



# A Bibliometric study of the application of Carbon quantum dots in the fluorescence sensing for water pollution

Fatkhiyatus Sa'adah<sup>1,\*</sup>

<sup>1</sup> Doctoral Program of Environmental Science, School of Postgraduate Studies, Universitas Diponegoro, Semarang, Central Java 50241, Indonesia.

\*Correspondence: fatkhiyatussdh@gmail.com

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## ABSTRACT

**Background:** Carbon quantum dots (CQDs) have emerged as promising nanomaterials due to their unique optical properties, low toxicity, chemical stability, and eco-friendly characteristics. Their fluorescence capabilities make them particularly attractive for sensing applications, including the detection of antibiotics and heavy metals. The rapid expansion of research in this area indicates increasing scientific and technological interest in CQD-based sensing systems. **Methods:** This study employs a bibliometric analysis based on title searches in the Scopus database covering publications from 2014 to 2024. A total of 3,427 documents were identified and analyzed to evaluate publication trends, research growth, and thematic development. The analysis maps research hotspots, innovation patterns, and emerging applications of fluorescent CQDs in antibiotic and heavy metal detection. **Findings:** The results demonstrate a significant increase in CQD-related publications over the past decade, reflecting accelerated global research activity. Thematic mapping indicates growing emphasis on fluorescence-based sensing, environmental monitoring, and biomedical detection. Research hotspots reveal expanding applications of CQDs in detecting antibiotic residues and toxic heavy metals, highlighting their versatility and analytical sensitivity. **Conclusion:** The rapid growth of CQD research underscores their strong potential as efficient and environmentally friendly sensing materials. Bibliometric mapping provides valuable insights into research directions and emerging innovations, supporting the advancement of CQD applications in environmental and biomedical detection fields. **Novelty/Originality of this article:** This study offers a comprehensive bibliometric mapping of a decade of CQD research, specifically focusing on their application in antibiotic and heavy metal detection. By systematically identifying publication trends and research hotspots, it provides a structured overview of the field's evolution and establishes a strategic foundation for guiding future innovation and interdisciplinary research in CQD-based sensing technologies.

**KEYWORDS:** bibliometric analysis; carbon quantum dots; sensing; water pollution.

## 1. Introduction

The rapid growth of agriculture, aquaculture, and industrial activities particularly in coastal regions, has significantly increased the pollution of marine environments with antibiotics and heavy metals on a global scale. The contamination of water and soil by these pollutants (Table 1) has emerged as a critical environmental and public health concern (Zhu et al., 2023). Antibiotics, extensively used in human healthcare and agriculture, frequently enter the environment through wastewater. Recent reports indicate that global antibiotic consumption in 2018 reached 40 billion Defined Daily Doses (DDD) (95% confidence interval: 37 billion–43 billion DDD), reflecting a 46% increase since 2000 (Barathe et al.,

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2024). The presence of antibiotic in environment can cause the emergence of antibiotic-resistant bacteria. The resistance complicates the treatment of infections and raises the likelihood of disease transmission. Even at minimal concentrations, antibiotics found in the environment can alter microbial communities, enabling resistant bacteria to persist and spread their resistance to other organisms. This poses harmful consequences on ecosystems and can affect aquatic organisms and health risks.

Heavy metals such as lead (Alharbi et al., 2024), mercury (Mohamadi & Saeedi, 2024), cadmium (Tao et al., 2024), and arsenic (Khan et al., 2024) are highly toxic even at minimal concentrations and can accumulate in biological entities, presenting significant risks to ecosystems and human health. These metals may derive from various sources, including industrial waste, mining activities, agricultural runoff, and the incorrect disposal of metal-containing products (Yao et al., 2024). In contrast to other forms of pollution, heavy metals are non-biodegradable and can remain in the environment for prolonged durations, accumulating in soil, water, and biota. Heavy metals can easily enter the food chain, presenting significant health hazards to both animals and humans (Du et al., 2024). Prolonged exposure to heavy metals, even at minimal concentrations, can lead to detrimental effects, including neurological impairment, renal disease, and developmental issues in humans.

Consequently, detecting antibiotics and heavy metals in the environment and food is essential for protecting human health. Advanced analytical techniques, such as High-Performance Liquid Chromatography (HPLC) and Liquid Chromatography-Mass Spectrometry (LC-MS), are commonly employed for this purpose due to their high sensitivity and accuracy (Balkrishna et al., 2024; Ge et al., 2020). These methods are accurate but often expensive, time-consuming, and require specialized equipment. Techniques like Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) are widely used for detecting heavy metals, owing to their exceptional sensitivity and capability to identify trace metal concentrations accurately (Emily et al., 2023). But these procedures are sometimes costly, complex, and require extensive sample preparation. Biosensors provide more easy and rapid detection options; nevertheless, they may encounter interference from other substances in the sample and typically require further calibration for field application (Zhang et al., 2024). Although traditional methods are accurate, they present several challenges, including high costs, complicated instruments, and time-consuming procedures. These issues have led to a search for simpler and more accessible alternatives.

