A bibliometric analysis of pre- and post-Stockholm Convention research publications on the Dirty Dozen Chemicals (DDCs) in the African environment

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Abstract

Persistent organic pollutants (POPs) are toxic chemicals that stay in the environment for a long time. To address the toxicity issues, global nations, including 53 African countries, ratified the Stockholm Convention to minimize or eliminate the production of 12 POPs known as the "Dirty Dozen". However, these Dirty Dozen Chemicals (DDCs) still exist in significant concentration in the African environment, prompting numerous research to investigate the level of their occurrences. Here, we conducted a bibliometric analysis to examine the publication trends in DDCs-related research in Africa using articles published between 1949 and 2021 from the Web of Science and Scopus databases. A total of 884 articles were published within the survey period, with a publication/author and author/publication ratio of 0.36 and 2.76, respectively. South Africa ranked first in terms of number of publications (n = 133, 15.05%), and total citations (n = 3115), followed by Egypt (n = 117), Nigeria (n = 77), USA (n = 40), and Ghana (n = 38). Research collaboration was relatively high (collaboration index = 2.88). The insignificant difference between the theoretical and observed Lotka's distribution indicates Lotka's law does not fit the DDC literature. An annual growth rate of 0.57% implies that a substantial increase of articles in years to come is not expected. More research programs should be established in other African countries to measure up to South Africa's supremacy. This is critical in order to provide a basis for effective compliance to the Stockholm Convention on POPs in Africa.

Keywords: Bibliometric; Africa; Stockholm Convention; Organic Pollutants; Pollution; Pesticides

1. INTRODUCTION

Persistent organic pollutants (POPs) are organic chemicals that exist in our environment for a long period. They are known as "forever chemicals" since they can withstand biological, chemical, and photolytic degradation to varying degrees allowing them to persist in the environment (Bresson et al., 2022; Prabhu and Lakshmipraba, 2022). These groups of chemicals are widely distributed geographically and can biomagnify and bioaccumulate across the food chain due to their lipophilic and hydrophobic properties. They are of global concern because of their ability to adversely affect human health and are therefore listed as possible carcinogens (Jones, 2021; Vasseghian et al., 2021). Their continuing presence in the ecosystems and long-range environmental transport has led to acute and chronic toxic effects in many life forms. To address the toxicity issues, 91 nations and the European Community including 20 African countries (Benin, Burkina Faso, Côte d'Ivoire, the Gambia, Ghana, Guinea, Kenya, Mali, Mauritius, Morocco, Mozambique, Nigeria, Senegal, South Africa, Sudan, Togo, Tunisia, Tanzania, Zambia and Zimbabwe) signed the United Nations treaty, in Stockholm, Sweden on May 23 2001. The number of African countries that have ratified the convention currently now stands at 53 (UNEP, 2019). As declared in the treaty, also known as the Stockholm Convention, countries signed an agreement to reduce or stop the production, usage, or release of 12 POPs known as the "Dirty Dozen." The identified POPs include the organochlorine pesticides (OCPs) such as aldrin, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, heptachlor, mirex, toxaphene, and hexachlorobenzene. Other listed POPs include polychlorinated biphenyl (PCBs), polychlorinated dibenzo-p-dioxin (PCDD), and polychlorinated dibenzofuran (PCDF) (Figure 1).

Despite the embargo and restricted use, these legacy pollutants have continued to threaten all lifeforms. Although numerous projects have reported the bioaccumulation of these pollutants and their associated adverse effects (Williams et al. 2020, Weijs et al. 2020), their long-term environmental effect cannot be overemphasised. Several African countries continue to use OCPs for mosquito control in malaria-endemic regions (Cressey, 2011). DDTs, in particular, have been given exemptions for usage in vector-infested areas in some African nations. OCPs are incorporated into insecticides treated nets or sprayed in homes in certain situations. Stockpiles of obsolete chemicals are also likely to exist in some regions of the continent (Olisah et al., 2020a). Furthermore, population growth and rapid industrialisation in the African continent in the past decades are possible reasons for the illegal importation of new and fairly used products containing some of the ban POPs (Turok and McGranahan, 2013; Gioia et al. 2014; Lebbie et al. 2021). The unlawful transboundary movement of electronic wastes (banned under the Basel Convention) from developed countries into the African continent has continued to create new pollution sources (Grant and Oteng-Ababio, 2012; Gioia et al., 2014). The improper and unregulated methods used for treating this waste are major sources of PCDD/F and PCBs in Africa (Ssebugere et al., 2019). The leakage of mineral oil from transformers containing PCBs, and waste incineration are other sources of PCBs in the African environment

(Gioia et al., 2011, 2014). Apart from the ubiquitous nature of these pollutants, these practices are possible reasons for their high prevalence in the African ecosystem. Extensive studies have been conducted by researchers to unravel the levels of these pollutants in biological and environmental matrices as well as to identify hotspots in the African ecosystems (Bouwman, 2003; Ssebugere et al., 2013; Polder et al., 2016; Sun et al., 2016; Olisah et al., 2019a, 2020b; Vaccher et al., 2020; Adebusuyi et al., 2022). Several narrative reviews have been written to discuss these pollutants' levels and sources (Mansour, 2009; Pius et al., 2019; Ssebugere et al., 2019; Akinrinade et al., 2020; Olisah et al., 2020a). However, studies analysing the research trend of the Dirty Dozen Chemicals (DDCs) in the African ecosystem are extremely scarce.

The advent of new ideas and discoveries necessitates researchers to expand their literature search to understand a research domain and potential knowledge gaps for future investigations. Researcher’s often carried out narrative reviews to understand a broad perspective of a topic but face limitations in retrieving all relevant records. Another major issue is the author’s inability to set selection criteria for article retrieval (Galvagno, 2017). Furthermore, knowledge development in a particular field happens over time, and mapping the evolution of such field is considered imperative for academics and other organisational structures. Therefore, to better understand the dynamics and progress of a research area literature, an assessment of its underlying knowledge framework is necessary. Researchers have used bibliometric tools to retrieve relevant literature and study research progression by quantitatively analysing encoded bibliographic data. This tool has uncovered and mapped research trends in different subject areas by visualizing and summarizing bibliographic information into a single document (Samiee and Chabowski, 2012; Ye et al., 2020; Niñerola et al., 2021). We took advantage of this tool to statistically analyse literature published on DDCs in the African environment.

