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Research Trends on Cobalt-Doped Hydroxyapatite: Bibliometric Analysis and Emerging Applications

Tren Penelitian tentang Hidroksiapatit yang Didoping Kobalt: Analisis Bibliometrik dan Aplikasi yang sedang Berkembang

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Abstract

This bibliometric review is on 98-article (2015-2025) review of cobalt-doped hydroxyapatite (Co-HAP) that emphasizes the trends in catalysis, biomedicine, and environmental remediation. The study is based on Scopus data and bibliometric tools to find out the key research findings, the most active contributors, and the most popular journals. Commonly reported methods of characterization include XRD and SEM. The results highlight the growing global cooperation and the continuous growth in publications, which indicates the continued presence of innovation and interdisciplinary applicability of Co-HAP studies.

Keywords*: Co-HAP, anti-cancer, environmental remediation, bibliometric*

Abstrak

Tinjauan bibliometrik ini adalah tinjauan terhadap 98 artikel (2015-2025) mengenai hidroksiapatit yang didoping kobalt (Co-HAP) yang menekankan tren dalam katalisis, biomedis, dan remediasi lingkungan. Studi ini didasarkan pada data Scopus dan alat bibliometrik untuk mengetahui temuan penelitian utama, kontributor paling aktif, dan jurnal yang paling populer. Metode karakterisasi yang sering dilaporkan meliputi XRD dan SEM. Hasilnya menyoroti meningkatnya kerja sama global dan pertumbuhan publikasi yang terus berlanjut, yang menunjukkan keberlanjutan inovasi dan penerapan lintas disiplin dari studi Co-HAP.

Kata Kunci: *Co-HAP, anti-kanker, remediasi lingkungan, bibliometric.*

INTRODUCTION

Research output and development in materials science have accelerated, necessitating in-depth knowledge and sustainability of innovations in materials science, particularly in relation to compounds such as cobalt hydroxyapatite

(Co-HAP) (Lim et al. 2025; Rocha et al. 2022). Co-HAP publications have continued to rise in the past century, as there has been an increase in the varied uses of Co-HAP in catalysis, biomedical engineering, and environmental remediation (Munirathinam, Pham Minh, and Nzihou 2020a; Yang et al. 2022). Innovations are necessary to deal with the current issues in the world, like the reduction of pollution, improvement of health, and creation of efficient catalysts. Co-HAP has generated interest because of its special physicochemical characteristics, such as biocompatibility, catalysis, and its applications in multifunctional applications (Doan et al. 2022a; Yook et al. 2023).

Over the past few years, there have been many works synthesizing Co-HAP and its derivatives by many different chemical pathways as a result of the need to focus on eco-friendly strategies and performance. The clusters of 98 research articles published between 2015 and 2025 are identified through bibliometric mapping. The literature search pattern (seen in keywords) indicates that people not only concentrated on the area of pollutant degradation via photocatalysis, but expanded to more extensive biomedical fields, i.e., anti-cancer treatments, which emphasizes the interdisciplinary nature of Co-HAP studies (Bharali et al. 2023; Rocha et al. 2022).

The most widely used methods of characterization are X-ray diffraction (XRD), FTIR, and scanning electron microscopy (SEM) to explain the crystal structure and morphology (Kareem et al. 2025; Sadetskaya et al. 2021a). Collaboration between nations leading in research, like China, India, and Iran, has coupled the strength of the scientific community in Co-HAP, and the number of publications has continued to rise after 2018. Such influential journals as Ceramics International and Applied Catalysis B: Environmental have been used as leading avenues of spreading findings. Systematic bibliometric review provides an overview of the current knowledge and the opportunities of the Co-HAP synthesis, properties, and applications, and guides sustainable and meaningful material development based on the vast data provided in the Scopus database (Irfan, Jeshurun, and Mallikharjuna Reddy 2025; Karunakaran et al. 2021; Mondal et al. 2023).

METHODOLOGY OF REVIEW

A systematic approach was used to conduct this bibliometric review to identify, collect, and analyze relevant research articles in the Scopus database (Moral-Muñoz et al. 2020). The initial search employed the query (TITLE-ABS-KEY (Co-HAP) and TITLE-ABS-KEY (synthesis OR doping OR catalytic OR biomedical), with no years specified, to ensure all papers on the Co-HAP synthesis method and its applications were captured. Scopus was chosen because it contains a large number of high-quality scientific journals and credible data (Baas et al. 2020). However, some articles published in smaller or local journals, or in languages other than English, might not be identified (Walpole 2019). Each article was carefully reviewed by reading its title, abstract, and full text when necessary, to confirm its relevance to Co-HAP synthesis, use, and properties. Only relevant studies were retained. Maps showing relationships among keywords, authors, and countries were created using VOSviewer software. Furthermore, Biblioshiny in R-Studio was employed to identify primary research areas and collaboration networks. VOSviewer and Biblioshiny are free accessible with compact analysis to provide a clear picture of the current state and development of research based on indexed publication, so the trend and state of the art highlighting key research themes and the interactions among the references data could be clearly and objectively described (Megha et al. 2023).

DATA COLLECTION AND SELECTION

The search used targeted keywords to collect the data that was used in this review; the systematic search in the Scopus database was conducted to cover the entire scope of the research on cobalt-doped hydroxyapatite (Co-HAP). All obtained articles were filtered by their titles and abstracts, and the full texts were checked where appropriate, to ensure that they were related to Co-HAP synthesis, properties, and uses. All studies that dealt directly with these areas were selected to be analyzed. Bibliometric tools were used to trace the trends and research collaborations, and most of the articles offered all available bibliometric data, which makes the analysis reliable even though there were some minor data gaps at times (Subramanyam 1983). This methodology brought a clear and strong base to assess the state of Co-HAP research.

DISCUSSION

440 papers were searched for Co-HAP, and 98 research articles focusing on Co-HAP and other transition metals combining with cobalt were synthesized through chemical processes and mapped using VOSViewer, whereby 29 keyword items were clustered into 3 clusters, 330 connections are depicted in **Figure 1**, and the number of links with strength was 1016. In this map, the new studies (2021-2022) are painted yellow, and older studies (2020)

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are painted with blue to green colors. Such keywords as application, HAP, activity, catalyst, and time are bigger, indicating that they were the ones extensively covered in the 98 papers. It is also possible to see other keywords like biocompatibility, cell, coating, and implant, which show that

centered on the pollutant-degrading catalytic activity of Co-HAP. The similar occurring words as toxicity, biocompatibility, and cell, reflect the prevailing trend of the researchers on the biocompatibility of Co-HAP by conducting tests and the medical applications of Co-HAP, like anti-cancer. The keywords like X-ray diffraction, electron microscopy, and SEM indicate that diffraction of Co-HAP is normally characterized by XRD and SEM to determine crystal structure and morphology (Amedlous et al. 2022; Dobosz, Małecka, and Zawadzki 2018).

Table 1 shows the data quality of the 98 papers that were used for Co-HAP VOSviewer analysis. Most of the important information, like abstract, author, title, journal, language, year, and citation, is complete, so it's marked excellent. There are a few missing parts like DOI (1%), recent studies on Co-HAP do not concentrate on photo-catalytic activity solely, but also on its biomedical use (Huang et al. 2015). There are also terms such as Co-HAP, catalyst, and activity that are closely related to each other, and this shows that lots of research works are

Keywords Plus (6%), Keywords (7%), and the corresponding author (8%), but these are still good and won't affect the analysis much. However, cited references and science categories are missing in all papers (100%), so they are marked as completely missing.

98 research papers were reviewed from 2015-2025 based on 75 sources. The number of authors is 459, and there are 5 co-authors per paper, and 12.24% international cooperation. There is only 1 single-author paper. The articles contain 344 keywords; however, no reference information. The mean age of documents is 4.22 years, with every paper receiving an average of 22 citations. The publications grow at the level of 6.25% per year, which means there is no decline in the research efforts on this topic.