In recent years, carbon quantum dots (CQDs) have emerged as highly versatile nanomaterials with promising applications in environmental sensing. These carbon-based nanoparticles, typically 2–10 nm in size, have garnered considerable attention due to their unique optical properties, excellent biocompatibility, and eco-friendly nature. CQDs are particularly notable for their strong fluorescence, outstanding photostability, and tuneable emission wavelengths, making them ideal candidates for various sensing applications (Patra et al., 2023). The tuneable fluorescence makes CQDs useful for a variety of applications such as fluorescence sensors (Pooja & Chowdhury, 2021). Most CQDs are water-insoluble and may exhibit toxicity, primarily due to the incorporation of antibiotics or heavy metals within their core structure. The development of CQDs featuring ultra-high quantum yield, straightforward production methods, and substantial output to facilitate their widespread applications across several domains remains a primary focus for researchers (Lim et al., 2015).

To enhance the quantum yield, researchers have conducted numerous experimental trials. Fluorescence properties of CQDs can often be modified by using the synthesis method. Several synthesis techniques, such as electrochemical oxidation, ultrasonic treatment, laser ablation, and one step hydrothermal (Chen et al., 2025; Mohandoss et al., 2025; Shi et al., 2025; Wang et al., 2023; Yat et al., 2024). These synthesis procedures typically necessitate the use of organic solvents and potent oxidants to modify or passivate the CQDs. In comparison, the green synthesis using microwave irradiation method has emerged as the optimal strategy due to its straightforward operation and ease of management during the

reaction (Backes et al., 2025). The primary benefits of microwave irradiation in comparison to alternative procedures include an environmentally friendly chemistry process, utilisation of low-toxicity chemicals and solvents like water, straightforward chemicals and plant extracts, as well as elevated product yields.

Table 1. Antibiotics and heavy metals contamination in the environment

Location	Sources	Contaminants	Concentrations	References
Indonesia (Brebes, Tegal, and Pemalang)	Aquaculture Estuary Effluent of Hospital	Acetaminophen Oxytetracycline Sulfamethoxazole	2.1 - 11.3 ngL <sup>-1</sup> 1.0 - 12.9 ngL <sup>-1</sup> 0.8 - 3.2 ngL <sup>-1</sup>	(Hidayati et al., 2021)
Hongkong	Pearl River Estuary	Paracetamol	0.02 ngL <sup>-1</sup>	(Xie et al., 2019)
Portugal	Coastal Area	Paracetamol	12 ngL <sup>-1</sup>	(Gadelha et al., 2019)
China	Xiangjiang River	Paracetamol	16 ngL <sup>-1</sup>	(Lin et al., 2018)
Mexico	Surface Water	Paracetamol	354 - 4460 ngL <sup>-1</sup>	(Rivera-Jaimes et al., 2018)
Vietnam	Surface water	Doxycycline, Oxytetracycline, Lincomycin, and Sulfamethoxazole	17 - 91 ngL <sup>-1</sup>	(Do et al., 2020)
Indonesia	Urban sewage	Sulfamethoxazole, Lincomycin, Erythromycin, and Trimethoprim	17 - 1489 ngL <sup>-1</sup>	(Shimizu et al., 2013)
Malaysia	Surface water	Erythromycin, Tetracycline, Ciprofloxacin, Ofloxacin and Trimethoprim	66.9 - 1261 ngL <sup>-1</sup>	(Low et al., 2021)
China	Yellow Sea	Sulfamethoxazole Trimethoprim	1.0 ngL <sup>-1</sup> 1.4 ngL <sup>-1</sup>	(Zhang et al., 2013)
Ghana	Dumpsite soil	Pb, Cd, Ni, Cr, As, Hg, Cu, Mn, and Zn	0.11 - 171.08 mg.kg <sup>-1</sup>	(Oluyinka et al., 2024)
Ghana	Mining Soil	Fe, Zn, Cd, Cu, As, and Mn	31.26 - 3631.33 mg.kg <sup>-1</sup>	(Doku & Belford, 2024)
Poland	River	Zn, Pb, Cd, Cr, Cu, and Ni	0.03 - 96.86 mg.kg <sup>-1</sup>	(Bhat & Janaszek, 2024)
India	Sediment	Fe, Mg, Mn, Zn, Pb, Cu, Ni, Cr, Co, Cd, and Hg	0.002 - 3418.7 mg.kg <sup>-1</sup>	(Kumar et al., 2023)
Bangladesh	Mangrove, Soil, and Water	Mn, Cu, Zn, Pb, Cd, Cr, As, Ni, and Hg	1.2153 - 7.2 mg.kg <sup>-1</sup>	(Hossain et al., 2024)
Tanzania	Fish	Fe, Zn, Ni, Cu, and Cr	1.82 - 19.95 mg.kg <sup>-1</sup>	(Mwambene et al., 2023)

CQDs-based sensors have been extensively researched due to the possibility for new methodologies in detecting various pollutants. This approach was proposed as an effective method for identifying contaminants, including antibiotics and heavy metals (Sharma & Chowdhury, 2024). For instance, Boron and Nitrogen doped CQDs (B-N-CQDs) synthesized using citric acid and urea with thermal decomposition method. Synthesis of unique high-fluorescence B-N-CQDs probes can be detected antibiotics penicillin, erythromycin and phenol derivatives (Mousa et al., 2023). Consequently, CQDs can serve as probes for the detection of doxycycline. The CQDs synthesized by melting techniques were utilized as

probes to assess the fluorescence intensity of doxycycline, exhibiting fluorescence quenching effectiveness within the range of 5 – 30  $\mu\text{M}$  (Huang et al., 2024). Besides antibiotic detection, the utilization of CQDs doped with heteroatoms (N, S, and O) serve as probes for the electrochemical detection of heavy metals. The N, S, and O-doped CQDs display blue fluorescence emission and a notable quenching effect specifically with  $\text{Cu}^{2+}$  ions during interactions with heavy metal ions (Algethami & Abdelhamid, 2024).