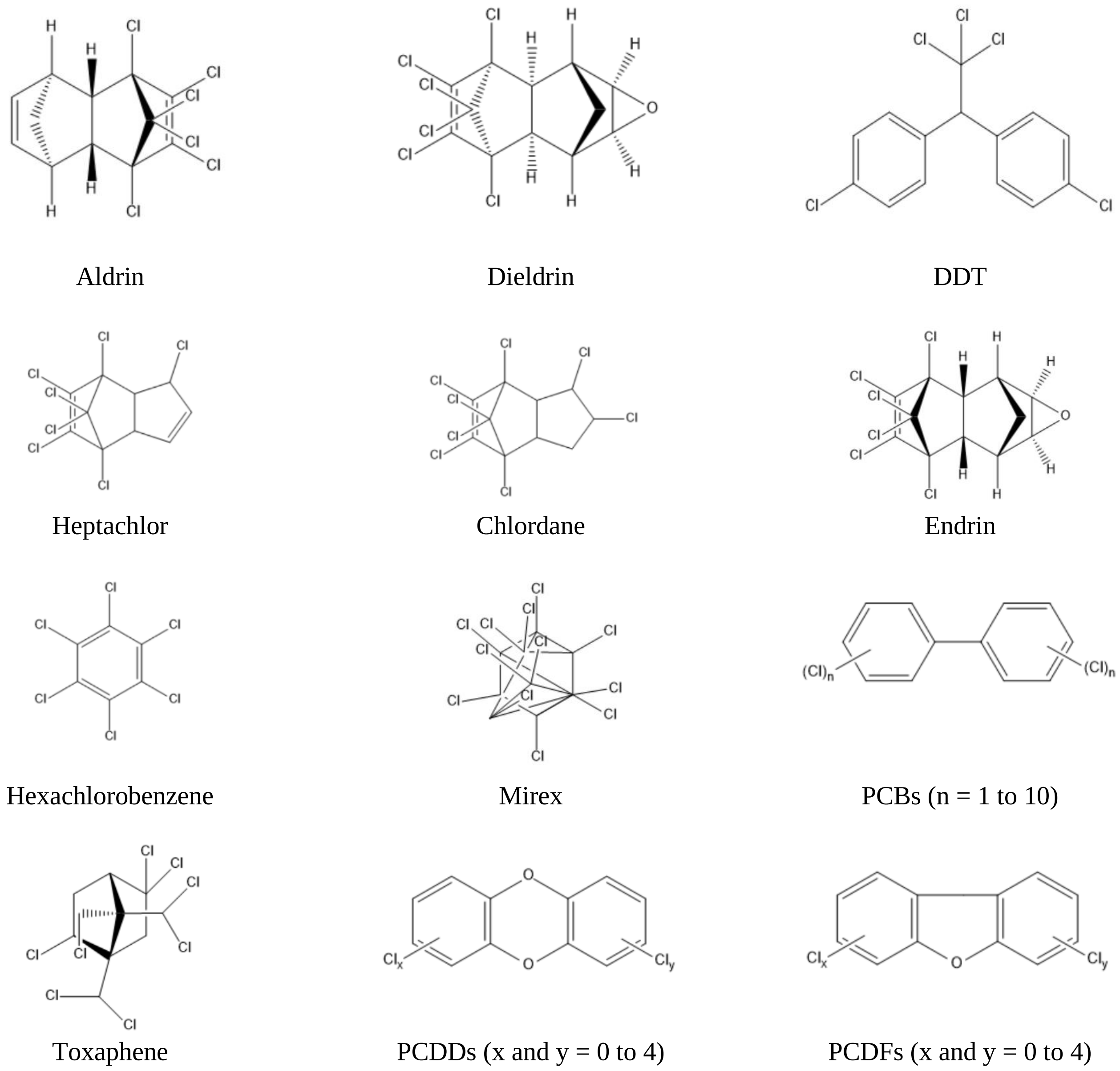

Figure 1. The Dirty Dozen Chemicals (DDCs) as declared by Stockholm Convention.

This was necessary to better understand the advancements and track the evolution of knowledge on the evaluation of these legacy pollutants in the African environment (Figure 1), thus helping future research initiatives in this field. These objectives were achieved by conducting an in-depth bibliometric analysis, complemented with reviewing the articles' contents. Our study contributes to the body of literature by offering comprehensive literature on the current state of research in this field, based on six main research questions: (1) What is the research outputs on the assessment of DDCs in African ecosystems before and after the ban? (2) How has this subject of research progressed over the past seven decades in terms of publication outputs? (3) What are the citation records and authorships trends? (4) What pollutants from the "Dirty Dozen" have sparked more research in Africa's environment? (5) What thematic areas connected to these pollutants have been investigated the most? (6) Do these themes serve as possible drivers for future research? These questions were answered using bibliometric statistical programs to analyse encoded metadata of articles indexed in the Web of Science (WoS) and the Scopus databases.

2. METHODOLOGY

2.1 Selection of Databases and Inclusion Criteria

The Clarivate Analytics' Web of Science (WoS) has gradually evolved as one of the world's leading online citation databases and analytical information platforms. This database was chosen for this study because it covers a wide range of multidisciplinary literature and a large number of rich datasets and citation networks (Li et al., 2018). The WoS, which is mainly utilised for academic research, has a higher number of physical and biological articles, and this is where the subject of current study lies (Joshi, 2016). Launched by Elsevier in 2004, the Scopus represents a comprehensive literature database with enriched citation metrics and abstract sources of various disciplines. Adopting guidelines from previous bibliometric studies (Olatunji et al., 2021; Olisah et al., 2019b, 2018), we map and synthesize findings from retrospective African DDCs literature indexed in both the WoS and Scopus databases. Only publications that analysed the occurrence of DDCs in biological and environmental matrices from the African environment were retrieved. This includes cohort and environmental monitoring studies of the DDCs in environmental and biological matrices (water, soil, sediments, air, as well as animal and human tissues).

2.2 Data Retrieval and Search Strategy

Data retrieval was done according to the protocol described in Olisah et al. 2020. To identify studies conducted on the assessment of DDCs in the African environment, a list of African countries (North et al., 2020), together with the listed POPs (US EPA, 2022) was searched on the “topic” module (title, abstract and keyword) from January 1, 1990, to December 31, 2021, on the Clarivate Analytic’s WoS platform. We ran our search on February 22, 2022 using the following search strings – TS=("Algeria" OR "Angola" OR "Benin" OR "Botswana" OR "Burkina Faso" OR "Burundi" OR "Cabo Verde" OR "Cape Verde" OR "Cameroon" OR "Central African Republic" OR "Chad" OR "Comoros" OR "Congo" OR "Côte d'Ivoire" OR "Ivory Coast" OR "Democratic Republic of the Congo" OR "Djibouti" OR "Egypt" OR "Equatorial Guinea" OR "Eritrea" OR "Ethiopia" OR "Gabon" OR "Gambia" OR "Ghana" OR "Guinea" OR "Guinea-Bissau" OR "Kenya" OR "Lesotho" OR "Liberia" OR "Libya" OR "Madagascar" OR "Malawi" OR "Mali" OR "Mauritania" OR "Mauritius" OR "Morocco" OR "Mozambique" OR "Namibia" OR "Niger" OR "Nigeria" OR "Rwanda" OR "São Tomé" OR "Príncipe" OR "Senegal" OR "Seychelles" OR "Sierra Leone" OR "Somalia" OR "South Africa" OR "South Sudan" OR "Sudan" OR "Swaziland" OR "Tanzania" OR "Togo" OR "Tunisia" OR "Uganda" OR "Zambia" OR "Zimbabwe" OR "Western Sahara") AND TS=("aldrin"OR "chlordane" OR "DDT*" OR "dichlorodiphenyltrichloroethane" OR "dieldrin" OR "endrin" OR "heptachlor" OR "mirex" OR "toxaphene" OR "hexachlorobenzene" OR "polychlorinated biphenyl*" OR "polychlorinated dibenzo-p-dioxin*" OR "dioxin*" OR "polychlorinated dibenzofuran*" OR "PCDD*" OR "PCDF*" OR "PCDD/PCDF*" OR "dioxin-like PCB*" OR "dioxin-like polychlorinated biphenyl*"). Only

“Article”, “Review”, “Book Chapter”, “Book”, and “Editorial” were targeted. Records such as “Note”, “Meeting Abstract”, “Correction Addition”, “Early Access”, and “Data Paper”, where excluded. A total of 1 567 records was initially identified. The results were manually screened and only 561 documents satisfied the search criteria (Figure 1). The search string highlighted above was inputted into the TITLE-ABS-KEY component in the Scopus database targeting “Article”, “Review”, “Book Chapter”, “Book”, and “Editorial” published from January 1, 1949 to December 31, 2021. While “Proceedings Papers”, “Meeting Abstracts”, “Early Access”, “Notes”, “Corrections”, “News Items”, “Retracted Publications”, and “Retractions” were excluded. These document types were excluded from both databases because they often contain pre-published or post-published data. The initial search yielded 2 400 publications, but only 764 met the search criteria (Figure 2).

