitations should be acknowledged.

Firstly, this analysis was limited to the WoS core collection. Although WoS is a reputable database, it may not encompass all pertinent research. This could lead to an incomplete representation of studies, particularly those from developing nations or those published in languages other than English, which might be found in databases like Scopus, PubMed, Google Scholar, or various regional repositories. Also, this current study predominantly included English-language publications. This could mean we didn't capture valuable research, especially from regions with significant AFM_1 contamination, where studies are often published in local languages and may not be easily accessible internationally. The period under review for this study (2010 to 2024) captures recent trends; it excludes foundational literature published prior to 2010 that may still be highly relevant, particularly in establishing analytical methods or regulatory frameworks. Similarly, the results were interpreted through bibliometric mapping and visualization tools, whose accuracy hinges on precise metadata. Discrepancies in details like author names, affiliations, or keywords might affect how clusters and co-occurrence patterns appear, thereby introducing a bias into the analysis. Finally, this study didn't incorporate key insights from various sources such as unpublished reports, conference proceedings, regulatory agency publications, or industry white papers. Consequently, the comprehensiveness of this global assessment may be constrained, particularly in its coverage of practical interventions and regional mitigation approaches.

Conclusions

This study comprehensively analysed scientific output on AFM1 in milk and milk products over 15 years (2010-2024). We retrieved 901 research articles from 231 sources indexed in the Science Citation Index Expanded (WoS), ensuring data consistency by excluding other publication types (*e.g.*, books, meeting abstracts, editorials). Our analysis identified 3237 authors contributing to the examined literature. The field exhibited negative growth with a compound annual growth rate of -6.71% and a collaboration index of 5.41, indicating a moderate level of co-authorship.

We assessed country-level contributions using several bibliometric indicators, including total publications, total citations, single-country publications, MCP, and the MCP ratio. The top five contributing countries by total publication output and corresponding author affiliations were China, Iran, Brazil, Italy, and Turkey. However, when considering the MCP ratio, a metric reflecting international collaboration per document, Brazil, Austria, and Belgium emerged as leaders. China and Iran dominate countries that supported research on AFM1 in milk and milk products during the period under review. While authors such as Wang JQ, Zheng N, and Iqbal SZ are central figures with multiple publication linkages and total research output. International collaboration in the study under consideration is very low compared with other fields, especially in the African continent. Researchers are therefore encouraged to actively engage in this important area of study, particularly given its relevance to public health and food safety. Likewise, funding agencies are urged to provide financial support and research infrastructure, especially in countries with limited or no representation in the current body of literature. It is anticipated that the findings of this study will assist scholars in identifying key thematic areas, as well as potential collaborators and regions for future research endeavors.

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Online supplementary material

Table 1. Main information about aflatoxins in milk and milk products related studies from 2010 to 2024.

Description	Results
Main information about data	
Timespan	2010-2024
Sources (Journals, Books, etc)	231
Documents	844
Annual Growth Rate %	-6.71
Document Average Age	6.93
Average citations per doc	24.39
References	16272
Document contents	
Keywords Plus (ID)	1123
Author's Keywords (DE)	1506
Authors	
Authors	3237
Authors of single-authored docs	16
Authors collaboration	
Single-authored docs	17
Co-authors per doc	5.41
International co-authorships %	24.29
Document types	
Article	832
Article; early access	3
Article; proceedings paper	8
Article; retracted publication	1

Table 2. Twenty-five most relevant journals in studies relating to aflatoxin M_1 milk and milk products from 2010 to 2024.

Sources	Articles
Food Control	122
Toxins	57
Food Additives & Contaminants Part B-Surveillance	27
Journal of Dairy Science	23
Food and Chemical Toxicology	22
Food Chemistry	21
Mycotoxin Research	21
Food Additives and Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment	18
International Journal of Dairy Technology	16
Foods	14
Toxicon	13
Journal of Food Safety	10
World Mycotoxin Journal	10
Microchemical Journal	9
Mljekarstvo	9
Talanta	9
Analytica Chimica Acta	8
Food Analytical Methods	8
Journal of AOAC International	8
Journal of Food Composition And Analysis	8
Journal of Food Protection	8
Kafkas Universitesi Veteriner Fakultesi Dergisi	8
Biosensors & Bioelectronics	7
Food and Agricultural Immunology	7
Food Science & Nutrition	7

Table 3. Sources of production over time for the 5 top journals among the top 25 journals that published in the field of study.