As global interest in wastewater treatment continues to grow, it becomes more important to identify how the research landscape into the treatment of pharmaceutical wastewater has changed over the years, especially in the fields of CQDs for water pollution sensing. Through bibliometric analysis of research articles published between 2014 and 2024, this study seeks to completely establish the scientific trends, dominant research issues, and knowledge gaps present in this field.

A bibliometric study is a systematic analysis of various articles or publications within a research domain, providing valuable contemporary insights into a specific subject area. These analyses offer information on bibliographic connections, co-authorship and co-citation networks, research gaps, trending topics, saturated studies, research trends, journals, subjects, and the evolution of emerging fields over time, along with statistics on the development of these areas (Sun et al., 2019). Bibliometrics, therefore, provide insights into the impact of articles, as well as their visibility and content reach. In this paper, a bibliometric analysis was conducted using the Scopus database to ensure academic integrity and quality, employing VOSviewer software version 1.6.19 for the analysis. Key terms were examined to assess the evolution of country-specific distribution over the last decade. Furthermore, the most frequently referenced papers have been analysed, and a comprehensive cognitive model for the CQDs sensing for water pollution. The results aim at giving a complete picture of technical progress, reveal main research groups, and facilitate additional research in creating scalable, affordable, and green solutions for wastewaters.

## 2. Methods

### 2.1 Research design

This study employed a bibliometric analysis approach to critically examine global patterns, hotspots, and collaboration networks related to the utilisation of carbon quantum dots (CQDs) in wastewater sensing. Bibliometric analysis is a quantitative analytical method that applies statistical and network-based evaluations of scientific literature to identify patterns, trends, and research developments within a specific field. This approach enables the systematic mapping of scientific productivity, thematic evolution, and scholarly collaboration associated with CQD-based sensing technologies.

### 2.2 Data source and search strategy

The analysis in this study was limited to data retrieved from the Scopus database. Scopus is recognised as one of the largest abstract and citation databases, covering a broader range of disciplines compared to several other indexing platforms, including Web of Science. The literature data were restricted to publications published between 2014 and 2024. Data collection was conducted on 10 October 2025 to ensure the inclusion of publications available up to that date. The search process utilised keywords related to CQDs and detection applications in titles, abstracts, and keywords through the Scopus search engine. The search query applied in the database was: “Carbon” AND “quantum” AND “dots” AND “detection”. The search yielded 3,427 publications containing relevant bibliographic information, including keywords, author details, journal sources, document types, institutional affiliations, funding agencies, and countries. These data were subsequently exported in Research Information Systems (.ris) format for further analysis.

### 2.3 Data analysis

Bibliometric analysis employs statistical techniques to quantitatively evaluate bibliographic information. In this study, descriptive and summary statistical analyses were conducted to examine publication trends, document types, countries, institutional affiliations, and funding organisations. Microsoft Excel 2013 and Origin software were utilised to process and visualise the statistical data. Only the top 10 most productive journals, countries, affiliations, and funding organisations were presented in the analysis. In addition, keyword analysis and co-occurrence mapping were performed to identify major research themes, emerging topics, and relationships among subfields within CQD-based sensing studies. These analyses enabled the exploration of thematic development and research connectivity across the literature.

### 2.4 Network visualisation

The graphical visualisation of bibliometric networks was conducted using VOSviewer version 1.6.20. This software was used to generate co-occurrence maps, collaboration networks, and thematic clusters based on bibliometric data. The methodological workflow of the study is illustrated in Fig. 1.

