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Article

Trends and Challenges in Forensic Image Processing: A Bibliometric Study

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ABSTRACT

Forensic image processing plays a crucial role in modern criminal investigations by enhancing, analyzing, and interpreting visual evidence. This bibliometric study evaluates global research trends, influential publications, and collaborative networks in forensic image processing from 1962 to 2024 using the Scopus database. A total of 4,463 articles were identified, with an annual average of 72 publications. Research outputs grew significantly after 1993 and peaked in 2017, focusing on image authentication, enhancement, and deep learning applications. Co-authorship analysis revealed four major clusters, led by key authors such as Swaminathan Ashwin, Liu K.J. Ray, and Cozzolino Davide, emphasizing digital forensics and artificial intelligence. In terms of productivity, China (791 articles), the United States (739 articles), and India (649 articles) dominated, while the United Kingdom demonstrated the broadest international collaboration (44 partner countries). Leading institutions include Sun Yat-Sen University (58 publications) and the Chinese Academy of Sciences (52 publications). The most cited article, by Lukáš, Fridrich, and Goljan (2006), received 1,113 citations, and *Forensic Science International* was the top journal with 270 contributions. These findings highlight the rapid advancement and interdisciplinary nature of forensic image processing, underscoring its importance in strengthening the reliability of visual evidence in legal contexts.

INTRODUCTION

Medical forensics is a branch of forensic science that focuses on the application of medical principles to aid legal investigations, particularly in determining causes of death, injuries, or suspected crimes[1,2]. One of the rapidly advancing technologies in this field is image processing.

Image processing is a technique used to analyze, enhance, and interpret images to obtain clearer and more accurate information[3,4]. In the context of medical forensics, this technique assists in wound examination, facial identification, fingerprint analysis, DNA matching, and various other aspects related to visual evidence[5–7].

Image processing plays a crucial role in medical forensics as it enhances the accuracy of visual evidence analysis[8]. In criminal investigations, every minute detail can be critical in reaching precise conclusions. Image processing enables the enhancement of image resolution, noise removal, and extraction of specific features that are difficult to observe with the naked eye. The primary advantages of utilizing this technology in medical forensics include improved accuracy in identification through pattern matching, such as fingerprints, bone structures, and iris patterns[9,10]; acceleration of forensic analysis through automated algorithms[11,12]; increased objectivity in analysis, reducing human subjectivity in visual evidence assessment[13]; and assistance in post-mortem analysis for facial reconstruction and body identification in cases of significant degradation[14].

With technological advancements, image processing in medical forensics has seen rapid progress. Initially, forensic image analysis was conducted manually using microscopes and conventional photography techniques. However, with the development of Artificial Intelligence (AI), Machine Learning, and Computer Vision, numerous new algorithms have been designed to enhance forensic analysis accuracy. Significant advancements in this field include AI-based image processing with Neural Networks to identify patterns in images with higher accuracy, the application of Deep Learning techniques such as Convolutional Neural Networks (CNN) for forensic image analysis, including facial identification and image reconstruction, image metadata analysis and detection of digital manipulation in digital forensics, as well as Super-Resolution Imaging to improve the quality of forensic evidence that is blurred or of low resolution[15,17].

Various techniques have been developed in image processing for medical forensics to assist in image analysis. Key techniques include enhancement and denoising. These methods improve image quality by removing noise and enhancing contrast, allowing for better visibility of details. Another technique is edge detection and feature extraction, such as Canny Edge Detection, which helps extract critical features from images. Pattern recognition is also used for matching patterns in fingerprints, facial features, and anatomical structures. Image segmentation isolates important parts of an image, such as identifying traumatized tissues or analyzing wounds. Lastly, 3D reconstruction creates three-dimensional models from medical imaging results, such as CT scans or MRIs, for further analysis[18].