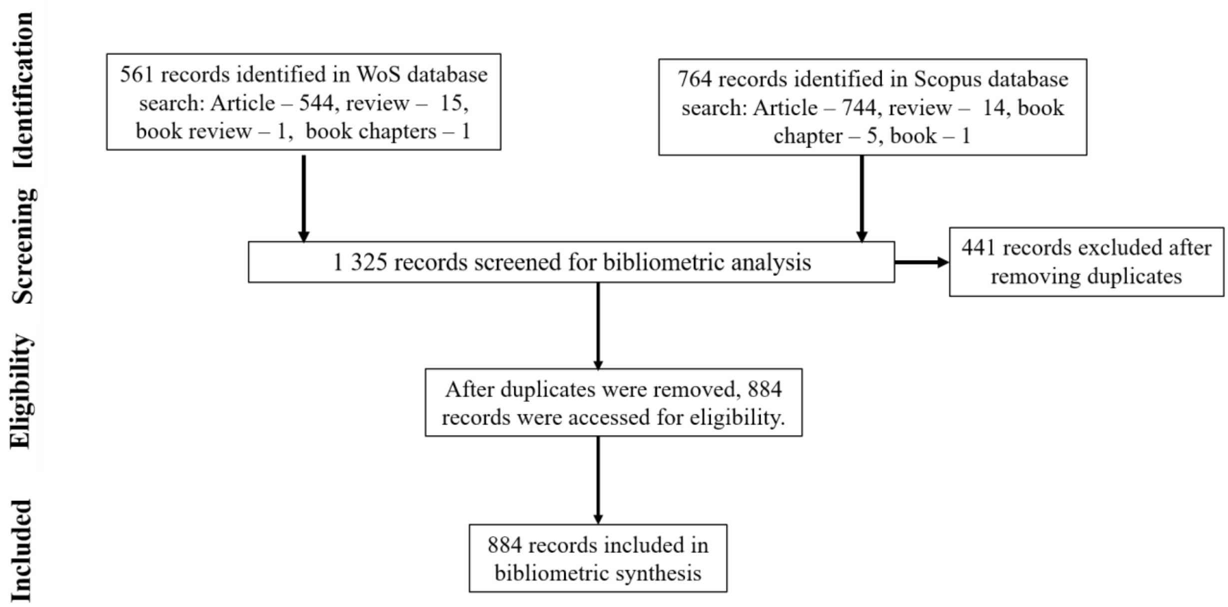

Figure 2. Schematic diagram for the selection of publications used in the bibliometric analysis.

2.3 Data Processing

A total of 561 WoS and 764 Scopus publications were downloaded in Bibtex and uploaded into RStudio (version 1.4.1106 © 2009 – 2021) for further processing. Duplicate publications from both databases were merged with the R command [(h<-duplicatedMatching(M, Field =

"TI",tol = 0.95)], giving rise to 884 publications which was then used for bibliometric analysis. RStudio with installed bibliometric package “bibliometrix” was used for analysing, visualising and tabulating the following bibliometric indicators - publication types, authors collaboration, annual scientific production, most productive authors, top publication per citations, corresponding author’s countries, top citation per country, most relevant sources, and citation matrices. Codes for these bibliometric indicators and statistical variables (Kolmogorov-Smirnoff (K-S) p-value, goodness of fit, and β-coefficient) were retrieved from Aria and Cuccurullo (2017). We performed bibliometric coupling using the equation $S = B \times B^T$, where B represent the bipartite network and S symmetrical matrix $S = S^T$. Two publications are said to be bibliometrically coupled if a cited reference appears in both publications (Kessler, 1963). Country collaboration networks was graphed using the following set variables: n = 20, type = size, label size = 1.4. The default parameter settings were used for other bibliometric parameters. Merged publications from both databases were exported from R in csv file format and uploaded into VOSviewer software (version 1.6.15 © 2009 – 2020) for keyword co-occurrence and thematic area visualisation. As a result, major topics were clustered using word cloud. The bibliometric techniques employed in this study were complemented with manual publication content analysis to allow us articulate new areas that needs further research. Linear, logarithmic, and polynomial models were considered for spotting temporal publication trends. However, we chose the polynomial model as a predictive growth model due to its high R^2 value (Zou et al., 2019).

3. RESULTS AND DISCUSSION

3.1 Publication Trends

A total of 884 publications were retrieved from both databases from 1951 to 2021 (Table S1). Of these documents, 856 were primary articles while the remaining 28 were reviews (n = 23), book chapters (n = 4) and book (n = 1). The studies were conducted by 2436 scholars with a publication/author and author/publication ratio of 0.36 and 2.76, respectively. Apart from 42 single-authored publications, all others were multiple-authored (n = 2394), retrieved from 257 journal sources. These documents accumulated citation/publications and citation/year averages of 19.1 and 1.83, respectively. A collaboration index of approximately 3 indicated in this study reveals a high engagement of co-authorship per publication (Siamaki et al., 2014). Figure 3 shows the publication trends from 1951 to 2021. The growth trajectory between the survey periods was relatively steady, with major fluctuations between years. A flat article production was observed between 1951 and 1982, after which the trajectory slowly started moving upwards. The green revolution in agriculture, which started in the early 1950's, was affirmed by the ubiquitous use of pesticides and industrial chemicals manufactured by substituting carbon molecules in hydrocarbon structures with chlorines so they can readily bind to lipids (Nadal et al. 2015; Miner et al. 2017). In this era, researchers were beginning to get interested in this class of chemicals and identify numerous possible projects connected to it, particularly those related to health consequences. This may be why a flat profile was noticed between 1951 and 1982. Approximately 79% of the articles were published after the Stockholm Convention (2002 – 2020, n = 689) with peak numbers recorded in 2017 (n = 72) and 2021 (n = 76). The Stockholm Convention, which increased the awareness of the toxicity of the DDCs may have prompted more studies during this period, particularly in African regions where they were previously used. Furthermore, the growing industrialisation in Africa over the past two decades may have resulted in more polluted study locations for researchers to investigate the presence of some of these chemicals (Turok and McGranahan, 2013; Ssebugere et al., 2019), thus resulting in higher research outputs. The relationship between the number and years of publications generated an R^2 of 0.83 when fitted into a polynomial regression, demonstrating a direct association between the two variables. We used Lotka's inverse square law of author productivity to evaluate the authorship distribution pattern (Ekundayo and Okoh, 2018). The scientific outputs analysed by Lotka's law revealed a β-coefficient and constant of 2.46 and 0.61, respectively, with a K-S goodness-of-fit of 0.92 (p = 0.07, two-sample t-test). The insignificant difference between the theoretical and observed Lotka's distribution indicates that Lotka's law does not fit the Dirty Dozen literature. A 0.57% annual growth rate suggests that a significant rise in the number of articles is not anticipated in the upcoming years.

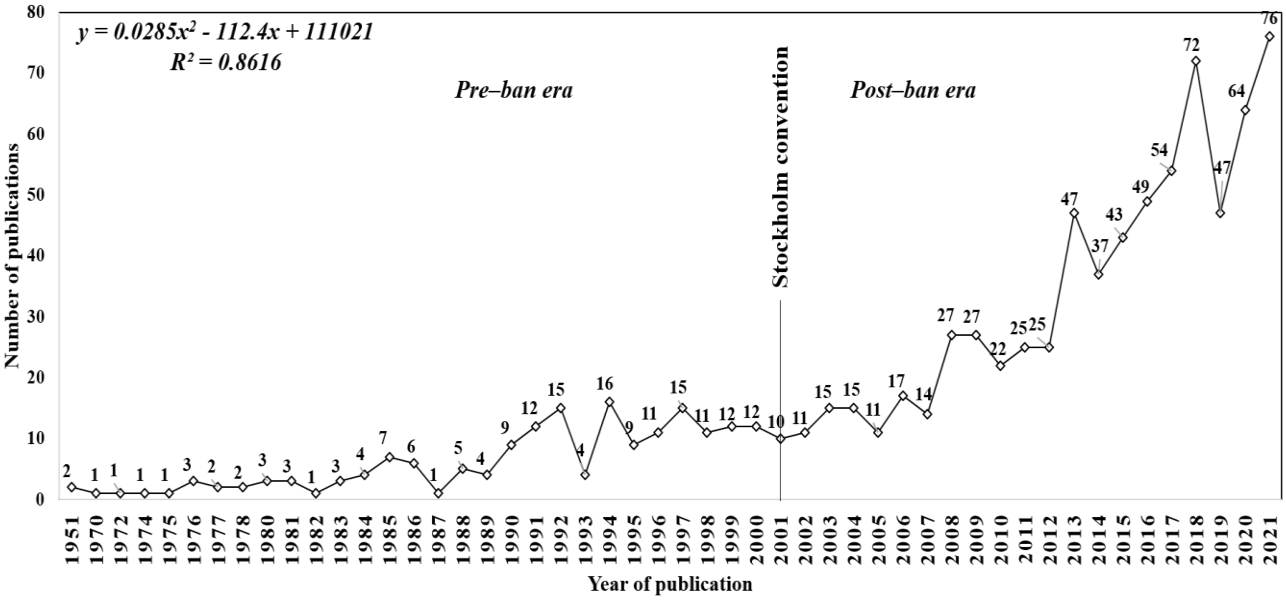

Figure 3. The annual publication frequencies on Dirty Dozen chemicals in Africa published between 1949 and 2020. The annual growth rate was 0.57%.