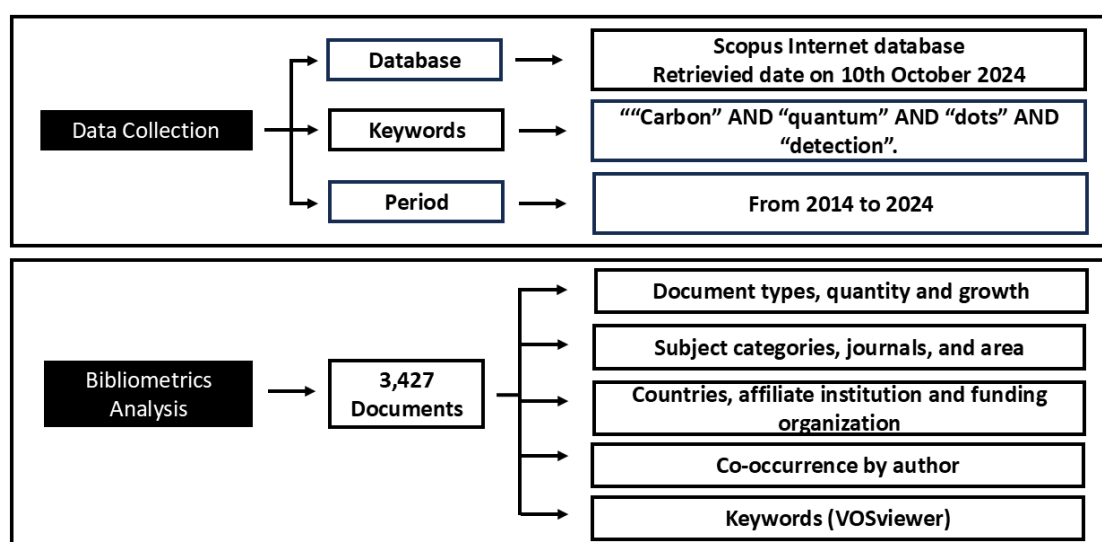


Fig. 1. Method approach of bibliometric study

## 3. Results and Discussion

### 3.1 Trend in publication of articles in journals

We used a data from Scopus database on 10<sup>th</sup> October 2025 based on keywords "Carbon" AND "quantum" AND "dots" AND "detection" within period 2014 to 2024. A total of 3,427 research articles from 156 various esteemed journals. Of these publications, 2730 articles are classified as original article, 436 as review article, while the remaining 261 categorized as book chapter, conference, book, erratum, etc. The evolution of the number publications and citations on application of CQDs detection for antibiotic and heavy metals is depicted in Figure 2(a). The study in this field progresses in two stages. The first stage, from 2014 to 2018, indicates that only a limited number of papers were published annually, with the average percentage of journal publications ranging from 1.8% to 6.7%. This could be attributed to the relatively low level of research activity during this period. This is due to the nascent stage of research on CQDs. Moreover, researchers have not comprehensively investigated or implemented studies on antibiotics and heavy metals utilizing CQDs, nor have adequate resources for this subject. The accessibility of instruments is essential for



concentrated on a country, evaluating the robustness of collaborative links and the volume of publications, derived from a dataset of 998 documents across 44 countries. As can be seen, the productive country that has been visualization using VOSviewer is shown in Fig. 2(c) and table 2. the five most published documents based on their countries are those from China, India, Iran, United States, and South Korea. China, as the most productive country with a link 27 and total link strength 227, followed by India with 28 link and 169 total link strength, Iran, United States and South Korea with the total link strength 114, 71, and 59 accordingly. Moreover, the leading author is from China, signifying that China has the highest publication rate about environmental and public health issues, as well as deteriorating water pollution problems (Ola et al., 2023). The thickness of the line connecting the two countries is supported by the frequency of collaboration in publications. The strongest collaborations are formed between India and South Korea, succeeded by a significant partnership between China and Canada, as well as between China and South Korea. Additionally, it is evident that China has several cooperation with countries such as Hong Kong, Singapore, Taiwan, Thailand, Saudi Arabia, Malaysia, and Japan. The majority are located in Asia, particularly a Chinese research group specialising in the use of CQDs, notably the group from Shuang, Dong, Gong, and Gong, which has established robust collaborations with other countries in Asia.

Table 2. Most productive author in the field

Authors	Country	Document	Percentage	Total link strength
Mathew, B.	India	21	7.6	175
Shuang, S.	China	21	7.6	164
Dong, C.	China	19	6.9	143
Gong, X.	China	15	5.4	154
Dong, C.	China	14	5.1	132
Hasanzadeh, M.	Iran	14	5.1	102
Liu, Y.	China	14	5.1	110
You, T.	China	14	5.1	87
Ensafi, A.A.	Iran	13	4.7	96
John, B.K.	Iran	13	4.7	77
Rezaei, B.	Iran	13	4.7	67
Shadjou, N.	Iran	13	4.7	55
Kim, K.H.	South Korea	12	4.3	64
Korah, B.K.	India	12	4.3	21
Lee, Y.R.	South Korea	12	4.3	56
Ma, Q.	China	12	4.3	78
Hou, C.	China	11	3.9	86
Huang, X.	China	11	3.9	98
Li, L.	China	11	3.9	87
Li, Z.	China	11	3.9	69

### 3.2 Contribution of journals and subjects

From 2014 to 2024, a total of 3,427 articles related to the application of CQDs for detection of antibiotic and heavy metals were published in 156 journals. The top 10 journals over the past decade were analysed for their contribution to the total number of articles, which represents the highest productivity in this research field in Fig. 2(a). The journal with the most published is *Spectrochimica Acta Part A Molecular and Biomolecular Spectroscopy* with 154 published articles (4.5% of 3,427), followed by *Sensors and Actuators B Chemical* with 126 articles (3.7%), *Biosensors and Bioelectronics* with 92 published articles (2.7%), *Talanta* with 82 articles (2.4%), and *Analytical Chimica Acta* with 81 articles (2.3%). During 2017-2018, several new journals, including *New Journal of Chemistry*, *Microchemical Journal*, and *Food Chemistry*, published articles pertinent to this subject. This signifies that associated subjects begin to evolve swiftly during that year. Significantly, the majority of journals experienced rapid publication growth post-2018, while *Pectrochimica Acta Part A*

Molecular and Biomolecular Spectroscopy, *Microchemical Acta*, *RSC Advances*, and *Talanta*, which concentrate on chemistry, material sciences, engineering, and various multidimensional techniques and detection methods like spectroscopy, did not follow this trend. This suggests that the detection of antibiotics and heavy metals utilizing CQDs may be focal points and priority in the initial phase of study, as further corroborated by the textual analysis in Section 4.4.