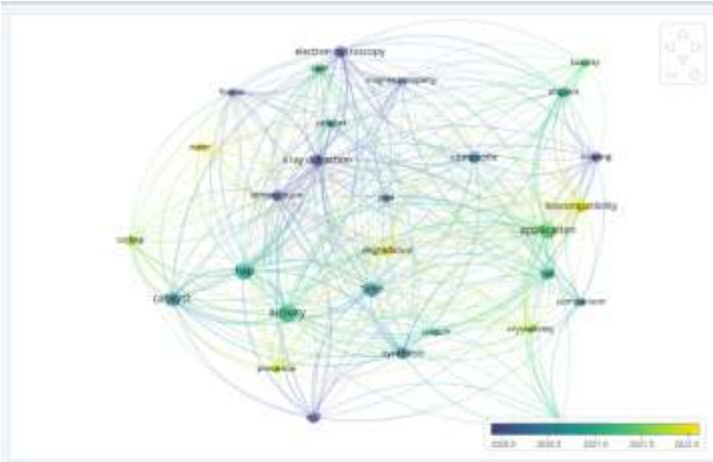

Fig 1. Connection of the keywords for Co-HAP

Table 1. Data quality of collected papers

Metadata	Description	Missing counts	Missing %	Status
AB	Abstract	0	0.00	Excellent
CI	Affiliation	0	0.00	Excellent
AU	Author	0	0.00	Excellent
DT	Document Type	0	0.00	Excellent
SO	Journal	0	0.00	Excellent
LA	Language	0	0.00	Excellent
PY	Publication Year	0	0.00	Excellent
TI	Title	0	0.00	Excellent
TC	Total Citation	0	0.00	Excellent
DI	DOI	1	1.02	Good
ID	Keywords Plus	6	6.12	Good
DE	Keywords	7	7.14	Good
RP	Corresponding Author	8	8.16	Good
CR	Cited References	98	100	Completely missing
WC	Science Categories	98	100	Completely missing

Figure 2 shows the number of scientific articles that have been provided in this graph on an annual basis between the years 2015 and 2025. The number of articles published per year was approximately 7 in 2015 and reduced to 3 in 2017. Subsequently, the number of publications began to grow, peaking in 2020 with 16 articles. The number, however, decreased again to approximately 10-11 articles in 2021 and 2022, and again to 8 in 2023. There was again an increase in 2024 to 12 articles, but in 2025, it was slightly lower at 11. In general, there are ups and downs in the trend, with the highest date being 2020.

The information in Fig 2 indicates the quantity of the yearly number of publications between 2015 and 2025 on Co-HAP. Initially, there was slow research, and only 13 papers were published from 2015 to 2017. There are total of 8 and 10 papers in 2018 and 2019, respectively, with a sharp rise to 16 papers in 2020, indicating a lot of attention paid to this topic during this year.

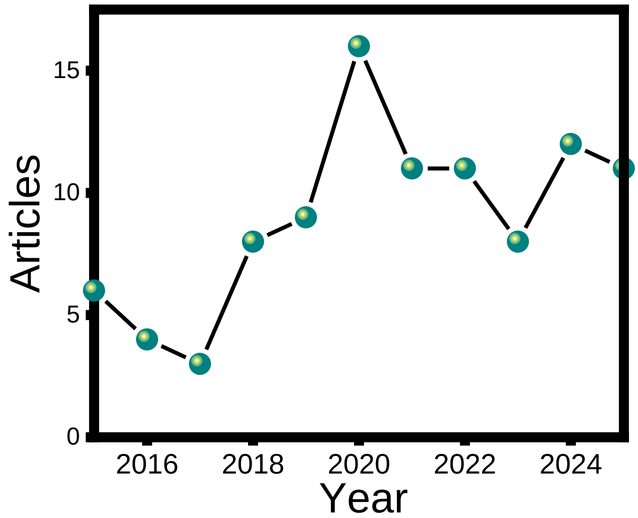

Fig. 2. Annual scientific publication graph of papers from 2015 to 2025

Fig.3 Main information of searched papers

Fig.3 shows the progress of publication between 2021 and 2022, the publications remained regular at 10 articles per year, and in 2023, it has reduced by a very small margin to 8. Nevertheless, there was growth in the publications in 2024 and 2025 to 12 and 11 articles, which are indicative of stable and consistent research in the field. Altogether, this table indicates that the studies on Co-HAP are becoming more frequent, and this domain has still been actively developing since 2018, and there are steady publications every year. Based on Fig. 3, the majority of the 98 papers on Co-HAP doping published in journals are listed. Fig. 4 presents the details on published paper. It exhibits that most relevant topic, as Ceramics International is the best journal with 7 papers. The 4 papers about Materials Science and Engineering C signify that this is also an important scientific area to deal with materials and biomedical investigations that are to be identified by Co-HAP.

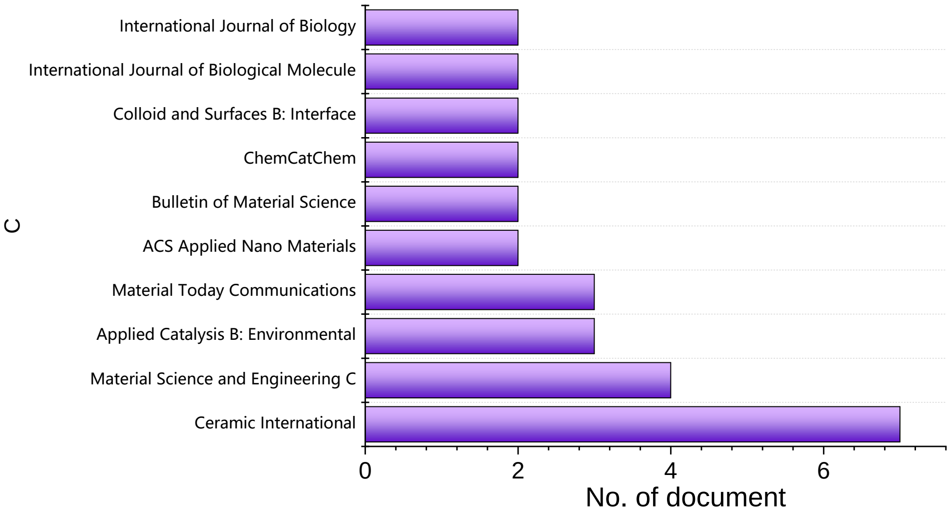

Figure 4. Relevant source on Co-HAP

Each has 3 papers in Applied Catalysis B: Environmental and Materials Today Communications, which shows the interest of my topic in photo-catalysis and advanced materials. There are also several other journals with Co-HAP studies, with 2 articles each: ACS Applied Nano Materials, Bulletin of Materials Science, CHEMCATCHEM, Colloids and Surfaces B: Bio interfaces, International Journal of Biological Macromolecules, and International Journal of Hydrogen Energy, reflecting the variety of research topics in which published Co-HAP studies are found. All in all, this chart indicates that my research field is popular in materials, catalysis journals.

Fig. 5 shows which journals have the most influence in my Co-HAP research area based on citations. Applied Catalysis B: Environmental has the highest impact with 250 citations, followed by Ceramics International with 245, and Materials Science and Engineering C with 223 citations. The Journal of Hazardous Materials also has a strong impact with 173 citations. Other journals like Colloids and Surfaces B and the Journal of Biomaterials Science each have 90 citations, while journals like ACS Applied Nano Materials

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and Dental Materials have around 55 citations. This means these journals are not only publishing papers on my topic but are also highly cited, showing they are important sources in this research area.

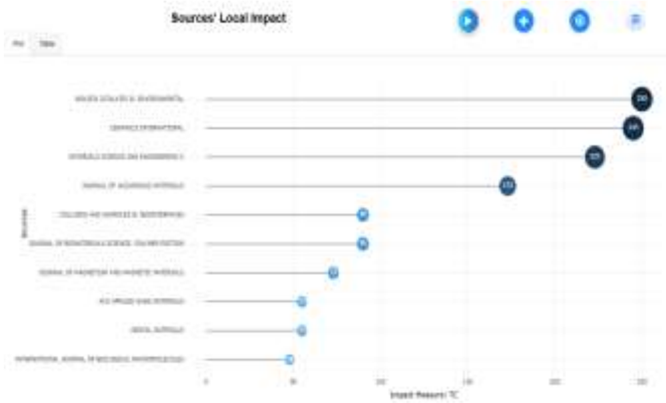

Fig.5. Local impacts of research journals

Fig. 6 gives information about the production of authors with reference to the Co-HAP study over a period. The number of publications each of the authors has contributed to is one per particular year, which is displayed in column "freq". AGARWAL T published four papers in 2015, 2016, and 2021, and the number of citations as well as the number of citations per year were 104, 129, and 38, respectively, and the total figures of citations per year (TCpY) were 9.455, 12.900, and 7.600. ASGHARI E was a contributor in 2024 and 2025, and TCs were 11 and 6, whereas TCpYs were 5.500 and 6.000. BANERJEE I was published in 2015, 2016, and 2021, and have TC values of 104, 129, and 38, and TCpY of 9.455, 12.900, and 7.600. BHATTACHARJEE A wrote papers in 2020 and 2025, which have TC of 35 and 0, and TCpY of 5.833 and 0.000.