3.2 Country Publications Distribution and Collaboration

Figure 4 shows the geographical distribution of publications based on all author's affiliations. Different shades of red depict different levels of productivity. Grey colour shadings represent countries that were not considered in the collection. As expected, African countries dominated the most productive countries profile. South Africa had the highest number of publications with 15.05% (n = 133) of the total number of published articles, followed by Egypt (n = 117, 13.24%), Nigeria (n = 77, 8.71%), USA (n = 40, 4.52%), and Ghana (n = 38, 4.30%) (Table

1). These countries except Nigeria also had the highest number of citations. In a regional context, North African countries (n = 5) dominated the publication profile in the 30 most prolific countries, followed by East and West Africa with four countries apiece. Data showed that countries in North Africa like Morocco and Egypt were among the highest intensive users of pesticides in the past (Mansour, 2009). This may have influenced their article production since scholars may have conceptualised research in the area of their application.

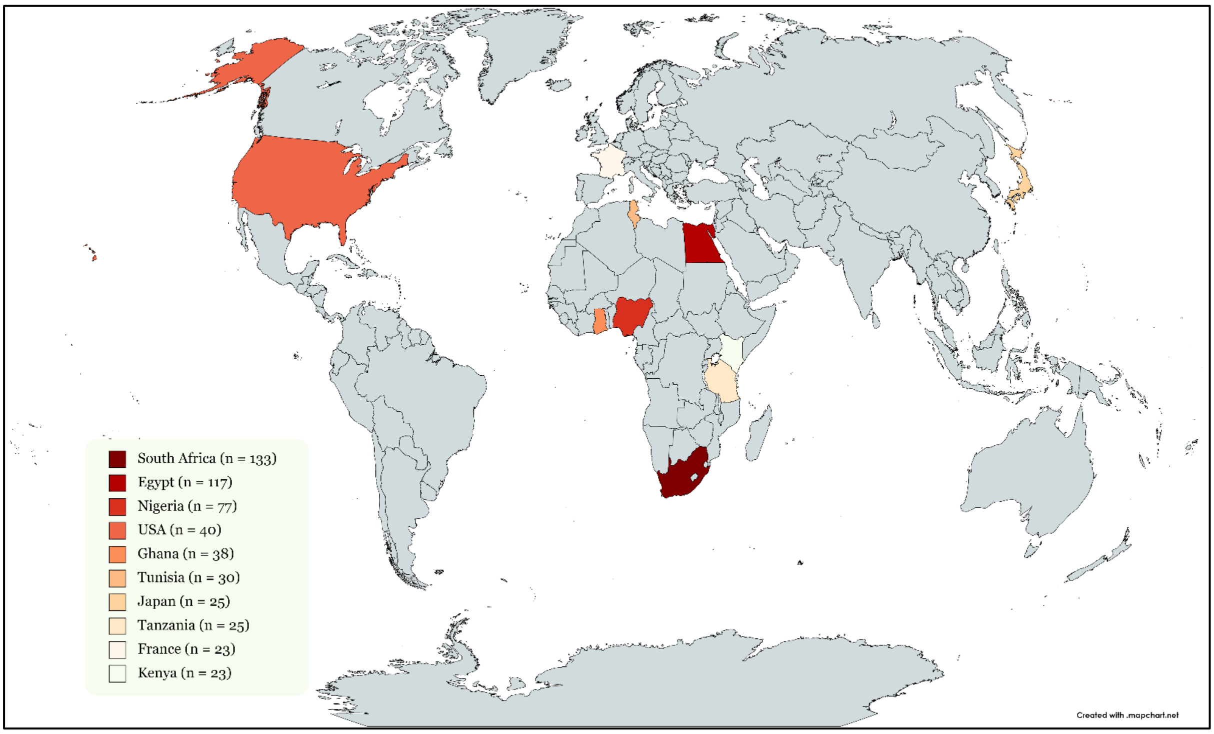

Figure 4. Top 10 most productive countries in Dirty Dozen Chemicals (DDCs) in Africa. Dark red shadings indicate countries with a higher number of publication. Grey colour shadings denote countries not considered in the collection.

Table 1. Top 30 author countries on research conducted on the assessment of Dirty Dozen Chemicals (DDCs) in the African environment from 1951 to 2021 ranked based on publication and citation indices.

Most productive countries								Total number of citations per country			
Rank	Countries	Articles	% of 884	Freq	SCP	MCP	MCP/P Ratio	Rank	Country	Total citations	Citation average
1	South Africa	133	15.05	0.161	82	51	0.38	1	South Africa	3115	23.42
2	Egypt	117	13.24	0.141	101	16	0.14	2	Egypt	2482	21.21
3	Nigeria	77	8.71	0.093	59	18	0.23	3	Ghana	1169	30.76
4	USA	40	4.52	0.048	22	18	0.45	4	USA	1162	29.05
5	Ghana	38	4.30	0.046	33	5	0.13	5	Japan	737	29.48
6	Tunisia	30	3.39	0.036	23	7	0.23	6	Tunisia	729	24.30
7	Japan	25	2.83	0.030	6	19	0.76	7	United Kingdom	611	32.16
8	Tanzania	25	2.83	0.030	17	8	0.32	8	Nigeria	554	7.19
9	France	23	2.60	0.028	5	18	0.78	9	Norway	543	31.94
10	Kenya	23	2.60	0.028	22	1	0.04	10	Belgium	509	25.45
11	Belgium	20	2.26	0.024	10	10	0.50	11	Canada	430	28.67
12	Germany	20	2.26	0.024	12	8	0.40	12	France	426	18.52
13	Italy	19	2.15	0.023	11	8	0.42	13	Spain	345	23.00
14	Netherlands	19	2.15	0.023	12	7	0.37	14	Germany	333	16.65
15	United Kingdom	19	2.15	0.023	10	9	0.47	15	Netherlands	317	16.68
16	Norway	17	1.92	0.021	3	14	0.82	16	Tanzania	306	12.24
17	Uganda	16	1.81	0.019	7	9	0.56	17	Kenya	271	11.78
18	Canada	15	1.70	0.018	6	9	0.60	18	Italy	253	13.32
19	China	15	1.70	0.018	9	6	0.40	19	Sweden	247	27.44
20	Spain	15	1.70	0.018	9	6	0.40	20	Uganda	233	14.56
21	Ethiopia	14	1.58	0.017	10	4	0.29	21	Switzerland	182	30.33
22	Zimbabwe	13	1.47	0.016	12	1	0.08	22	Austria	176	58.67
23	Algeria	11	1.24	0.013	6	5	0.45	23	China	176	11.73
24	Sweden	9	1.02	0.011	6	3	0.33	24	Zimbabwe	145	11.15
25	Benin	8	0.90	0.010	8	0	0.00	25	Benin	95	11.88
26	Botswana	8	0.90	0.010	2	6	0.75	26	Ethiopia	80	5.71
27	Morocco	8	0.90	0.010	5	3	0.38	27	Algeria	79	7.18
28	Sudan	6	0.68	0.007	4	2	0.33	28	rwanda	54	54.00
29	Switzerland	6	0.68	0.007	1	5	0.83	29	botswana	47	5.88
30	Senegal	4	0.45	0.005	3	1	0.25	30	denmark	40	20.00

SCP – Single country publication; MCP – multiple country publication.

Most critical challenges in scientific research can often be solved by collaboration involving a multidisciplinary team with diverse background ideas (Bansal et al., 2019; Dusdal and Powell, 2021). The incorporation of different ideas makes it easier to achieve set objectives (Vasilevsky et al., 2021). To foster research progression, some government agencies incorporate collaboration initiatives as part of their funding conditions. In this study, we took advantage of the VOSviewer to explore the collaboration pathways between the top countries involved in effective collaboration in the aforementioned research area. Each bubble in Figure 5 represents a country, while the size of each bubble in the network map denotes the number of publications in which an author from a particular country is enlisted as a co-author.