The publication analysis revealed that CQDs were studied across 24 subjects, indicating that this topic is interdisciplinary research topic. As seen in Fig. 3(b), Chemistry is the most relevant subject (2,131 publications), followed by Material Science (1,203 articles), Engineering (931 articles), Physics and Astronomy (910 articles), and Chemical Engineering (708 articles). The primary category of Chemistry pertains to the identification of antibiotics and heavy metals, which are utilized in various procedures and entail distinct chemical reactions. The domains of Material Science encompass numerous investigations pertaining to the synthesis and characterisation of CQDs. Approximately 45% of the issues have appeared in the past five years, demonstrating a growing tendency in transdisciplinary research over time.

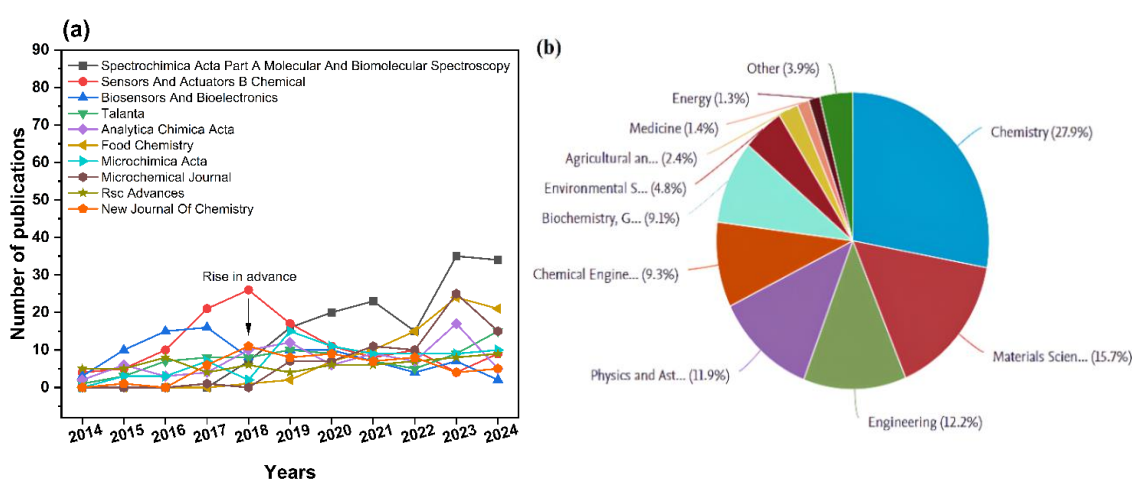


Fig. 3. (a) Contribution of journals, and (b) Top categories of Scopus subject area

### 3.3 Analysis of the most cited articles

Significant articles typically garner substantial attention and interest, as evidenced by citation metrics. Widely referenced papers offer valuable insights regarding the subject. Intense citation surges for specific articles may signify a significant discovery, hence playing a vital role in advancing a particular field (Senthil et al., 2024). A list of highly cited articles is crucial to this work, since it includes significant publications regarding the application of CQDs for the detection of antibiotics and heavy metals. Table 3 presents the ten most often cited articles pertaining to the research areas. Wang's publication titled "Carbon Quantum Dots: Synthesis, Properties, and Applications" has garnered the highest citation count, with 121,308 citations, as indicated in the feature article (Wang & Hu, 2014). This paper offers significant insights into the manufacture and utilization of CQDs for the detection of antibiotics and heavy metals. The 2014 publication acknowledges the substantial impact of researchers on the pace of research advancement. Pomerantseva's research that published in 2019, titled "Energy Storage: The Future Enabled by Nanomaterials," has garnered considerable attention, evidenced by 1,983 citations, underscoring its significance in the field (Pomerantseva et al., 2019). A study by Prasad et al. highlighted the significance of advancements in nanotechnology for addressing challenges and fostering open research. This research elucidates how nanotechnology, namely carbon-based nanomaterials (CQDs), might function as sensors for assessing soil quality in agricultural fields, thereby promoting the health of crops (Prasad et al., 2017). Ding et al. investigate CQDs as a potential framework for applications such as chemical sensors, biosensors, pharmaceuticals, and

medical uses. This research has developed CQD ratio metric biosensors for the detection of copper and fluorescent probes for pH measurement. The probes possess high-resolution fluorescence and are effective for real-time monitoring of targets (Ding et al., 2014). Furthermore, this study also initiates the application of CQDs as probes for the detection of pollutants, including heavy metals. Investigations into CQDs as a sensor are currently going on. Li, M. et al. review an article that encapsulates fundamental knowledge on CQDs and GQDs, subsequently concentrating on their current applications in sensing, and concluding with an exploration of prospective research avenues for CQD- and GQD-based nanomaterials in this domain (Li et al., 2019). In addition, Sun and Lei has published a significant study about fluorescence CQDs and their sensing applications that has been published in 2017, received more than 744 citations (Sun & Lei, 2017). The analysis of the extensively referenced publications indicates that researchers have demonstrated considerable interest in CQDs as sensors for prospective advancements, especially in the identification of antibiotics and heavy metals.