The chart shows the most relevant affiliations based on the number of articles published. Chung Shan Medical University has the highest number of publications, with 16 articles. This is followed by the National Institute of Technology with 13 articles, and Université de Toulouse with 11 articles.

Both Guilin University of Technology and the University of the Basque Country UPV/EHU have published 10 articles each. Busan and Guangzhou

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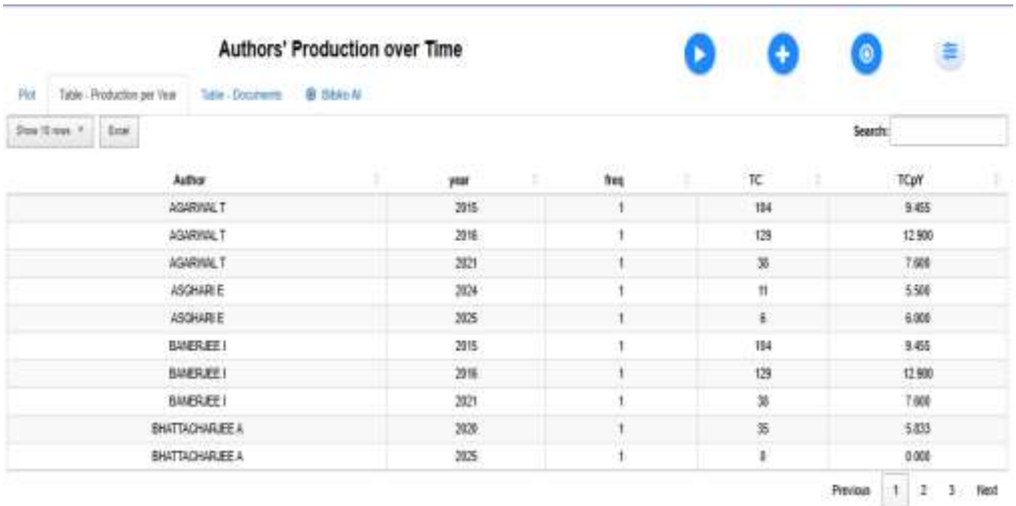
University each contributed 9 articles. Northwest Normal University and Sichuan University published 8 articles each. Lastly, the Complex Structure of Surgical Sciences and Technologies has 7 articles.



Authors' Production over Time

Plot | Table - Production per Year | Table - Documents | Biblio AI

Author	year	freq	TC	TCpY
AGARWAL T	2015	1	104	9.455
AGARWAL T	2016	1	129	12.900
AGARWAL T	2021	1	38	7.600
ASGHARI E	2024	1	11	5.500
ASGHARI E	2025	1	6	6.000
BANERJEE I	2015	1	104	9.455
BANERJEE I	2016	1	129	12.900
BANERJEE I	2021	1	38	7.600
BHATTACHARJEE A	2020	1	35	5.833
BHATTACHARJEE A	2025	1	0	0.000

Previous 1 2 3 Next

Fig.6 Productive authors on Co-HAP

The number of research documents published by the corresponding authors from various countries shows that the largest number of documents is observe in China, and then in India and Iran. There are smaller contributions by Malaysia, Egypt, Korea, Poland, and Turkey. Brazil and France occupy the last position in this list. The contributors of papers within the same country are reflected by blue bars (SCP), whereas the pink bars (MCP) signify international collaboration.

Both types of papers are also found in China, India, and Korea, meaning they also worked with other nations. Papers published by other countries were mainly not based on international collaboration.

To display the most cited countries, the table lists these countries, ranked by total citations (TC) and average article citations. The maximum number of total citations was in India, which had 466 citations, and the average of the citations per article was 33.30. China comes next with a total number of 407 citations with an average of 22.60. France occupies the top position with number total of citations being 168 citations and a citations per article of 56.00. The total number of citations in Spain is 129, where the average is 43.00. Poland got 105, and the average is 26.20, whereas Iran got 90, and the average is 12.90. Portugal has 87 citations of with there is an average of 43.50. The three countries, Turkey, Italy, and Korea, have 75, 74, and 60 citations, respectively, with averages of 18.80, 24.70, and 15 citations per article.

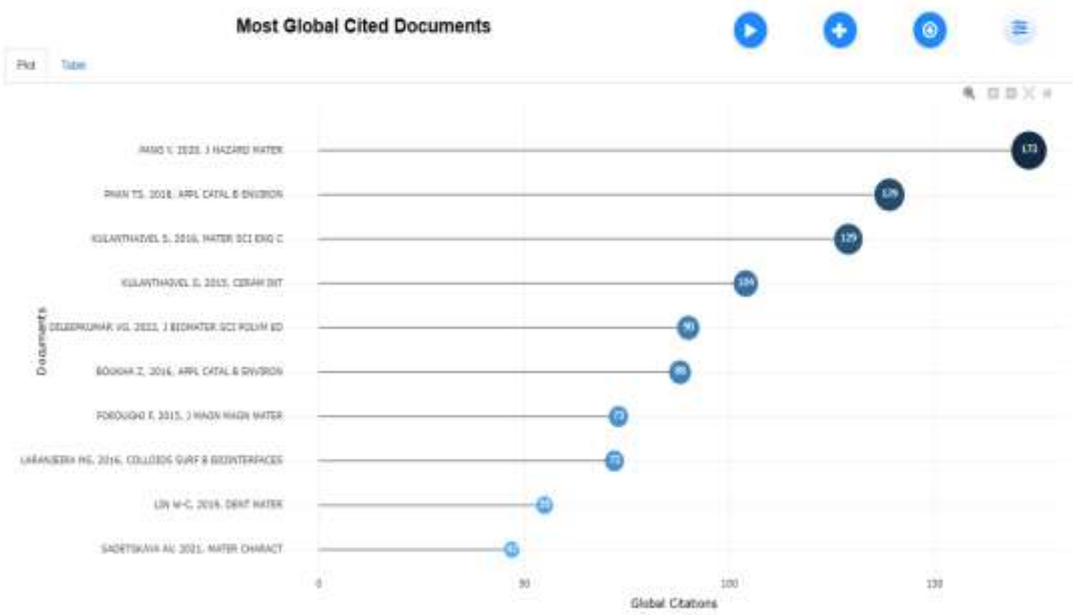


Fig 7. Most globally cited papers for Co-HAP

Fig. 7 shows the most globally cited documents based on the number of global citations. The most cited document is by Pang Y, 2020, published in Journal of Hazardous Materials, with 173 citations. The second is by Phan TS, 2018, in Applied Catalysis B: Environmental, with 139 citations. KulanthaiVel S has two papers from 2016 and 2015 with 129 and 104 citations, respectively. Dileepkumar VG, 2022, received 90 citations, followed by Boukha Z, 2016, with 88 citations. Foroughi F, 2015, has 73 citations, and Laranjeira MS, 2016, has 72. Lin W-C, 2019, received 55 citations, while Sadetskaya AV, 2021, has 47 citations. Details on the papers are presented in Table 2.