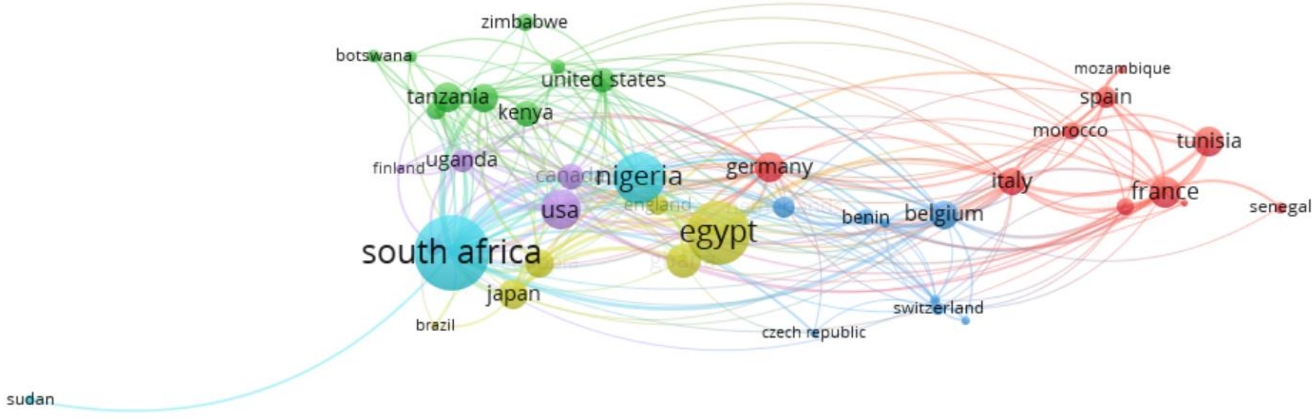

Figure 5. Collaboration pathways of countries involved in Dirty Dozen Chemicals (DDCs) research in Africa.

The thickness of connecting lines shows the collaboration frequencies between countries. Similar to the findings presented in Figure 4 and Table 1, South Africa, Egypt and Nigeria have collaborated the most with other countries in this research area. More so, 35% of the 20 most prolific researchers in this field of study are domiciled in South Africa (Table 1). The fact that some of the DDCs (especially DDT) are still utilized for mosquito control in some regions of the country may explain the high number of research outputs from this country. Environmental scholars have conceptualized projects around these locations, specifically in terms of environmental monitoring and toxicity studies, thereby increasing the number of research outputs. Besides, South Africa has a significant number of research institutions that promote research and create new knowledge in a variety of disciplines, including chemistry. These institutions, such as the National Research Foundation, the Council for Scientific and Industrial Research, the Medical Research Council – MRC, the Water Research Commission, amongst others, create a platform and funding programs for both national and international academics to collaborate on scientific projects that result in publications (Kozma and Calero-Medina, 2019). South Africa's success in this subject might also be attributed to the country's substantial research and development (R&D) gross domestic product (GDP) proportion. According to the UNESCO Institute for Statistics (2018), South Africa spent the most money on R&D compared to other African countries on the list of the most productive DDCs research countries. Furthermore, research productivity in South Africa has increased as a result of good institutionalized grant management (from 1918) and the introduction of institution performance-based financing in 1985 (North et al., 2020). South Africa's significant presence in many disciplines might also be connected to the R&D funds it receives through the BRICS partnership, which began in 2010 (Chen and Chen, 2016). The existence of research networks, such as, the African Network for Chemical Analysis of Pesticides (and other POPs), supported by the International Science Programme based in Uppsala, whose membership included Tanzania, Kenya, Uganda, Ethiopia, Nigeria, Rwanda, Sudan, and Zimbabwe, might have been a key factor in increased awareness about POPs research in member countries, especially, between 2000 – 2020 (ISP, 2002). Furthermore, several international programs on POPs research may have driven collaboration between African countries and other countries abroad (USA, Japan, Finland, Germany, Brazil, Belgium, Czech Republic, Switzerland, Italy, Spain, and France). The United Nations Environment Chemicals and Health Branch, in collaboration with the Secretariat of the Stockholm Convention, the Global Environment Facility, the Strategic Approach to International Chemicals Management, and the Government of Norway, established several projects in 2004 to produce high-quality data on the occurrence and human exposure of the legacy POPs. The first phase of the project was implemented in regions in 32 countries, including Africa, America, the Caribbean, and the Pacific Island regions, from 2009 to 2012. While the second phase was implemented through four regional projects in 42 countries across the regions mentioned above from 2016 to 2020. (UNEP, 2022). The Africa

Stockpiles program is another collaboration initiative, which the Global Environmental Fund funds through the World Bank. The program's primary objective is to clean up and appropriately dispose of all outdated pesticide stocks from Africa and put in place preventive measures to avoid continuous contamination.

3.3 Citation Analysis and Authorship Pattern

Our fourth research question deals with the most cited DDCs publications in the African context. Citation is used to measure an article's impact on a research area (Colavizza et al., 2020). We prioritise this bibliometric indicator to identify the most influential publications from the WoS and Scopus databases collections. The top 20 most cited articles are listed in Table 2. Sorensen et al. (2015) top the retrieved records with 173 citations, accounting for 21.6 % of the total citation. These authors evaluated the level of over 1000 organic contaminants in groundwater sources in Kabwe, Zambia. Interestingly, the primary focus of Sorensen and his team was both on emerging and legacy contaminants. While throwing light on the level of both classes of pollutants in urban and peri-urban settings, they also analysed the risk factors of the analysed contaminants. Aneck-Hahn et al. (2007) occupied the second spot on the list with 162 citations (10.1%). This was an epidemiological study that evaluated the impact of DDT in the semen of men living in endemic malaria regions where DDT is sprayed annually. Finally, Bouwman et al. (2006), with 146 citations, also assessed the presence of organic contaminants in human fluids from malaria-endemic regions. In this case, DDT and pyrethroids were analysed in 152 breast-milk samples collected from Jozini, Mkuze, and Kwaliweni, KwaZulu Natal in South Africa. Because these pollutants were found in the samples collected, the authors expressed worry about their toxicological interactions. Research on the presence of the DDCs in environmental matrices (air, water, soil, and sediments) had a more significant influence, accounting for 47% of the top 30 cited papers. Approximately 90% (n = 27) of the 30 most cited articles were published in the last two decades. Although older articles receive more citations than newer papers, the expansion of research scope, the evolvement of new ideas, and the emergence of sophisticated analytical tools for detecting ultra-trace levels of the DDCs may have resulted in a significant increase in citations of more recent literature.

Table 2. The top 30 cited publications on the assessment of Dirty Dozen Chemicals (DDCs) in the African environment from 1951 to 2021 ranked based on their citation frequencies.