Table 3. Top 10 most cited articles

Rank	Document title	Authors	Year	Journal title	Number of citations
1	Carbon quantum dots: Synthesis, properties and applications	Wang, Y. & Hu, A.	2014	Journal of Materials Chemistry C	121,308
2	Energy storage: The future enabled by nanomaterials	Pomerantseva, E. et. al	2019	Science	1,983
3	Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives	Prasad, R. et. al	2017	Frontiers in Microbiology	1,049
4	Functional surface engineering of C-dots for fluorescent biosensing and in vivo bioimaging	Ding, C. et. al	2014	Accounts of Chemical Research	980
5	Review of carbon and graphene quantum dots for sensing	Li, M. et. al	2019	ACS Sensors	845
6	Fluorescent carbon dots and their sensing applications	Sun, X. & Lei, Y.	2017	TrAC - Trends in Analytical Chemistry	744
7	High- k Gate Dielectrics for Emerging Flexible and Stretchable Electronics	Wang, B. et. al	2018	Chemical Reviews	650
8	Nitrogen and sulphur co-doped carbon dots with strong blue luminescence	Ding, H. et. al	2014	Nanoscale	555
9	Electrochemical sensing of heavy metal ions with inorganic, organic and bio-materials	Cui, L. et. al	2020	Biosensors and Bioelectronics	520
10	Carbon quantum dot-based nanoprobe for metal ion detection	Gao, X. et. al	2016	Journal of Materials Chemistry C	485

### 3.2 Research progress overview

Keyword analysis in a bibliometric study is crucial for visualizing and examining the interrelationships among keywords through co-occurrence in VOSviewer software. Numerous scholars employ term co-occurrence analysis to delineate the current and prospective trajectories of scientific inquiry within specific domains. Nonetheless, this

activity is arduous and time-consuming due to its manual nature (Wang et al., 2023). Figure 4 illustrates the frequency of distinct terms in diverse publications. The keywords "semiconductor carbon dots" appears 138 times, while "carbon" follows with 112 occurrences, "gas detectors" with 72 occurrences, carbon dots (65), and fluorescence (58). The keywords of "carbon dots" and "semiconductor carbon dots" reveal research on carbon quantum dots, and many studies conducted experiment in synthesis of carbon dots or carbon quantum dots. The keyword "fluorescence" is the one of the parameters of main properties of CQDs. Other keywords related with this topic are "gas detectors", "chemical sensors", "fluorescent sensors", "metal ion", "photodetector", "biosensing", "metals", "probe", "cadmium compound", and "mercury compound" indicated that most frequently occurring keywords in documents related with the topic of CQDs for detection antibiotic and heavy metals.

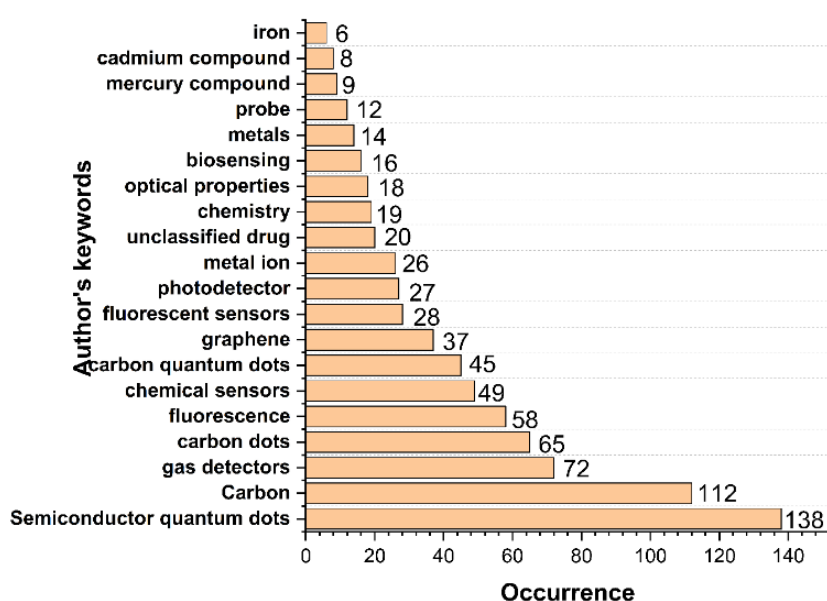


Fig. 4. The occurrence of keywords in publication related

A total of 266 pertinent keywords with 19,358 link strength were retrieved from the titles, keywords, and abstracts of publications to construct the co-occurrence network using VOSviewer software. In figure 5(a), the overlay depiction illustrates that the bubble size correlates with the frequency of occurrences, while the colours signify unique clusters identified using co-occurrence analysis. The average emergence time can be determined using network visualisation, as demonstrated in figure 5(b). The collected keywords can be categorised into five groups, represented by five colours (red, green, yellow, blue, and purple), indicating the various stages of research advancement over the past decade. The size of the circle indicates the number of occurrences.