Table 2. Top cited papers

Authors	Paper Title	Citations
1. Pang , Y., Kong, L., Chen, D., Yuvaraja, G., Mehmood, S. (2020) (Pang et al. 2020)	Facilely synthesized cobalt-doped hydroxyapatite as a hydroxyl-promoted peroxymonosulfate activator for the degradation of Rhodamine B.	173
2. Phan, Thanh Son, Abdoul Razac Sane, Bruna Rêgo De Vasconcelos, Ange Nzihou, Patrick Sharrock, Didier Grouset, and Doan Pham Minh (Phan et al. 2018)	Hydroxyapatite-supported bimetallic cobalt and nickel catalysts for syngas production from dry reforming of methane.	139
3. Kulanthaivel, S.; Roy, B.; Agarwal, T.; Giri, S.; Pramanik, K.; Pal, K.; Ray, S. S.; Maiti, T. K.; Banerjee, I. (Kulanthaivel et al. 2016)	Cobalt-doped proangiogenic hydroxyapatite for bone tissue engineering application.	129
4. S. Kulanthaivel, U. Mishra, T. Agarwal, S. Giri, K. Pal, K. Pramanik, Indranil Banerjee (Kulanthaivel et al. 2015)	Improving the osteogenic and angiogenic properties of synthetic hydroxyapatite by dual doping of bivalent cobalt and magnesium ions.	104
5. DileepKumar, Mysore Santosh Sridhar, Pornanong Aramwit, Valentina K. Krut'ko, Olga N. Musskaya, Ilya E. Glazov (DileepKumar et al. 2022)	A review on the synthesis and properties of hydroxyapatite for biomedical applications.	90
6.Zouhair Boukha, Jonatan González-Prior, Beatriz de Rivas, Juan R. González-Velasco, Rubén López-Fonseca, José I. Gutiérrez-Ortiz (Boukha et al. 2016)	Synthesis, characterisation and behaviour of Co/hydroxyapatite catalysts in the oxidation of 1, 2-dichloroethane	88
7.Firoozeh Foroughi, S.A. Hassanzadeh-Tabrizi, Jamshid Amighian (Foroughi et al. 2015)	Microemulsion synthesis and magnetic properties of hydroxyapatite-encapsulated nano $CoFe_2O_4$	73
8. Marta S Laranjeira, Ana Moço, Jorge Ferreira, Susana Coimbra, Elísio Costa, Alice Santos-Silva, Paulo J Ferreira, Fernando J Monteiro 7 (Laranjeira et al. 2016)	Different hydroxyapatite magnetic nanoparticles for medical imaging: Their effects on hemostatic, hemolytic activity, and cellular cytotoxicity	72
9. Wei-Chun Lin; Chia Yao; T. Y. Huang; S. J. Cheng; C. M. Tang (Lin et al. 2019)	Long-term in vitro degradation behavior and biocompatibility of polycaprolactone/cobalt-	55

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	substituted hydroxyapatite composite for bone tissue engineering.	
10. Anastasia V. Sadetskaya; Natalia P. Bobrysheva; Mikhail G. Osmolowsky; Olga M. Osmolovskaya; (Sadetskaya et al. 2021b)	Correlative experimental and theoretical characterization of transition metal-doped hydroxyapatite nanoparticles fabricated by the hydrothermal method.	47
11. Munirathinam R., Rajesh N., Marimuthu K. and Nzihu (Munirathinam et al. 2020b)	Hydroxyapatite as a new support material for cobalt-based catalysts in Fischer-Tropsch synthesis.	36
12. Peng, Yong, Horatiu Szalad, Pavle Nikacevic, Giulio Gorni, Sara Goberna, Laura Simonelli, Josep Albero, Núria López, and Hermenegildo García. (Peng et al. 2023)	Co-doped hydroxyapatite as a photothermal catalyst for CO_2 hydrogenation.	29
13.Justyn Wayne Jaworski; Sunghwa Cho; Yeoungyong Kim; Jong Hwa Jung; Hyo Sang Jeon; Byoung Koun Min; Ki Young (Jaworski et al. 2013)	Hydroxyapatite-supported cobalt catalysts for hydrogen generation.	48
14. Vakh, Christina, Artem Kuzmin, Anastasia Sadetskaya, Polina Bogdanova, Mikhail Voznesenskiy, Olga Osmolovskaya, and Andrey Bulatov.(Vakh et al. 2020)	Cobalt-doped hydroxyapatite nanoparticles as a new eco-friendly catalyst of luminol-H2O2-based chemiluminescence reaction: Study of key factors, improvement of the activity, and analytical application.	20
15. Umar Nishan, Nighat Jabeen, Amir Badshah, Nawshad Muhammad, Mohibullah Shah, Irfan Ullah, Saifullah Afridi, Jibran Iqbal, Muhammad Asad, Riaz Ullah, Essam A. Ali, Sarfraz Ahmed, Suvash C. Ojha. (Nishan et al. 2024)	Nanozyme-based sensing of dopamine using cobalt-doped hydroxyapatite nanocomposite from waste bones.	13

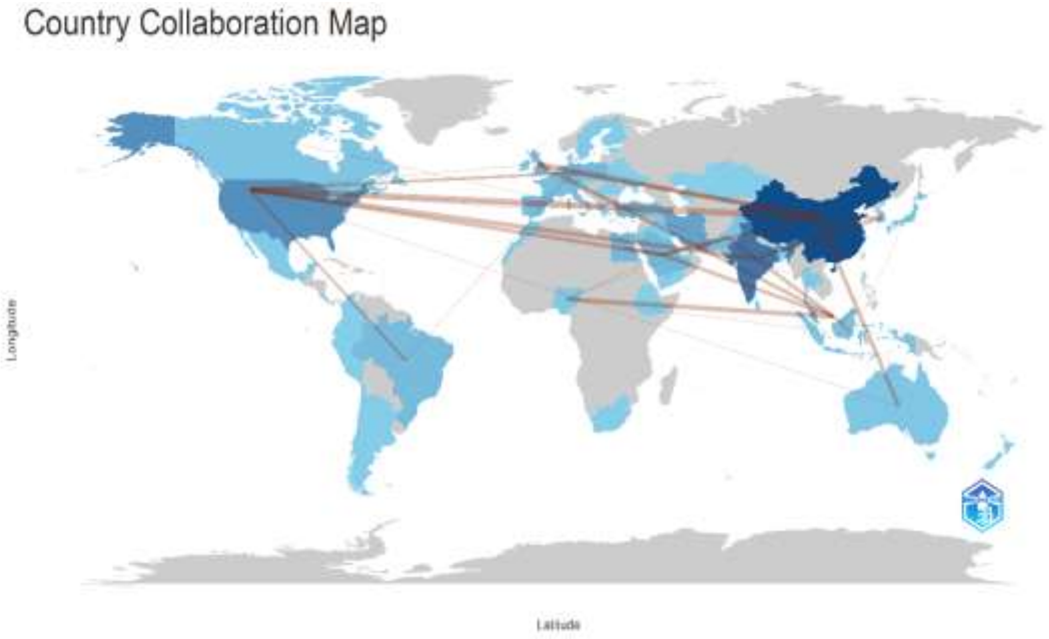

Fig 8. Countries' collaboration world map

Figure 8 shows which countries are working together in Co-HAP research. Darker blue countries like China, India, and Iran are the most active in publishing and collaborations. Other countries like the USA, Brazil, European countries, and some Asian countries also contribute, shown in lighter blue. This means Co-HAP research is growing globally with strong collaboration, especially in Asia, helping to advance this research area faster.

Future direction

The study of cobalt-doped hydroxyapatite (Co-HAP) is set to develop even more in research in the future, as it is very useful in areas of catalysis, biomedicine, and environmental remedies (Ibrahim et al. 2020; Li et al. 2022; Verma et al. 2023a). Due to the increasing popularity of the need to use sustainable and high-performance materials, future research will probably focus on the creation of eco-friendly synthesis techniques that would be able to control the material's physicochemical properties in the most optimal way possible (Gupta et al. 2023; Khatami and Iravani 2021; Rani et al. 2023).

The future of cobalt-doped hydroxyapatite (Co-HAP) studies is set to

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experience growth due to the growing demand for materials with sustainable and high-performance functions in different sectors (Doan et al. 2022b; Kurinjinathan, Arul, and Ramya 2018; Nishan et al. 2024; Safari-Gezaz et al. 2024). The focus will be on the creation of eco-friendly synthesis approaches, which will enable them to control the physicochemical properties of the material in order to maximize its functionality. Further research on techniques of characterization, like X-ray diffraction, FTIR, and scanning electron microscopy, will enhance what is known about the structural and morphological characteristics of Co-HAP, directly affecting its performance (Panchu et al. 2023; Rajendran et al. 2018; Tank et al. 2013). Moreover, greater cooperation on the international forum, especially between major research centers such as China, India, and Iran, will enhance innovation.

Connecting future research to the sustainable development objectives, the researchers will develop solutions to the urgent environmental and health problems, which will enhance the interdisciplinary potential of Co-HAP in catalysis, biomedicine, and environmental cleanup (Verma et al. 2023b; Yook et al. 2023).