Image processing technology in medical forensics has been widely applied to support legal and medical investigations. One major application is facial identification, which helps match

victims or suspects with police databases[14,19]. It is also crucial in injury and wound analysis, where image processing can determine the cause of injuries from blunt objects, sharp objects, or gunshot wounds[15,20].Fingerprint forensics relies on digital algorithms for accurate fingerprint matching, aiding in precise identification[9]. In addition, radiological image analysis utilizes image processing from CT scans, MRI, or X-rays to identify fractures, head trauma, or other internal injuries. Facial reconstruction plays a vital role in cases where the body has undergone severe degradation, making conventional identification methods difficult. Finally, digital forensics includes techniques such as image manipulation detection, metadata analysis, and verification of visual evidence authenticity to ensure the integrity of digital evidence.

Image processing has revolutionized medical forensics by enhancing precision, efficiency, and reliability in investigations. With technological advancements such as artificial intelligence and deep learning, forensic image analysis will continue to evolve towards greater sophistication and accuracy. In the future, the integration of this technology with other forensic analysis systems will further strengthen the accuracy of legal investigations and forensic identification processes. By analyzing large volumes of data, this bibliometric study can identify emerging research trends, popular topics, and key areas of scientific inquiry. This study also quantifies research outputs such as journal articles, citations, and social media mentions, providing a means to evaluate researcher productivity, collaboration, and impact [21-23].

METHOD

This study analyzed global research trends in forensic image processing from 1962 to 2024 using the Scopus database. This study uses the Scopus database, because it is one of the largest curated abstract and citation databases, covering a broad range of scientific journals, conference proceedings, and books globally and regionally. It ensures high-quality data through rigorous content selection and continuous re-evaluation by an independent Content Selection and Advisory Board [24,25]. The search query used was TITLE-ABS-KEY (forensic AND image AND processing), conducted in January 2025, resulting in 4,463 articles. The filter applied in this study was publications released from the first record up to the year 2024. Data mining techniques were employed to extract bibliometric information, such as publication year, aAuthorship, country of origin, and key research topics. The retrieved data, including publication years, authors, affiliations, and keywords, were analyzed using VOSviewer for network visualization and Microsoft Excel for descriptive statistics [26-28].

RESULTS

Based on Fig 1., The first article about forensic image processing published in 1962 that the title "Petrography Applied to Portland-Cement Concrete". The article discuss about photo analysis and interpretation in engineering geology investigations [29]. After that article is published, the related topic article tends to stagnant until 1993. After 1993, publications on forensic image processing increased drastically and peaked in 2017, reaching an all-time high. In that year, the majority of publications discussed image authentication, enhancement, and applications of deep learning. America and China led in publications that year with Forensic Science International Journal being the largest publication venue.

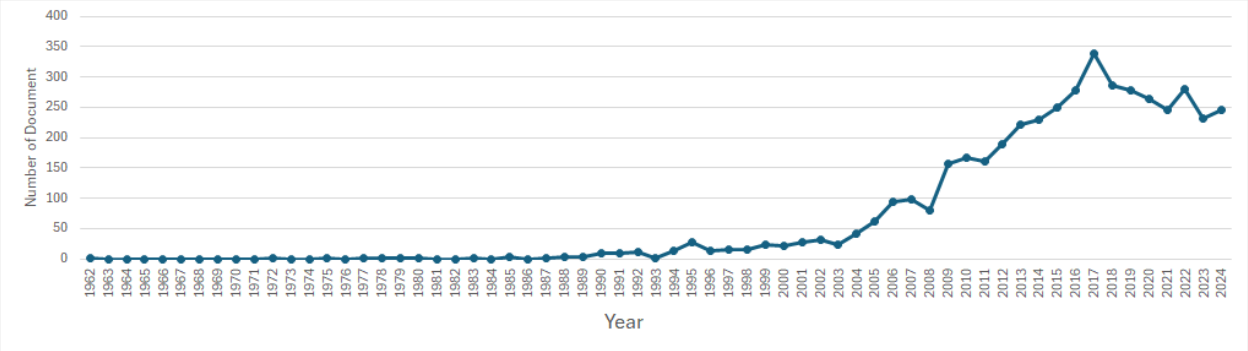

Fig. 1. Publication trend on forensic image processing

Based on the relationship between co-authorship and alignment of research topics, four major clusters were found in the bibliometric analysis of the author cooperation network (Figure 2) using VOSviewer. Several writers who dominated publications between 2014 and 2016 are included in the first cluster (purple), including Swaminathan Ashwin, Stamm Matthew C., and Liu K. J. Ray. The digital revolution fueled advances in forensic image processing between 2014 and 2016, resulting in the creation of new methods and techniques that could have a big influence on forensic investigations. As a result, forensic evidence became more dependable and of higher quality, which made it simpler to provide in court [30].