Year	Food Control	Toxins	Food Additives & Contaminants Part B-Surveillance	Journal of Dairy Science	Food and Chemical Toxicology
2010	7	0	1	0	4
2011	14	0	4	2	5
2012	24	0	5	4	8
2013	42	2	7	4	10
2014	53	2	12	5	12
2015	63	2	16	7	13
2016	76	6	17	9	14
2017	88	7	19	12	14
2018	93	10	21	15	14
2019	96	18	24	17	15
2020	103	22	26	17	16
2021	109	28	26	17	18
2022	113	42	26	18	18
2023	116	50	26	21	19
2024	119	57	27	23	22

Table 4. Most relevant authors who published in the field of study during the period under review (top 25).

Author	h_index	g_index	m_index	TC	NP	PY_start
Wang JQ	23	35	1.769	1252	40	2013
Zheng N	22	34	1.692	1228	39	2013
Li SL	15	20	1.154	752	20	2013
Gao YN	13	17	1.3	344	17	2016
Oliveira CAF	10	11	0.667	391	11	2011
Li PW	9	9	0.6	303	9	2011
Zhang Q	9	9	0.6	303	9	2011
Asi MR	8	8	0.5	440	8	2010
Bilandzic N	8	9	0.5	292	9	2010
Corassin CH	8	11	0.615	390	11	2013
Iqbal SZ	8	8	0.533	377	8	2011
Rosim RE	8	10	0.533	421	10	2011
Xiong JL	8	8	0.615	431	8	2013
El Khoury A	7	9	0.467	328	9	2011
Fallah AA	7	7	0.438	482	7	2010
Lai WH	7	7	0.636	211	7	2015
Varenina I	7	8	0.438	268	8	2010
Yang X	7	8	1.167	105	8	2020
Zhang W	7	10	0.467	232	10	2011
Atasever M	6	7	0.375	145	7	2010
Bhand S	6	8	0.4	230	8	2011
Cvetnic Z	6	7	0.5	203	7	2014
Kolanovic BS	6	7	0.5	203	7	2014
Molina A	6	6	0.4	127	6	2011
Riaz M	6	7	0.6	173	7	2016