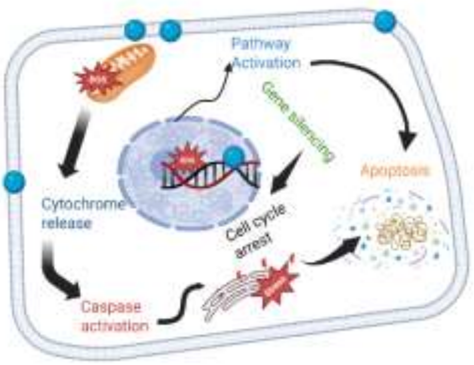
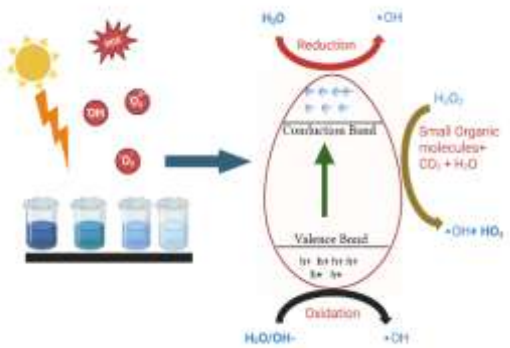


Fig. 9. Anticancer mechanism of metal-doped hydroxyapatite.

Fig 10. Mechanism for dye degradation by Co-HAP

Future studies will be directed at improving the selective toxicity of Co-HAP to cancer cells and its biocompatibility and targeting properties in terms of anticancer



use (De Lama-Odría, Del Valle, and Puiggalí 2022; Dhilip Kumar and Abrahamse 2022; Nguyen et al. 2023; Xiong et al. 2016). This will require creative surface alterations and incorporation with therapeutic agents to achieve maximum efficacy with minimal

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side effects (Fatimah et al. 2025; Jabeen et al. 2025). Further characterization of the advanced material will shed more light on the properties that promote anticancer activity, which will enable the translation of Co-HAP to clinical application (Awwad et al. 2017; Ghosh et al., 2020; Osial et al. 2023; Sun et al. 2018; Zhao et al. 2025).

Fig 9 represents the anticancer mechanism of nanocomposite consisting metal nanoparticles. Doping HAp with metal ions enhanced the activity through ion release to intrude the cell wall, for furthermore the particle-induced upregulation of receptors of apoptosis, production of reactive oxygen species (ROS), mitochondria-mediated cytotoxicity. Meanwhile, Fig 10 shows the photocatalytic mechanism of metal-doped HAp nanocomposite. The metal having semiconductor properties including cobalt could absorb photon to migrate the electron from valence band to the conduction band. The excitation leads the formation of hole (h^+) which by its interaction with ^-OH from solvent, •OH produced. In opposite way, the created electron could form •OH by the interaction with H_2O. These radicals could propagate to form ROS and create the oxidation of organic molecule-contaminated solution (Fatimah et al. 2025). To degrade dyes because they are polluting the environment, so there is a need to clean the environment (Arif et al. 2025; Das, Das, and Dhar 2020; Wang et al. 2025).

The priority will be on the green synthesis methods to maximize the catalytic activity of Co-HAP to decompose intractable pollutants at mild temperatures (Pai et al. 2020; Wan, Cui, and Wang 2024). The measures of scaling to produce sustainable and cost-effective catalytic systems will be developed through collaborative international resources and bibliometric approaches, the most significant findings of which will be obtained with the help of the FTIR and microscopy techniques (Verma et al. 2023c).

To enhance the use of Co-HAP against resistant pathogens, studies of the mechanism of interaction with bacterial cells will be conducted as part of research into the antibacterial uses of Co-HAP (Fatimah et al. 2024; Megha et al. 2023; Sinulingga et al. 2021). It will focus on the use of Co-HAP in medical casting and implants to prevent infection with the help of sustainable production and further characterization to personalize its antimicrobial potential (Charlena, Suparto, and Kurniawan 2019; Fatimah et al. 2025; Lin et al. 2022).

Cobalt-doped hydroxyapatite research is very promising and versatile. As improvements in synthesis methods are

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made to achieve environmental friendliness and the characteristics of the material are customized, Co-HAP is anticipated to excel in applications in a wide range of applications (Safari-Gezaz, Parhizkar, and Asghari 2025; Sarath Chandra et al. 2015). The combination of state-of-the-art characterization techniques will give a stronger insight into its structure-function relationships, which will be used to design the materials accurately. In addition, the growth in global and transdisciplinary partnerships will play a central role in fostering innovation and global solutions to environmental and health issues. These emerging tendencies in research show a dynamic and influential future of Co-HAP with great possibilities to make sustainable and innovative solutions.

CONCLUSION

This review shows that the research on the cobalt-doped hydroxyapatite (Co-HAP) has been on the rise over the last ten years, which indicates its growing applications in catalysis, biomedical, and environmental remediation. The application of its characterization methods and the development of cooperation among the top countries caused significant innovations in synthesis and utilization. As the number of publications and interdisciplinary research increases, Co-HAP research has a strong future growth, with the potential to provide viable solutions in the field of sustainable materials design and feasible healthcare and environmental solutions.

REFERENCES

Amedlous, Abdallah, Othmane Amadine, Mohammed Majdoub, and Mohamed Zahouily. 2022. “Engineered Magnetic Cobalt/Hydroxyapatite Core-Shell Nanostructure: Toward High Peroxymonosulfate Activation via Radical and Non-Radical Mechanisms.” *Applied Catalysis A: General* 646:118870. doi:10.1016/j.apcata.2022.118870.

Arif, Shafaq, Hira Fatima, Jawaria Tahir, and M. S. Anwar. 2025. “Doped Hydroxyapatite Photocatalyst for Efficient Degradation of Methylene Blue Dye.” *Inorganic Chemistry Communications* 172:113684. doi:10.1016/j.inoche.2024.113684.

Awwad, Nasser, Ali Alshahrani, Kamel Saleh, and Mohamed Hamdy. 2017. “A Novel Method to Improve the Anticancer Activity of Natural-Based Hydroxyapatite against the Liver Cancer Cell Line HepG2 Using Mesoporous Magnesia as a Micro-Carrier.” *Molecules* 22(12):1947. doi:10.3390/molecules22121947.

Baas, Jeroen, Michiel Schotten, Andrew Plume, Grégoire Côté, and Reza Karimi. 2020. “Scopus as a Curated, High-Quality Bibliometric Data Source for Academic Research in Quantitative Science Studies.” *Quantitative Science*

Studies 1(1):377–86. doi:10.1162/qss_a_00019.

Bharali, Linkon, Juri Kalita, Debarati Chakraborty, Siddhartha Sankar Dhar, and N. Shaemningwar Moyon. 2023. "Hydroxyapatite Nanoparticles Decorated with Metal–Organic Framework, Co-Cu/ZIF@HAp, and Evaluation of Photocatalytic Performance of the Prepared Nanocomposite in the Degradation of Organic Pollutants." *Applied Organometallic Chemistry* 37(10):e7235. doi:10.1002/aoc.7235.

Boukha, Zouhair, Jonatan González-Prior, Beatriz De Rivas, Juan R. González-Velasco, Rubén López-Fonseca, and José I. Gutiérrez-Ortiz. 2016. "Synthesis, Characterisation and Behaviour of Co/Hydroxyapatite Catalysts in the Oxidation of 1,2-Dichloroethane." *Applied Catalysis B: Environmental* 190:125–36. doi:10.1016/j.apcatb.2016.03.005.

Charlena, Irma Herawati Suparto, and Eldora Kurniawan. 2019. "Synthesis and Characterization of Hydroxyapatite-Zinc Oxide (HAp-ZnO) as Antibacterial Biomaterial." *IOP Conference Series: Materials Science and Engineering* 599(1):012011. doi:10.1088/1757-899X/599/1/012011.

Das, Krishna Ch., Bishal Das, and Siddhartha S. Dhar. 2020. "Effective Catalytic Degradation of Organic Dyes by Nickel Supported on Hydroxyapatite-Encapsulated Cobalt Ferrite (Ni/HAP/CoFe2O4) Magnetic Novel Nanocomposite." *Water, Air, & Soil Pollution* 231(2):43. doi:10.1007/s11270-020-4409-1.

De Lama-Odría, María Del Carmen, Luis J. Del Valle, and Jordi Puiggalí. 2022. "Hydroxyapatite Biobased Materials for Treatment and Diagnosis of Cancer." *International Journal of Molecular Sciences* 23(19):11352. doi:10.3390/ijms231911352.