Authors like Huang Jiwu and Kang Xangui, who were active in the middle of the decade and mostly concentrated on the field of digital forensics, make up the second cluster (blue). Advances in digital imaging methods have transformed the use of digital images in investigations and increased forensic capabilities [31,32]. The third cluster (yellow) is composed of Zhao Yao, Piva Alessandro, and Barni Mauro. This team advanced methods for detecting picture manipulation, increasing the precision of digital forensics and enhancing forensic technology's capacity to address the problems associated with digital image modification in the contemporary period. Cozzolino Davide, Bestagini Paolo, and Tubaro Stefano dominate the fourth cluster (green). Cozzolino Davide, Bestagini Paolo, and Tubaro Stefano dominate the fourth cluster (green). This group, which was active from 2018 to 2020, concentrated on the use of deep learning in

multimedia forensics, synthetic picture analysis, and source device identification. This suggests that research is moving in the direction of integrating AI technologies.

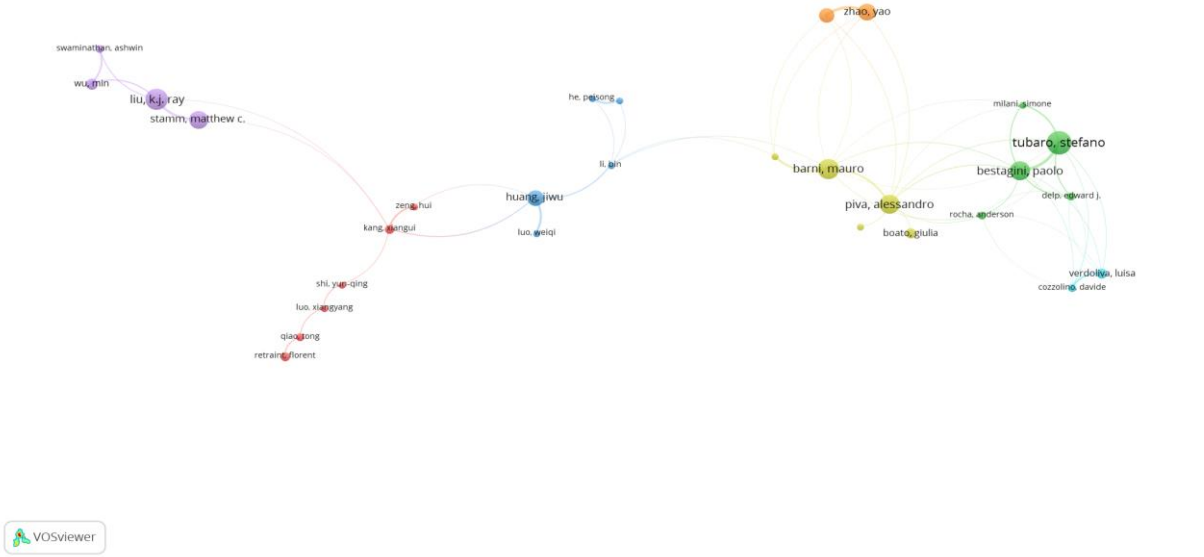

Figure. 2. (A) Network visualization of author distribution and collaboration with VOSviewer. The length of the connection indicates the level of linkage, with a minimum of eleven documents.