Rank	First author, initials, and year of publication	Publication title	Journal title	Total citation	Total citation/year	Normalized total citation
1	Sorensen JPR, 2015	"Emerging contaminants in urban groundwater sources in Africa"	Water Res	173	21.6	7.61
2	Aneck-Hahn NH, 2007	"Impaired semen quality associated with environmental DDT exposure in young men living in a malaria area in the Limpopo Province, South Africa."	J Androl	162	10.1	3.75
3	Bouwman H, 2006	"Simultaneous presence of DDT and pyrethroid residues in human breast milk from a malaria endemic area in South Africa"	Environ Pollut	146	8.59	3.93
4	Kidd KA, 2001	"Biomagnification of DDT through the benthic and pelagic food webs of Lake Malawi, East Africa: importance of trophic level and carbon source"	Environ Sci Technol	142	6.45	3.34
5	Fatoki OS, 2003	"Methods for selective determination of persistent organochlorine pesticide residues in water and sediments by capillary gas chromatography and electron-capture detection"	J Chromatogr A	131	6.55	3.50
6	Barakat AO, 2002	"Organochlorine pesticides and PCB residues in sediments of Alexandria Harbour, Egypt"	Mar Pollut Bull	129	6.14	3.35
7	Abou-Arab AAK, 1999	"Behavior of pesticides in tomatoes during commercial and home preparation"	Food Chem	128	5.33	3.78
8	Loutfy N, 2006	"Dietary intake of dioxins and dioxin-like PCBs, due to the consumption of dairy products, fish/seafood and meat from Ismailia city, Egypt"	Sci Total Environ	120	7.06	3.23
9	Abou-Arab AAK, 1999	"Quantity estimation of some contaminants in commonly used medicinal plants in the Egyptian market"	Food Chem	111	4.62	3.28
10	Norli HR, 2011	"Application of QuEChERS method for extraction of selected persistent organic pollutants in fish tissue and analysis by gas chromatography mass spectrometry"	J Chromatogr A	110	9.17	3.24
11	Asante KA, 2011	"Human exposure to PCBs, PBDEs and HBCDs in Ghana: Temporal variation, sources of exposure and estimation of daily intakes by infants"	Environ Int	106	8.83	3.12
12	Darko G, 2008	"Persistent organochlorine pesticide residues in fish, sediments and water from Lake Bosomtwi, Ghana"	Chemosphere	105	7.00	2.94
13	Jaward FM, 2004	"Evidence for dynamic air− water coupling and cycling of persistent organic pollutants over the open Atlantic Ocean"	Environ Sci Technol	101	5.32	2.61
14	Louiz I, 2008	"Monitoring of dioxin-like, estrogenic and anti-androgenic activities in sediments of the Bizerta lagoon (Tunisia) by means of in vitro cell-based bioassays: contribution of low concentrations of polynuclear aromatic hydrocarbons (PAHs)"	Sci Total Environ	96	6.40	2.69
15	Barakat AO, 2013	"Persistent organochlorine pesticide and PCB residues in surface sediments of Lake Qarun, a protected area of Egypt"	Chemosphere	95	9.50	4.65
16	Kuranchie-Mensah H, 2012	"Determination of organochlorine pesticide residue in sediment and water from the Densu river basin, Ghana"	Chemosphere	95	8.64	3.33
17	Gioia R, 2008	"Polychlorinated biphenyls (PCBs) in air and seawater of the Atlantic Ocean: sources, trends and processes"	Environ Sci Technol	94	6.27	2.64
18	Mansour SA, 2009	"Monitoring of pesticides and heavy metals in cucumber fruits produced from different farming systems"	Chemosphere	93	6.64	3.05
19	Cockcroft VG, 1989	"Organochlorines in bottlenose dolphins Tursiops truncatus from the east coast of South Africa"	S Afr J Mar Sci	93	2.74	3.44
20	Van Dyk JC, 2010	"DDT contamination from indoor residual spraying for malaria control"	Sci Total Environ	89	6.85	3.93
21	Tue NM, 2016	"Release of chlorinated, brominated and mixed halogenated dioxin-related compounds to soils from open burning of e-waste in Agbogbloshie (Accra, Ghana)"	J Hazard Mater	83	11.86	4.07
22	Hassine SB, 2012	"Determination of chlorinated pesticides, polychlorinated biphenyls, and polybrominated diphenyl ethers in human milk from Bizerte (Tunisia) in 2010"	Chemosphere	82	7.45	2.88
23	Ennaceur S, 2008	"Distribution of polychlorinated biphenyls and organochlorine pesticides in human breast milk from various locations in Tunisia: levels of contamination, influencing factors, and infant risk assessment"	Environ Res	81	5.40	2.27
24	Karlsson H, 2000	"Persistent chlorinated pesticides in air, water, and precipitation from the Lake Malawi area, southern Africa"	Environ Sci Technol	80	3.48	2.88
25	Gioia R, 2011	"Evidence for major emissions of PCBs in the West African region"	Environ Sci Technol	79	6.58	2.33

26	Akoto O, 2013	"Health risk assessment of pesticides residue in maize and cowpea from Ejura, Ghana"	Chemosphere	77	7.70	3.77
27	Abou-Arab AAK, 2001	"Pesticide residues in some Egyptian spices and medicinal plants as affected by processing"	Food Chem	77	3.50	1.81
28	El-Kabbany S, 2000	"Monitoring of the pesticide levels in some water supplies and agricultural land, in El-Haram, Giza (ARE)"	J Hazard Mater	77	3.35	2.77
29	Manirakiza P, 2002	"Persistent chlorinated pesticides and polychlorinated biphenyls in selected fish species from Lake Tanganyika, Burundi, Africa"	Environ Pollut	76	3.62	1.97
30	Gerber R, 2016	"Bioaccumulation and human health risk assessment of DDT and other organochlorine pesticides in an apex aquatic predator from a premier conservation area"	Sci Total Enviro	75	10.71	3.68

Next, we analysed the author citation patterns in DDCs literature. Table S2 shows the most productive and influential authors in terms of publications between 1959 and 2021. Bouwman H (North-West University) had the most publications (42), followed by Ikenaka Y and Ishizuka M both from Hokkaido University, Japan, with 18 articles each. Bornman R (University of Pretoria) and Yohannes Y (Hokkaido University) each had 17 publications. It is important to note the author's productivity over time. Some authors started publishing in the early 1990s. However, most started in the decade 2000 – 2010. The year 2001 appears to be the herald of research productivity. The top 20 author productivity over the survey period is shown in Figure 6, where the blue bubbles represent the total number of publications, and their transparency denotes their level of accumulated citation. Gaps between bubbles represent a temporal absence of author's publications in that particular year. Unsurprisingly, Bouwman M, who started publishing in 1990, had the highest number of citations in the collection (1292). It is worth noting that 40% of the most productive researchers in terms of the number of articles and citations are not domiciled in Africa (Figure 6) but from developed countries. A content analysis revealed that the connections to the non-African scholars were linked to instrumental analysis, where samples are taken from Africa and shipped overseas for analysis.

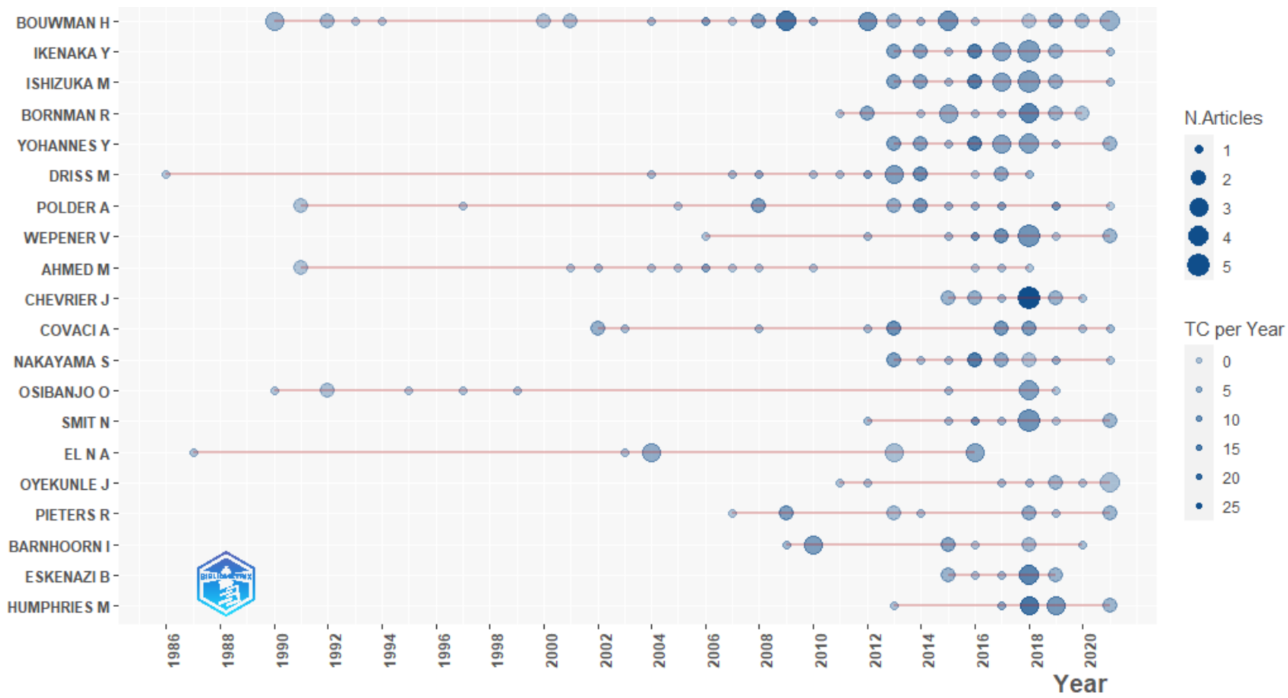

Figure 6. Author's productivity over time of the 20 most productive scholars on research related to the occurrence of Dirty Dozen Chemicals (DDCs) in Africa