Dhilip Kumar, Sathish Sundar, and Heidi Abrahamse. 2022. "Recent Advances in the Development of Biocompatible Nanocarriers and Their Cancer Cell Targeting Efficiency in Photodynamic Therapy." *Frontiers in Chemistry* 10:969809. doi:10.3389/fchem.2022.969809.

DileepKumar, V. G., Mysore Santosh Sridhar, Pornanong Aramwit, Valentina K. Krut'ko, Olga N. Musskaya, Ilya E. Glazov, and Narendra Reddy. 2022. "A Review on the Synthesis and Properties of Hydroxyapatite for Biomedical Applications." *Journal of Biomaterials Science, Polymer Edition* 33(2):229–61. doi:10.1080/09205063.2021.1980985.

Doan, Vu Hoang Minh, Sudip Mondal, Thi Mai Thien Vo, Cao Duong Ly, Dinh Dat Vu, Van Tu Nguyen, Sumin Park, Jaeyeop Choi, and Junghwan Oh. 2022a. "Fluorescence Conjugated Nanostructured Cobalt-Doped Hydroxyapatite Platform for Imaging-Guided Drug Delivery Application." *Colloids and Surfaces B: Biointerfaces* 214:112458. doi:10.1016/j.colsurfb.2022.112458.

Doan, Vu Hoang Minh, Sudip Mondal, Thi Mai Thien Vo, Cao Duong Ly, Dinh Dat Vu, Van Tu Nguyen, Sumin Park, Jaeyeop Choi, and

Junghwan Oh. 2022b. “Fluorescence Conjugated Nanostructured Cobalt-Doped Hydroxyapatite Platform for Imaging-Guided Drug Delivery Application.” *Colloids and Surfaces B: Biointerfaces* 214:112458. doi:10.1016/j.colsurfb.2022.112458.

Dobosz, J., M. Małecka, and M. Zawadzki. 2018. “Hydrogen Generation via Ethanol Steam Reforming over Co/HAp Catalysts.” *Journal of the Energy Institute* 91(3):411–23. doi:10.1016/j.joei.2017.02.001.

Fatimah, Is, Nunung Nurlaela, Anas Zahra Fauziyyah, Habibi Hidayat, Muhammad Fauzi Daud, and Suresh Sagadevan. 2025. “Green Synthesis of Ni-Doped Nanohydroxyapatite for Photocatalysis and Antibacterial Agent Applications.” *Materials Letters* 394:138621. doi:10.1016/j.matlet.2025.138621.

Fatimah, Is, Nunung Nurlaela, Anas Zahra Fauziyyah, Suresh Sagadevan, Habibi Hidayat, Mehru Nisha Muhamad Haneef, Muhammad Fauzi Daud, Azlan Kamari, and Won-Chun Oh. 2025. “Clitoria Ternatea Flower Extract Mediated Synthesis of Ni-Doped Hydroxyapatite as Photocatalyst, Antibacterial, and Drug Delivery Agent for Anticancer Drug.” *Science and Technology Indonesia* 10(2):360–73. doi:10.26554/sti.2025.10.2.360-373.

Fatimah, Is, Gani Purwiandono, Galih Dwiki Ramanda, Nunung Nurlaela, Habibi Hidayat, Suresh Sagadevan, and Won-Chun Oh. 2024. “Zr-Doped Hydroxyapatite Nanorods from Cockle Shell and Study on Photocatalyst Activity and Cytotoxicity.” *Inorganic Chemistry Communications* 165:112559. doi:10.1016/j.inoche.2024.112559.

Foroughi, Firoozeh, S. A. Hassanzadeh-Tabrizi, and Jamshid Amighian. 2015. “Microemulsion Synthesis and Magnetic Properties of Hydroxyapatite-Encapsulated Nano CoFe2O4.” *Journal of Magnetism and Magnetic Materials* 382:182–87. doi:10.1016/j.jmmm.2015.01.075.

Ghosh, Saikat, Sampad Ghosh, and Nabakumar Pramanik. 2020. “Bio-Evaluation of Doxorubicin (DOX)-Incorporated Hydroxyapatite (HAp)-Chitosan (CS) Nanocomposite Triggered on Osteosarcoma Cells.” *Advanced Composites and Hybrid Materials* 3(3):303–14. doi:10.1007/s42114-020-00154-4.

Gupta, Deepshikha, Anuj Boora, Amisha Thakur, and Tejendra K. Gupta. 2023. “Green and Sustainable Synthesis of Nanomaterials: Recent Advancements and Limitations.” *Environmental Research* 231:116316. doi:10.1016/j.envres.2023.116316.

Huang, Yong, Xuejiao Zhang, Huanhuan Mao, Tingting Li, Ranlin Zhao, Yajing Yan, and Xiaofeng Pang. 2015. “Osteoblastic Cell Responses and Antibacterial Efficacy of Cu/Zn Co-Substituted Hydroxyapatite Coatings on Pure Titanium Using Electrodeposition Method.” *RSC Advances* 5(22):17076–86. doi:10.1039/C4RA12118J.

Ibrahim, Maya, Madona Labaki, Jean-Marc Giraudon, and Jean-François Lamonier. 2020. “Hydroxyapatite, a Multifunctional Material for Air, Water and Soil Pollution Control: A Review." *Journal of Hazardous Materials* 383:121139. doi:10.1016/j.jhazmat.2019.121139 .

Irfan, Mohammad, Ashok Jeshurun, and Bogala Mallikharjuna Reddy. 2025. "Microwave-Assisted Synthesis of Dual Responsive Luminomagnetic Rare Earth Metal Ions (Nd^{3+} , Dy^{3+}) Co-Doped Nanohydroxyapatite for Biomedical Applications." *Dalton Transactions* 54(9):3774–95. doi:10.1039/D4DT02664K.

Jabeen, Sabeeha, Ekhlakh Veg, Mohammad Imran Ahmad, Shashi Bala, and Tahmeena Khan. 2025. "A Comprehensive Review on Metal Oxide-based Nanomaterials: Synthesis, Characterization, Environmental, and Therapeutic Applications." *ChemistrySelect* 10(11):e202500080. doi:10.1002/slct.202500080.

Jaworski, Justyn Wayne, Sunghwa Cho, Yeoungyong Kim, Jong Hwa Jung, Hyo Sang Jeon, Byoung Koun Min, and Ki-Young Kwon. 2013. "Hydroxyapatite Supported Cobalt Catalysts for Hydrogen Generation." *Journal of Colloid and Interface Science* 394:401–8. doi:10.1016/j.jcis.2012.11.036.

Kareem, Rebaz Obaid, Tankut Ates, Azeez A. Barzinjy, Mehmet Mürşit Temüz, Turan İnce, Niyazi Bulut, Serhat Keser, and Omer Kaygili. 2025. "Investigation of the Structural, Thermal, Spectroscopic, and Electronic Properties of Praseodymium-Based Hydroxyapatites Co-Doped with Silver and Zinc in Varying Concentrations." *Periodica Polytechnica Chemical Engineering* 69(2):329–38. doi:10.3311/PPch.39496.

Karunakaran, Gopalu, Eun-Bum Cho, Govindan Suresh Kumar, Evgeny Kolesnikov, Arkhipov Dmitry, and Saheb Ali. 2021. "Microwave-Assisted Synthesis of Superparamagnetic Mesoporous Co-Doped Hydroxyapatite Nanorods for Various Biomedical Applications." *Ceramics International* 47(6):8642–52. doi:10.1016/j.ceramint.2020.11.23 4.

Khatami, Mehrdad, and Siavash Iravani. 2021. "Green and Eco-Friendly Synthesis of Nanophotocatalysts: An Overview." *Comments on Inorganic Chemistry* 41(3):133–87. doi:10.1080/02603594.2021.18951 27.

Kulanthaivel, Senthilguru, Upasana Mishra, Tarun Agarwal, Supratim Giri, Kunal Pal, Krishna Pramanik, and Indranil Banerjee. 2015. "Improving the Osteogenic and Angiogenic Properties of Synthetic Hydroxyapatite by Dual Doping of Bivalent Cobalt and Magnesium Ion." *Ceramics International* 41(9):11323–33. doi:10.1016/j.ceramint.2015.05.09 0.

Kulanthaivel, Senthilguru, Bibhas Roy, Tarun Agarwal, Supratim Giri, Krishna Pramanik, Kunal Pal, Sirsendu S. Ray, Tapas K. Maiti, and Indranil Banerjee. 2016. "Cobalt Doped Proangiogenic Hydroxyapatite for Bone Tissue Engineering Application." *Materials Science and Engineering: C* 58:648–58. doi:10.1016/j.msec.2015.08.052.