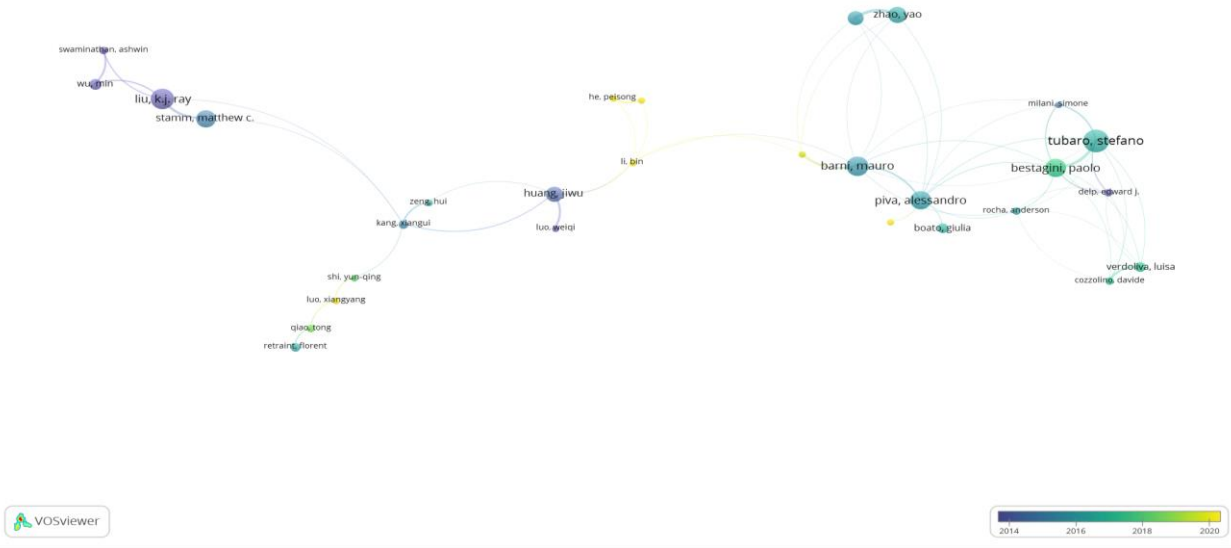

Figure. 2. (B) Overlay visualization of author distribution and collaboration with VOSviewer. The length of the connection indicates the level of linkage, with a minimum of eleven documents.

Research articles published by several countries is analyzed by VOS viewer. The result is divided into seven cluster according to amount of articles published. They are divided in different colours, which are purple, green, red, orange, yellow, dark blue and light blue. The greatest amount

of publication was belonged to China which is shown by purple colour, followed by United States and India which are shown by green and red colours. Institutions like Indian Institute of Technology (IIT) in India, Sun Yat-Sen University and Chinese Academy of Sciences (CAS) in China, and A. James Clark School of Engineering in United States have been pivotal in advancing research in image processing and forensics. Collaborative efforts and the establishment of specialized databases have also played a significant role [33]. United States and United Kingdom publish a lot of articles in 2012, on the other hand China and India publish a lot of articles between 2016 to 2018. The most recent articles is published in Egypt and Oman around 2020.