The first stage is synthesis and properties of CQDs, represented with red color accommodates 925 total link strength. In the first cluster, "quantum dots" (704), "limit of detection" (349), "chemistry" (339), "particle size" (218), "procedures" (217), "electrochemical analysis" (90), "chemical analysis" (88), "electrochemical technique" (84) has the highest frequency, which is closely related with synthesis and characteristics of CQDs. Interestingly, in the cyan cluster in figure 4, these phrases emerged predominantly between 2020 and 2021, signifying that the synthesis and properties of CQDs are critical components in the sector, typically utilised in the preliminary research phase. The initial phase commenced in the 1990s when scientist Mounji G. Bawendi and colleagues synthesised quantum dots with tuneable sizes and compositions for the first time (Acharya et al., 2024). In the initial stage, the primary focus was on optimising the critical factors that influenced the efficacy of the CQD synthesis procedure. The important properties of CQDs in

first stage is "particle size". In the synthesis process, particle size of CQDs can be controlled by varying the heating time in the presence of a catalyst. Synthesis process of CQDs often exhibit a wide range of particle size due to forming carbon particles of varying dimensions, and will show different effect of quantum confinement (Bacon et al., 2014).

The second stage of development in the modified of fluorescent CQDs succeeded the first stage from 2021 to 2022. This stage is depicted as a green cluster with a total link strength of 660. The typical words were "fluorescence" (660), "carbo dots" (580), "metal ions" (315), "doping" (302), "photoluminescence" (235), "synthesised" (135), "fourier transform infrared spectroscopy" (108), "fluorescent sensors" (99), "quenching" (73), and "fluorescence spectroscopy" (47). Fluorescence is the most frequently utilised keyword in this context, indicating its significance in CQDs. CQDs are a category of robust fluorescent nanoparticles characterised by superior optical characteristics (Vibhute et al., 2022). The metal ions are one of the ways to enhance the fluorescence of CQDs. Doping CQDs with metal ions can enhance their fluorescence and photoluminescence characteristics, hence increasing their sensitivity for applications involving CQDs (Lin et al., 2018). Many researchers have developed the fluorescence of CQDs. This can be seen from the keywords "fluorescent sensors", "quenching", and "fluorescence spectroscopy". These keywords show that fluorescent CQDs have potential application in the fields of sensing, such as biochemical sensing (Mankoti et al., 2024), heavy metal ions sensing (Soni et al., 2024), delivery drugs (Gurunathan et al., 2018), photocatalysis (Chu et al., 2019), and other field related.

The third phase involves the implementation of CQDs, commencing in 2022. The total link strength at this level is 1579, with the greatest frequency being "semiconductor quantum dots" and "photon" (286). The final stage comprises the most commonly utilised terms, as indicated by the co-occurrence network. This phase is crucial for the advancement of CQDs applications, as evidenced by the significant increase of publications in 2022, indicating substantial growth. The other keywords related in this stage is "graphene quantum dots" (329), "photo detector" (265), "optical properties" (213), "light absorption" (169), "multiwalled carbon nanotube" (103), and "infrared detector" (100). These keywords imply the research important for application of CQDs especially for detector.

The fourth level, indicated by the yellow cluster, is comprised of CQDs for sensing purposes. Following over 30 years of development, CQDs have garnered increasing interest from both basic and applied perspectives. Since 2022, research into CQDs as detectors has begun to expand. The keywords characterizing this stage exhibit a total link strength of 906, with the most prevalent keywords being "detectors" (906), "chemical sensor" (669), "chemical detection" (486), "ii-vi semiconductor" (379), "gas sensor" (330), "ammonia" (266), "sulfur compound" (157), "chemical structure" (144), and "sensing mechanism" (100). Consequently, the predominant subject inside the yellow cluster remained associated with research pertaining to carbon quantum dots, carbon dots, and carbon. "Detector," "chemical sensor," and "chemical detection" are the most prevalent terms associated with the sensing applications of CQDs. CQDs have been utilized in chemical sensing applications to identify heavy metals, given their substantial consequences for health and environmental concerns (Acharya et al., 2024). CQD-based sensors are extensively utilized for various gas detection applications, including the identification of volatile organic compounds (VOCs) and greenhouse gases, among others (Swathilakshmi & Anandhan, 2022).

Finally, the fifth stage is Fluorescent CQDs for detection represent in purple color. The keywords shown in purple color are relatively small section with total link strength 704, where "fluorescent dye" has the highest frequency (178). The purple cluster contain: "spectrofluorometry" (153), "colorimetry" (113), "quantum yield" (104), "low detection limit" (65), "pH" (64), and "drug delivery" (53). This section focuses on the development of fluorescent CQDs for detection purposes. The utilization of CQDs in detector applications is a prominent topic from 2022 to 2024. Recent research indicates that CQDs can serve as fluorescent probes for the identification of environmental contaminants, including heavy metals and antibiotics. All criteria pertinent to identifying the contaminant, including "quantum yield," "low detection limit," "colorimetry," and "spectrofluorometry," have been associated with the keyword in this section. The five typical steps outlined above may serve

as valuable guidelines for researchers to assess the progress of CQDs in the detection of antibiotics and heavy metals. Subsequently, the timing of research interventions and the trajectory of research may be determined by the developmental phase of the research domain.