Kurinjinathan, P., K. Thanigai Arul, and J. Ramana Ramya. 2018. "Cobalt

Ions Doped Bioactive Ceramics for Biosensor Biomedical Applications." *International Journal of Current Research and Review* 10(21):49–52. doi:10.31782/IJCRR.2018.4952.

Laranjeira, Marta S., Ana Moço, Jorge Ferreira, Susana Coimbra, Elísio Costa, Alice Santos-Silva, Paulo J. Ferreira, and Fernando J. Monteiro. 2016. "Different Hydroxyapatite Magnetic Nanoparticles for Medical Imaging: Its Effects on Hemostatic, Hemolytic Activity and Cellular Cytotoxicity." *Colloids and Surfaces B: Biointerfaces* 146:363–74. doi:10.1016/j.colsurfb.2016.06.042.

Li, Shuping, Yachun Li, Wen Shen, Yirou Bai, and Lingjun Kong. 2022. "Hydroxyapatite-Based Catalysis in Environmental Decontamination." *Journal of Cleaner Production* 380:134961. doi:10.1016/j.jclepro.2022.134961.

Lim, Kang Hui, Ming Hui Wai, Keyu Cao, Sonali Das, Ange Nzihou, and Sibudjing Kawi. 2025. "Rational Engineering of Hydroxyapatites for Sustainable Chemicals, H_2 , Biofuels and CO_2 Conversion." *Energy Materials* 5(10). doi:10.20517/energymater.2025.63.

Lin, Ruitian, Zhuoran Wang, Zihan Li, and Lisha Gu. 2022. "A Two-Phase and Long-Lasting Multi-Antibacterial Coating Enables Titanium Biomaterials to Prevent Implants-Related Infections." *Materials Today Bio* 15:100330. doi:10.1016/j.mtbio.2022.100330.

Lin, Wei-Chun, Chenmin Yao, Ting-Yun Huang, Shih-Jung Cheng, and Cheng-Ming Tang. 2019. "Long-Term in Vitro Degradation Behavior and Biocompatibility of Polycaprolactone/Cobalt-Substituted Hydroxyapatite Composite for Bone Tissue Engineering." *Dental Materials* 35(5):751–62. doi:10.1016/j.dental.2019.02.023.

Megha, M., Anjumol Joy, Gayathri Unnikrishnan, M. Haris, Jibu Thomas, Ayswaria Deepti, P. S. Baby Chakrapani, Elayaraja Kolanthai, and Senthilkumar Muthuswamy. 2023. "Structural and Biological Properties of Novel Vanadium and Strontium Co-Doped HAp for Tissue Engineering Applications." *Ceramics International* 49(18):30156–69. doi:10.1016/j.ceramint.2023.06.272.

Mondal, Sudip, Sumin Park, Jaeyeop Choi, Thi Thu Ha Vu, Vu Hoang Minh Doan, Truong Tien Vo, Byeongil Lee, and Junghwan Oh. 2023. "Hydroxyapatite: A Journey from Biomaterials to Advanced Functional Materials." *Advances in Colloid and Interface Science* 321:103013. doi:10.1016/j.cis.2023.103013.

Moral-Muñoz, José A., Enrique Herrera-Viedma, Antonio Santisteban-Espejo, and Manuel J. Cobo. 2020. "Software Tools for Conducting Bibliometric Analysis in Science: An up-to-Date Review." *El Profesional de La Información* 29(1). doi:10.3145/epi.2020.ene.03.

Munirathinam, Rajesh, Doan Pham Minh, and Ange Nzihou. 2020a. "Hydroxyapatite as a New Support Material for Cobalt-Based Catalysts in Fischer-Tropsch Synthesis." *International Journal of Hydrogen Energy*

45(36):18440–51. doi:10.1016/j.ijhydene.2019.09.043.

Munirathinam, Rajesh, Doan Pham Minh, and Ange Nzihou. 2020b. “Hydroxyapatite as a New Support Material for Cobalt-Based Catalysts in Fischer-Tropsch Synthesis.” *International Journal of Hydrogen Energy* 45(36):18440–51. doi:10.1016/j.ijhydene.2019.09.043.

Nguyen, Tristan, Anuj Maniyar, Mrinmoy Sarkar, Tapasree Roy Sarkar, and Gururaj M. Neelgund. 2023. “The Cytotoxicity of Carbon Nanotubes and Hydroxyapatite, and Graphene and Hydroxyapatite Nanocomposites against Breast Cancer Cells.” *Nanomaterials* 13(3):556. doi:10.3390/nano13030556.

Nishan, Umar, Nighat Jabeen, Amir Badshah, Nawshad Muhammad, Mohibullah Shah, Irfan Ullah, Saifullah Afridi, Jibran Iqbal, Muhammad Asad, Riaz Ullah, Essam A. Ali, Sarfraz Ahmed, and Suvash Chandra Ojha. 2024. “Nanozyme-Based Sensing of Dopamine Using Cobalt-Doped Hydroxyapatite Nanocomposite from Waste Bones.” *Frontiers in Bioengineering and Biotechnology* 12:1364700. doi:10.3389/fbioe.2024.1364700.

Osial, Magdalena, Sławomir Wilczewski, Joanna Szulc, Hai Dang Nguyen, Thi Kieu Oanh Nguyen, Katarzyna Skórczewska, Agnieszka Majkowska-Pilip, Kinga Żelechowska-Matysiak, Dorota Nieciecka, Agnieszka Pregowska, Thu Phuong Nguyen, Alicja Tymoszuk, Dariusz Kulus, and Michael Giersig. 2023. “Nanohydroxyapatite Loaded with 5-Fluorouracil and Calendula Officinalis L. Plant Extract Rich in Myo-Inositols for Treatment of Ovarian Cancer Cells.” *Coatings* 13(11):1944. doi:10.3390/coatings13111944.

Pai, Shraddha, Srinivas M Kini, Raja Selvaraj, and Arivalagan Pugazhendhi. 2020. “A Review on the Synthesis of Hydroxyapatite, Its Composites and Adsorptive Removal of Pollutants from Wastewater.” *Journal of Water Process Engineering* 38:101574. doi:10.1016/j.jwpe.2020.101574.

Panchu, Sandeep Eswaran, Saranya Sekar, Elayaraja Kolanthai, Moorthy Babu Sridharan, and Narayana Kalkura Subbaraya. 2023. “Extremely Fast and Efficient Removal of Congo Red Using Cationic-Incorporated Hydroxyapatite Nanoparticles (HAp: X (X = Fe, Ni, Zn, Co, and Ag)).” *Crystals* 13(2):209. doi:10.3390/cryst13020209.

Pang, Yixiong, Lingjun Kong, Diyun Chen, Gutha Yuvaraja, and Sajid Mehmood. 2020. “Facilely Synthesized Cobalt Doped Hydroxyapatite as Hydroxyl Promoted Peroxymonosulfate Activator for Degradation of Rhodamine B.” *Journal of Hazardous Materials* 384:121447. doi:10.1016/j.jhazmat.2019.121447.

Peng, Yong, Horatiu Szalad, Pavle Nikacevic, Giulio Gorni, Sara Goberna, Laura Simonelli, Josep Albero, Núria López, and Hermenegildo García. 2023. “Co-Doped Hydroxyapatite as Photothermal Catalyst for Selective CO2 Hydrogenation.” *Applied Catalysis B: Environmental*

333:122790. doi:10.1016/j.apcatb.2023.122790.

Phan, Thanh Son, Abdoul Razac Sane, Bruna Rêgo De Vasconcelos, Ange Nzihou, Patrick Sharrock, Didier Grouset, and Doan Pham Minh. 2018. “Hydroxyapatite Supported Bimetallic Cobalt and Nickel Catalysts for Syngas Production from Dry Reforming of Methane.” *Applied Catalysis B: Environmental* 224:310–21. doi:10.1016/j.apcatb.2017.10.063.

Rajendran, Abinaya, Subha Balakrishnan, Ravichandran Kulandaivelu, and Sankara Narayanan T. S. Nellaiappan. 2018. “Multi-Element Substituted Hydroxyapatites: Synthesis, Structural Characteristics and Evaluation of Their Bioactivity, Cell Viability, and Antibacterial Activity.” *Journal of Sol-Gel Science and Technology* 86(2):441–58. doi:10.1007/s10971-018-4634-x.