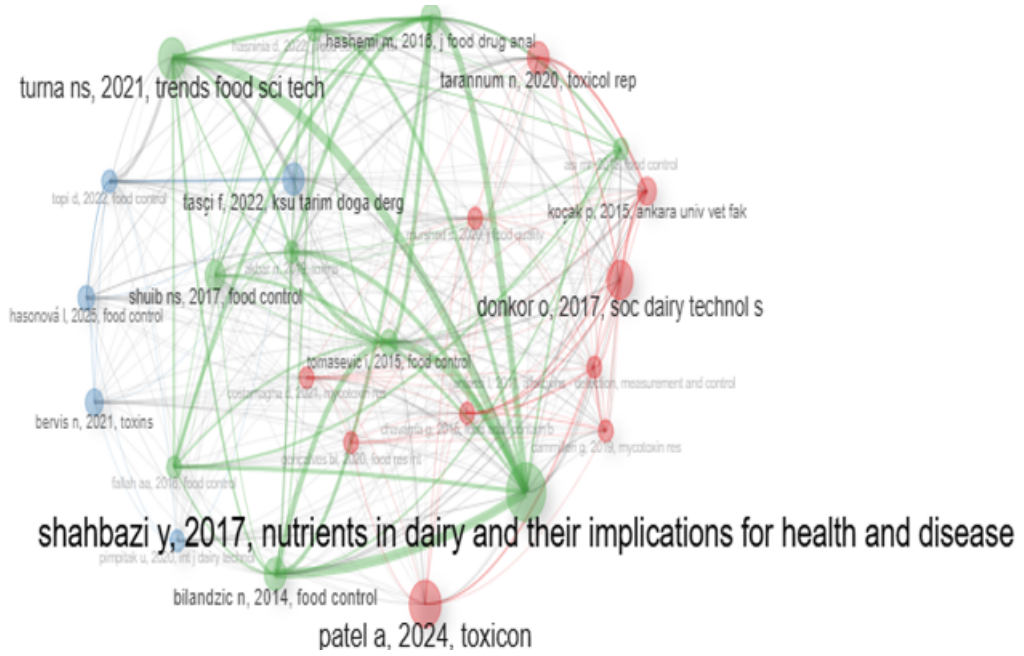

Figure 1. Author clustering *via* bibliographic coupling of articles on aflatoxin M_1 in milk and milk products (2010-2024).

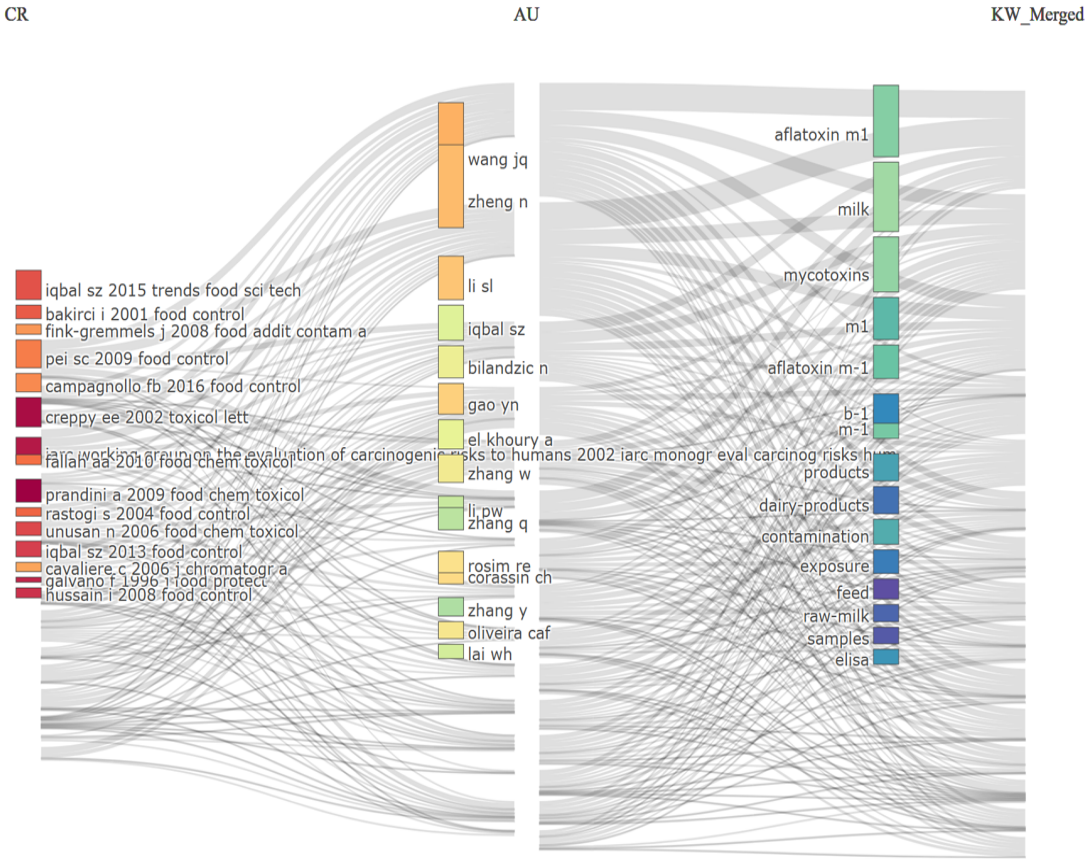

Figure 2. Three-field plot (publications-authors-keywords).