3.4 Publication Outlets

Figure S1 shows the distribution of journals with the most publications in the studied research area. *Chemosphere* had the most contributions to Dirty Dozen literature in Africa, with 90 papers (10.2% of the total), whereas *Science of the Total Environmental* and *Bulletin of Environmental Contamination and Toxicology* ranked second and third, respectively, with 58 (6.56) and 56 (6.33%) papers respectively. Occupying the fourth and fifth spots were *Environmental Science and Pollution Research* and *Marine Pollution Bulletin* with 35 (3.96%) and 34 (3.85%) articles, respectively. Despite their dominance, these journals only published 11 of the top thirty most referenced papers, demonstrating a distinct author preference (Lei et al. 2019). *Environmental International* was the most influential in terms of impact factor (9.621), followed by *Environmental Science & Technology* (9.028) and *Environmental Pollution* (8.071). Six of the top 30 most cited articles (Table 2) were published in

Chemosphere. This journal's dominance may be attributed to its preference for novel articles that focus on identification, quantification, toxicology, as well as fate and behaviour of chemicals in the entire ecosystem. In general, 40% of the most relevant sources were published by Elsevier, followed by Taylor and Francis (25%) and Springer (20%).

3.5 Keyword Analysis and Thematic Classification

To facilitate online search and assign specific editors and reviewers to review a manuscript, most journals require authors to add six to eight keywords to the manuscript during the submission process. In this study, we used the keyword occurrences to study the research trends of DDCs literature. Although this act is less common, it gives direction to the evolution of new topics in a research area (Cañas-Guerrero et al., 2013). Table S3 lists the top 30 keywords in four different phases of the survey: 1949 – 1990; 1991 – 2000; 2001 – 2010; and 2011 – 2020. Plural and singular forms of keywords appearing more than once were merged as one. According to keywords in the 1949 – 1990 publishing era, studies were mainly focused on the geographic distribution of pesticide residues and PCBs in animals and human tissues from some African countries. This is evident by the dominance of keywords such as DDE, DDT, fish, insecticides, animals, geographical distribution, pesticide residues, residue analysis, nonhuman, dieldrin, lindane, PCB, bird, milk, Egypt, Kenya, and South Africa. The decade 1991–2000 was similar to the preceding one, but with a broader scope encompassing water and food contamination. This was noticeable due to the emergence of new terms such as environmental monitoring, fish, water pollution, food contamination, pollution, amongst others. Between 2001 and 2010, research focus shifted slightly to the bioaccumulation of OCPs, PCBs and dioxins in fish tissues with the advent of keywords such as bioaccumulation and dioxins. In comparison, between 2011 and 2020, research was tailored towards exposure and risk assessment studies of the DDCs and other toxic organic compounds. This was obvious due to the appearance of unique keywords such as polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons, risk assessment, exposure, concentration (composition), and controlled study. In general, the most prominent keywords during the survey periods were polychlorinated biphenyls, appearing in 399 articles (45.13% of the total), followed by pesticides (n = 266, 30.09%), organochlorine pesticides (n = 250, 28.82%), DDT (n = 179, 20.25%) and sediments (n = 174, 19.68%). This indicate that PCBs and OCPs have been researched the most in the African region.

3.6 Thematic Content Analysis

Our fifth and sixth research questions deal with the themes explored in DDCs literature in an African context. Figure 7 shows the four thematic areas associated with this research area. This figure classified themes using keywords co-occurrences from all 884 articles. Studies from the survey period were classified into four broad themes: water pollution, environmental monitoring, bioaccumulation, biomonitoring, and epidemiological studies. Many countries in Africa are still experiencing chronic contamination of the Dirty Dozen chemicals in their environment. Pollutant residues in air, water, soil, and sediments pose a serious environmental hazard to wildlife and human consumers. Spillage from existing OCP stockpiles and PCB electrical equipment are a major route of pollution in the African environment. For example, environmental samples collected from Vikuge farm in Tanzania were found to be the most polluted in Africa due to the illegal disposal and storage of obsolete pesticides since 1986 (Kishimba and Mihale, 2004; Olisah et al., 2020a). The concentration of DDTs was found to be as high as 2.8×10^8 µg/kg in soil samples collected from the vicinity of the farm (Kishimba and Mihale, 2004). Another pollution source is industrial emissions which are not strictly regulated and controlled in Africa. Most industries dump their waste directly into an open environment to avoid treatment costs (Ssebugere et al., 2019). According to literature, the largest PCDD/Fs and dioxin-like PCBs emissions in Africa are from industrial chemical processes, open waste burning, and effluent discharge (Ssebugere et al., 2019). Therefore, more monitoring the DDCs in environmental samples from Africa is needed to provide a basis for effective compliance to the Stockholm Convention on POPs.

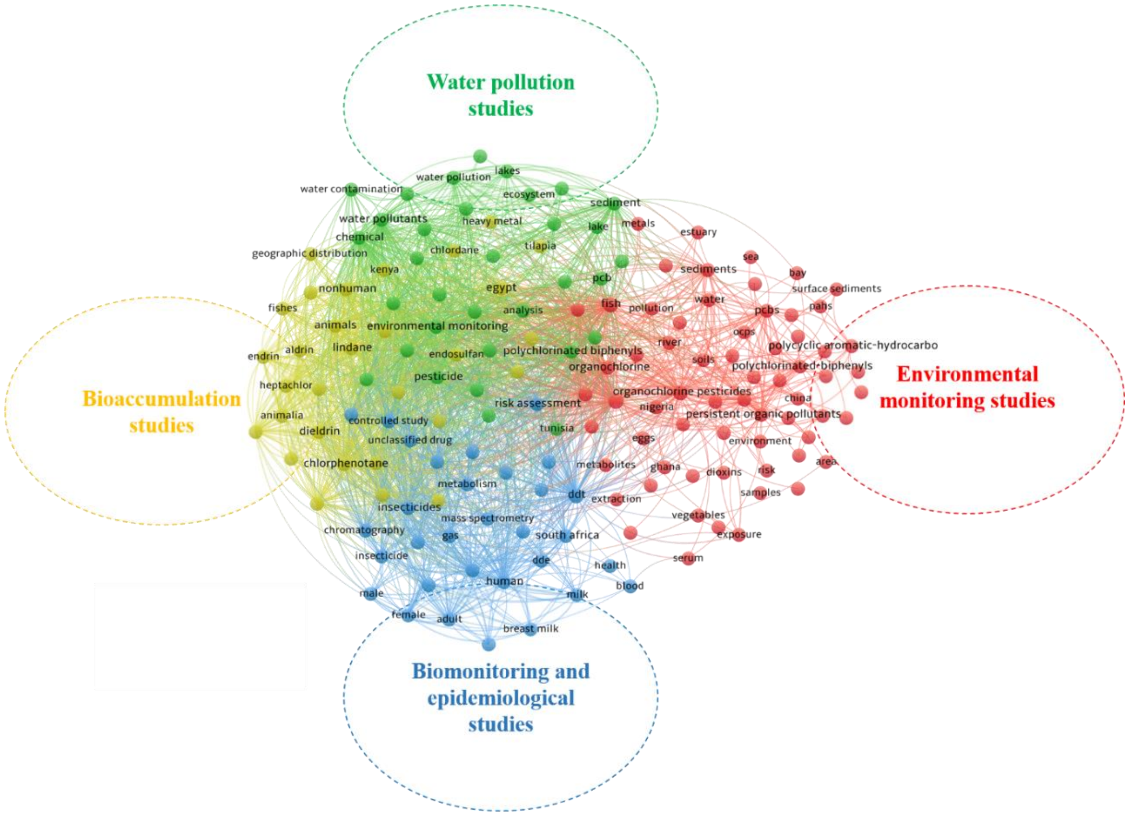

Figure 7. Thematic literature classification of research related to Dirty Dozen Chemical (DDCs) research in Africa based on data retrieved from the WoS and Scopus databases from 1949 – 2021.