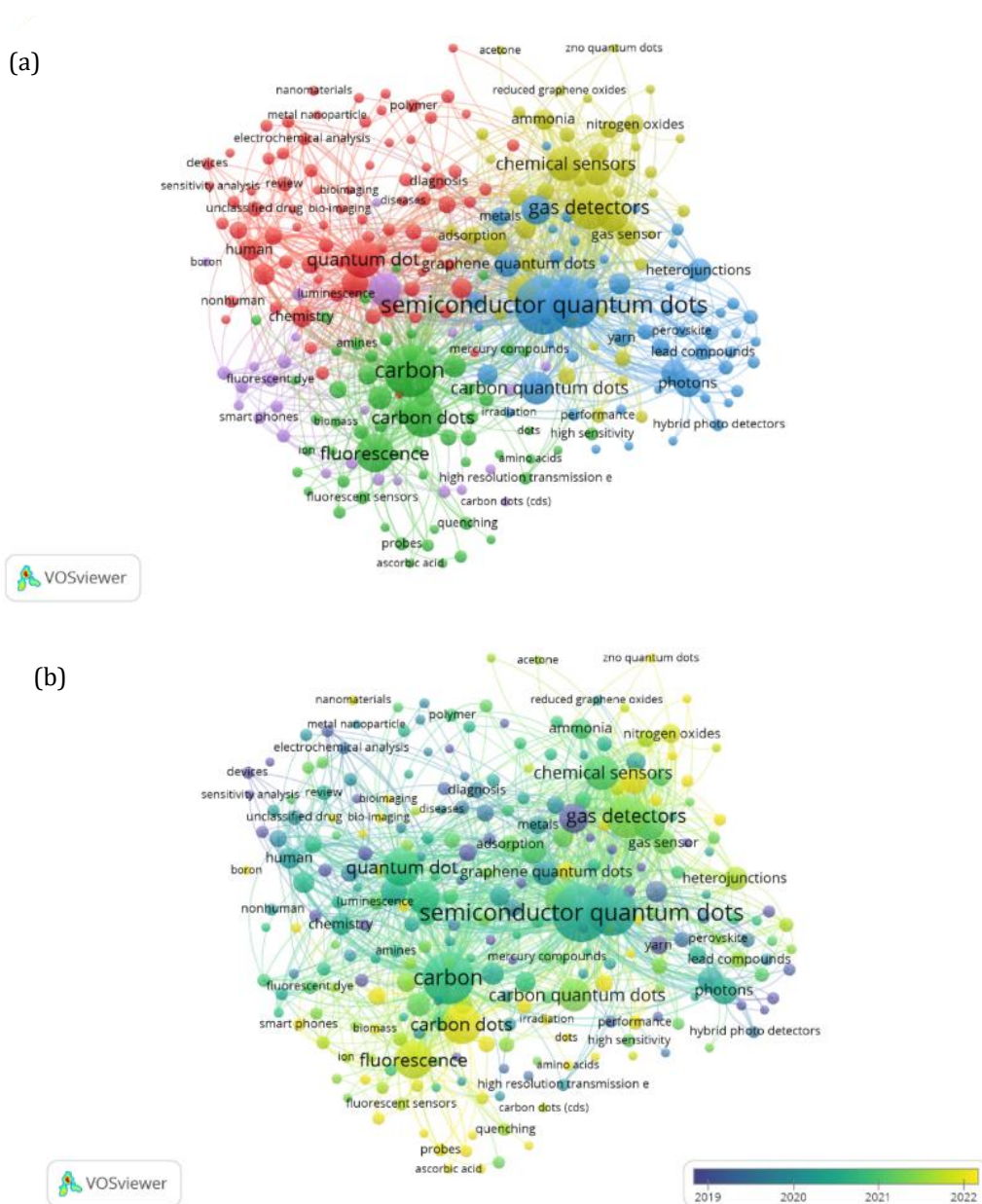


Figure 5. (a) Co-occurrence network visualization, and (b) Average emerging time in overlay visualization

Semiconductor carbon quantum dots, carbon quantum dots, fluorescence, gas detectors, chemical sensors, metals, lead compounds, and carbon are frequently referenced in this discussion, as illustrated in Fig. 6. To support this analysis, the relationships between keywords and their corresponding research are clarified. The strength of these connections varies, enabling the differentiation and categorization of terms. Over the past decade, keywords related to carbon quantum dots and their applications in detection were systematically analyzed in the literature, focusing on their link strengths as recorded in the Scopus database. This analysis examined the frequency of keyword occurrences and the robustness of their connections, particularly from 2019 to 2022. Word cloud visually represents the authors' most significant keywords associated with carbon quantum dots. The size of each word in the cloud reflects its importance, frequency of occurrence in the



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Conceptualization, methodology, data collection, formal analysis, visualization, and writing—original draft preparation were carried out by the author collaboratively. The author contributed to reviewing and editing the manuscript and approved the final version for publication.

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The authors declare no conflict of interest.

### Declaration of Generative AI Use

During the preparation of this work, the author used Grammarly and Quillbot to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

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### Biographie of Author

**Fatkhiyatus Sa'adah**, Doctoral Program of Environmental Science, School of Postgraduate Studies, Universitas Diponegoro, Semarang, Central Java 50241, Indonesia.

- Email: [fatkhiyatussdh@gmail.com](mailto:fatkhiyatussdh@gmail.com)
- ORCID: N/A
- Web of Science Researcher ID: N/A
- Scopus Author ID: N/A
- Homepage: N/A