Rani, Neeru, Permender Singh, Sandeep Kumar, Parmod Kumar, Vinita Bhankar, and Krishan Kumar. 2023. “Plant-Mediated Synthesis of Nanoparticles and Their Applications: A Review.” *Materials Research Bulletin* 163:112233. doi:10.1016/j.materresbull.2023.112233.

Rocha, Rafael Lisandro P., Luzia Maria C. Honorio, Roosevelt Delano De S. Bezerra, Pollyana Trigueiro, Thiago Marinho Duarte, Maria Gardennia Fonseca, Edson C. Silva-Filho, and Josy A. Osajima. 2022. “Light-Activated Hydroxyapatite Photocatalysts: New Environmentally-Friendly Materials to Mitigate Pollutants.” *Minerals* 12(5):525. doi:10.3390/min12050525.

Sadetskaya, Anastasia V., Natalia P. Bobrysheva, Mikhail G. Osmolowsky, Olga M. Osmolovskaya, and Mikhail A. Voznesenskiy. 2021a. “Correlative Experimental and Theoretical Characterization of Transition Metal Doped Hydroxyapatite Nanoparticles Fabricated by Hydrothermal Method.” *Materials Characterization* 173:110911. doi:10.1016/j.matchar.2021.110911.

Sadetskaya, Anastasia V., Natalia P. Bobrysheva, Mikhail G. Osmolowsky, Olga M. Osmolovskaya, and Mikhail A. Voznesenskiy. 2021b. “Correlative Experimental and Theoretical Characterization of Transition Metal Doped Hydroxyapatite Nanoparticles Fabricated by Hydrothermal Method.” *Materials Characterization* 173:110911. doi:10.1016/j.matchar.2021.110911.

Safari-Gezaz, Meysam, Meysam Mirzaei-Saatlo, Elnaz Asghari, and Mojtaba Parhizkar. 2024. “The Incorporation of Cobalt Ions into Hydroxyapatite Nanostructure for a Novel Range of Electrochemical Energy Storage Applications.” *Journal of Physics and Chemistry of Solids* 192:112118. doi:10.1016/j.jpcs.2024.112118.

Safari-Gezaz, Meysam, Mojtaba Parhizkar, and Elnaz Asghari. 2025. “Effect of Cobalt Ions Doping on Morphology and Electrochemical Properties of Hydroxyapatite Coatings for Biomedical Applications.” *Scientific Reports* 15(1):149. doi:10.1038/s41598-024-84055-2.

Sarath Chandra, V., Kolanthai Elayaraja, K. Thanigai Arul, Sara Ferraris, Silvia Spriano, Monica Ferraris, K. Asokan, and S. Narayana Kalkura. 2015. “Synthesis of Magnetic Hydroxyapatite by Hydrothermal–Microwave Technique: Dielectric, Protein Adsorption, Blood Compatibility and Drug Release Studies.” *Ceramics International* 41(10):13153–63. doi:10.1016/j.ceramint.2015.07.088.

Sinulingga, Karya, Makmur Sirait, Nurdin Siregar, and Maryati Evivani Doloksaribu. 2021. “Investigation of Antibacterial Activity and Cell Viability of Ag/Mg and Ag/Zn Co-Doped Hydroxyapatite Derived from Natural Limestone.” *ACS Omega* 6(49):34185–91. doi:10.1021/acsomega.1c05921.

Subramanyam, K. 1983. “Bibliometric Studies of Research Collaboration: A Review.” *Journal of Information Science* 6(1):33–38. doi:10.1177/016555158300600105.

Sun, Wen, Jiangli Fan, Suzhen Wang, Yao Kang, Jianjun Du, and Xiaojun Peng. 2018. “Biodegradable Drug-Loaded Hydroxyapatite Nanotherapeutic Agent for Targeted Drug Release in Tumors.” *ACS Applied Materials & Interfaces* 10(9):7832–40. doi:10.1021/acsami.7b19281.

Tank, Kashmira P., Kiran S. Chudasama, Vrinda S. Thaker, and Mihir J. Joshi. 2013. “Cobalt-Doped Nanohydroxyapatite: Synthesis, Characterization, Antimicrobial and Hemolytic Studies.” *Journal of Nanoparticle Research* 15(5):1644. doi:10.1007/s11051-013-1644-z.

Vakh, Christina, Artem Kuzmin, Anastasia Sadetskaya, Polina Bogdanova, Mikhail Voznesenskiy, Olga Osmolovskaya, and Andrey Bulatov. 2020. “Cobalt-Doped Hydroxyapatite Nanoparticles as a New Eco-Friendly Catalyst of Luminol–H2O2 Based Chemiluminescence Reaction: Study of Key Factors, Improvement the Activity and Analytical Application.” *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* 237:118382. doi:10.1016/j.saa.2020.118382.

Verma, Rahul, Soumya Ranjan Mishra, Vishal Gadore, and Md. Ahmaruzzaman. 2023a. “Hydroxyapatite-Based Composites: Excellent Materials for Environmental Remediation and Biomedical Applications.” *Advances in Colloid and Interface Science* 315:102890. doi:10.1016/j.cis.2023.102890.

Verma, Rahul, Soumya Ranjan Mishra, Vishal Gadore, and Md. Ahmaruzzaman. 2023b. “Hydroxyapatite-Based Composites: Excellent Materials for Environmental Remediation and Biomedical Applications.” *Advances in Colloid and Interface Science* 315:102890. doi:10.1016/j.cis.2023.102890.

Verma, Rahul, Soumya Ranjan Mishra, Vishal Gadore, and Md. Ahmaruzzaman. 2023c. “Hydroxyapatite-Based Composites: Excellent Materials for Environmental Remediation and Biomedical Applications.” *Advances in Colloid and Interface Science* 315:102890. doi:10.1016/j.cis.2023.102890.

Walpole, Sarah Catherine. 2019. “Including Papers in Languages Other than English in Systematic Reviews: Important, Feasible, yet

Often Omitted.” *Journal of Clinical Epidemiology* 111:127–34. doi:10.1016/j.jclinepi.2019.03.004.

Wan, Linling, Binfan Cui, and Lijun Wang. 2024. “A Review on Preparation Raw Materials, Synthesis Methods, and Modifications of Hydroxyapatite as Well as Their Environmental Applications.” *Sustainable Chemistry and Pharmacy* 38:101447. doi:10.1016/j.scp.2024.101447.

Wang, Lei, Yang Ruan, Zenghui Diao, Diyun Chen, and Lingjun Kong. 2025. “Catalytic Degradation of Rhodamine B through Peroxymonosulfate Activation by the Co-Doped Hydroxyapatite.” *Environmental Research* 267:120657. doi:10.1016/j.envres.2024.120657.

Xiong, Hui, Shi Du, Jiang Ni, Jianping Zhou, and Jing Yao. 2016. “Mitochondria and Nuclei Dual-Targeted Heterogeneous Hydroxyapatite Nanoparticles for Enhancing Therapeutic Efficacy of Doxorubicin.” *Biomaterials* 94:70–83. doi:10.1016/j.biomaterials.2016.04.004.

Yang, Zhihui, Hangyuan Gong, Fangshu He, Eveliina Repo, Weichun Yang, Qi Liao, and Feiping Zhao. 2022. “Iron-Doped Hydroxyapatite for the Simultaneous Remediation of Lead-, Cadmium- and Arsenic-Co-Contaminated Soil.” *Environmental Pollution* 312:119953. doi:10.1016/j.envpol.2022.119953.

Yook, Hyunwoo, Jinwoo Hwang, Woonsuk Yeo, Jungup Bang, Jaeyoung Kim, Tae Yong Kim, Jae-Soon Choi, and Jeong Woo Han. 2023. “Design Strategies for Hydroxyapatite-Based Materials to Enhance Their Catalytic Performance and Applicability.” *Advanced Materials* 35(43):2204938. doi:10.1002/adma.202204938.

Zhao, Rui, Xiang Meng, Zixian Pan, Yongjia Li, Hui Qian, Xiangdong Zhu, Xiao Yang, and Xingdong Zhang. 2025. “Advancements in Nanohydroxyapatite: Synthesis, Biomedical Applications and Composite Developments.” *Regenerative Biomaterials* 12:rbae129. doi:10.1093/rb/rbae129.