Bioaccumulation of the DDCs is expected due to their lipophilic nature and the tendency of aquatic and terrestrial organisms to accumulate lipids. Furthermore, the biomagnification process might lead to increased POP concentrations in top organisms, making them more susceptible to negative health impacts (Schiavone et al., 2009). The majority of study on the presence of DDCs in organisms in Africa has been done on fish, according to our theme literature classification results. This is most likely due to the fact that they provide a potential bioaccumulation route for humans. We believe other aquatic choice foods, such as crab, shrimp, and crab, should be the subject of more research in order to fully comprehend the bioaccumulation cycle of these contaminants in aquatic systems.

Biomonitoring data reflect the burden burdens of hazardous chemicals and their potential biological effect from all exposure routes. This is an essential metric in health impact assessment, especially for POPs that are stored in the body tissues for an extended period of time. In epidemiological investigations, biomonitoring data is combined with health status data to show a link between pollutant levels and illness in humans. This is one of the growing areas of research, as noticed in our thematic literature classification. According to the data gathered from the WoS database, only 60 studies evaluated the level of POPs in human tissue (semen, blood, placenta, and breast milk) in Africa. Furthermore, only ten studies looked at the direct relationship between DDCs exposure and human illnesses. This includes studies that linked DDCs exposure to cancer (Debela et al., 2021), effect on maternal thyroid hormone homeostasis (Matovu et al., 2021), inflammation in reproductive ages women (Cupul-Uicab et al., 2020), maternal peripartum infection (Chevrier et al., 2019), hypertensive disorders (Murray et al., 2018), diabetes (Azandjeme et al., 2014), sexual development diseases (Bornman and Bouwman, 2012), urogenital malformations (Bornman et al., 2010), impaired semen quality (Aneck-Hahn et al., 2007) and malaria (Bouwman et al., 1994). Such a small number of outputs is alarming due to the high number of diseases DDCs exposure is capable of causing. Global studies have linked DDCs exposure to neurological disorders in humans (Ahmed et al., 2021), arterial diseases (Min et al., 2011), (Sagiv et al., 2010), acute respiratory infections (Dallaire et al., 2006; Carpenter et al., 2008) , breast cancer (Aronson et al., 2000; Stellman et al., 2000), non-Hodgtin lymphoma (De Roos et al., 2005), Parkinson diseases

(Corrigan et al., 2000). Given the high incidence of the aforementioned diseases and the high level of DDC exposure in the African region, we strongly recommend that more epidemiologic studies be conducted in the African region to investigate the possible negative effects of DDCs.

3.7 Future Perspectives and Recommendations

The production of articles between years was progressive, from 1 article in 1949 to 76 articles in 2021. However, the annual increase was relatively very low (0.57%), suggesting a possible low output in article production in years to come. In recent years, legacy pollutants like the DDCs are not accorded the same attention as emerging organic contaminants (EOCs) (pharmaceuticals and personal care products, per- and polyfluoroalkyl substances PFASs, microplastic, ultraviolet filters). The shift in focus is a possible reason why low outputs of DDC literature are projected in the future. The EOCs suspected detrimental effects on ecosystems and human health had driven the expansion of new knowledge in this field, thus, resulting in an increase in research outputs on these subjects. For example, just ten articles on PFAS were published in 2003, but by 2018, that number had climbed to 469 (Wu et al., 2022). Similarly, ten publications on microplastics (MPs) were published in the years prior to 2010, but this number increased to 602 in 2018 (Zhang et al., 2020). While we recognize that research on EOCs and MPs is vital, we also believe expanding the study coverage in previously researched locations and establishing new sampling sites in unexplored areas are critical for DDC research. This is critical because of the transboundary movement of the DDCs and their potential to remain in the environment for a long time and cause negative adverse effects at low concentrations. Furthermore, some compounds such as PCDD/Fs have lacked a phasing out stage because they can be produced either intentionally or unintentionally via anthropogenic activities, production of chlorinated compounds, and natural processes (Güzel et al. 2020). These circumstances justify the necessity for a continued focus on legacy pollutants in toxicological and environmental monitoring research, particularly at a time when much attention has been devoted to the detection of emerging contaminants in different environmental matrices.

Despite its challenges, Africa has the capacity to participate in DDCs research. Such work requires significant resources (sophisticated laboratories, funding, experienced research assistants) and these cannot be prioritised over basic infrastructures and human needs. If research on DDCs in the African environment must grow, then the African government must increase the amount of GDP spent on R&D. Due to the high cost of DDC standards and the sophisticated analytical instruments used for their analysis (gas chromatography with tandem mass spectrometry – GC-MS/MS, gas chromatography with high-resolution mass spectrometry – GC-HRMS), progression of DDCs research is very unlikely. As with other subject areas (North et al., 2020; Verma et al., 2021; Niknejad et al. 2022), most of the leading authors in DDCs in Africa were from South Africa. Therefore, the government of African countries that are not prolific in DDC research should inject more funds into this aspect of study due to their potential threat to the ecosystem.

Some of the most frequently cited studies in the aforementioned field of study are related to the health impact of DDCs – for example, the impairment of semen quality due to DDT exposure (Aneck-Hahn NH, 2007) and the occurrence of DDT and pyrethroid in human breast milk (Bouwman et al., 2006). South Africa and Egypt dominated the list of the top 30 countries most active in DDC research in terms of the number of publications and citations. In addition to economic strength and availability of research funds and facilities in these countries, their productivity may be attributed to their effective collaboration with institutions in developed countries, which in turn drives research visibility and citation frequency. Researchers from other African countries need to make a significant effort to pursue collaborations with institutions in developed nations to bolster DDCs research. This is necessary in order to answer critical scientific questions, particularly those related to human health implications.

Our bibliometric review indicates that of the groups of DDC, PCBs and OCPs have been researched the most in the African region. Some ethical behaviours in Africa have resulted in persistent pollution, thus necessitating academic research. The continued inflow of e-waste, shipwrecks, and biomass burning, for example, are key sources of PCBs in Africa (Gioia et al. 2014). In the case of OCPs, unlawful use of prohibited OCPs, inappropriate pesticide application equipment, and overdosing of pesticides for crop protection have all been identified as potential contamination sources (Olisah et al. 2019a). We recommend that PCDD and PCDF should be accorded the same interest as those of the OCPs and PCBs due to the frequency of their polluting pathways in Africa (usage of solid fuel for cooking, open burning, leakages from electrical generation, burning of e-waste).

Although the current bibliometric analysis was based on certain statistical analysis and selection criteria, limitations were inevitable. First, the study relied on article metadata indexed in WoS and Scopus. As such, other articles indexed in different databases (Google Scholar, PubMed) that can influence the current study were excluded. Second, this analysis did not take into account grey literature and papers published by governments and commercial organisations. Moreover, the findings reported in this work is likely to change over time as research on the evaluation of DDCs in Africa grows. Nevertheless, this is the first bibliometric study on DDC-related research in Africa, and the findings will help in the direction of future research on this subject in the continent and beyond.

4. CONCLUSION

The current bibliometric study analysed the trends of DDC research in Africa between 1949 and 2021, based on articles indexed in the WoS and Scopus databases. Despite the worldwide ban placed on this class of pollutants during the Stockholm Convention in 2001, research productivity has continued to grow. However, with an annual growth rate of 0.57%, it is suggested that a substantial increase in articles in years to come is not anticipated. As found in other subject areas in Africa, South Africa dominated most bibliometric indicators (most productive countries, most prolific researchers, total citation per country, and collaboration index). More research programs should be established in other African countries to measure up to South Africa's supremacy, given the persistent nature of DDCs and their potential to have significant adverse effects on humans, plants, and animal species at low concentrations. Also, expanding the study coverage in previously studied locations and establishing new sampling sites in unexplored areas are critical for DDC research in order to provide a basis for effective compliance to the Stockholm Convention on POPs in Africa.

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Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

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