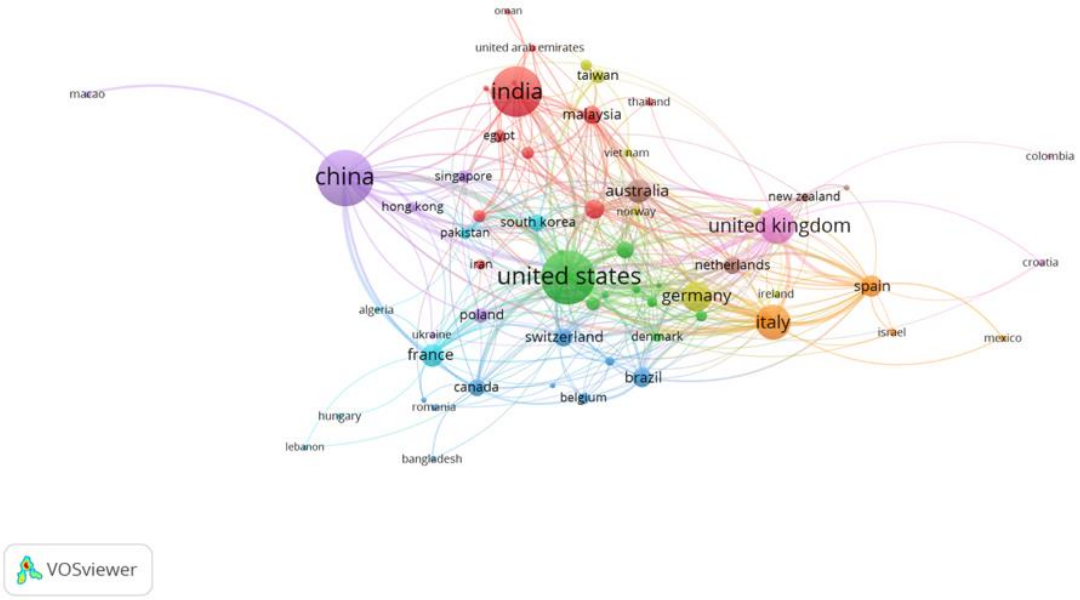

Figure. 3. (A) Network visualization of country mapping with VOS viewer. The length of the connection indicates the level of linkage, with a minimum number of documents per author is five documents

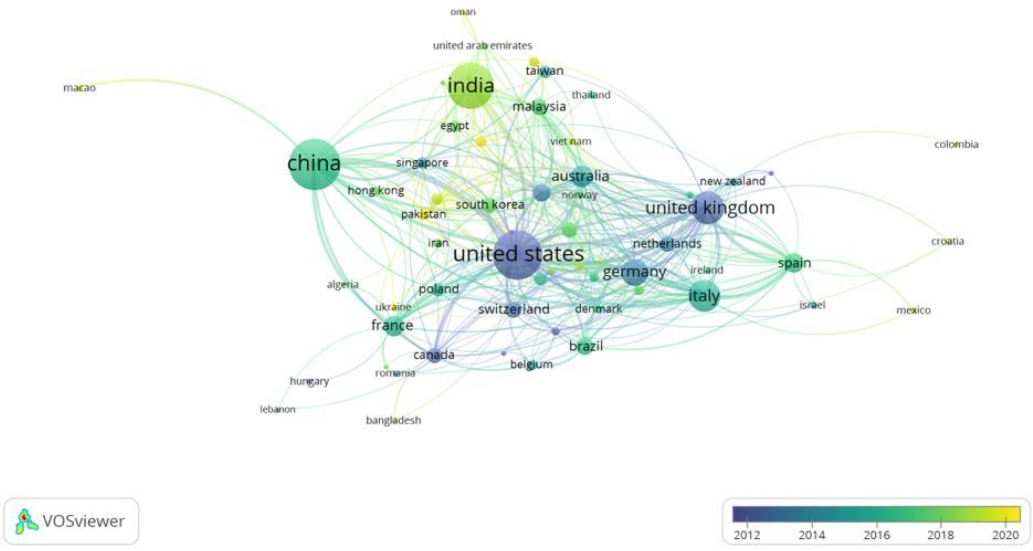

Figure. 3. (B) Overlay visualization of country mapping with VOS viewer. The length of the connection indicates the level of linkage, with a minimum number of documents per author is five documents.

The visualization produced using the VOSviewer software in Fig. 4 illustrates the conceptual relationships among various terms related to image processing and digital forensics. In the cluster density map, the term image processing is positioned at the center of the cluster, highlighting its central role within this domain. The left side of the visualization is predominantly red, indicating that keywords such as digital forensics, image forensics, deep learning, and convolutional neural network are closely interconnected, forming a primary network in the field of digital forensics. Meanwhile, the right side of the visualization is more dominated by green, linking image processing to medical forensic disciplines, including forensic medicine, forensic anthropology, and diagnostic imaging.

In the overlay visualization, the conceptual network not only illustrates the interconnections among terms but also provides a temporal indication of research development in this field. Blue hues represent terms more commonly used in earlier periods, while yellow hues reflect concepts that have increasingly gained traction in recent research. This progression demonstrates how the field of image processing has evolved, with technologies such as deep learning and pattern recognition becoming more prominent in recent years. The term digital forensics, which was more prevalent in the early stages, has become increasingly integrated with newer artificial intelligence methods.

The network structure in this visualization further highlights the close relationship between image processing and various related disciplines, both from computational and medical forensic perspectives. The network in the figure showcases how image processing is utilized not only in the context of digital forensics for analyzing images related to cybercrime but also in medical forensics and anthropology for forensic identification and diagnostic imaging purposes. The red and green colors in the network visualization demonstrate a conceptual separation between two major areas, yet reveal a strong connection through shared core terms such as image processing and image analysis.

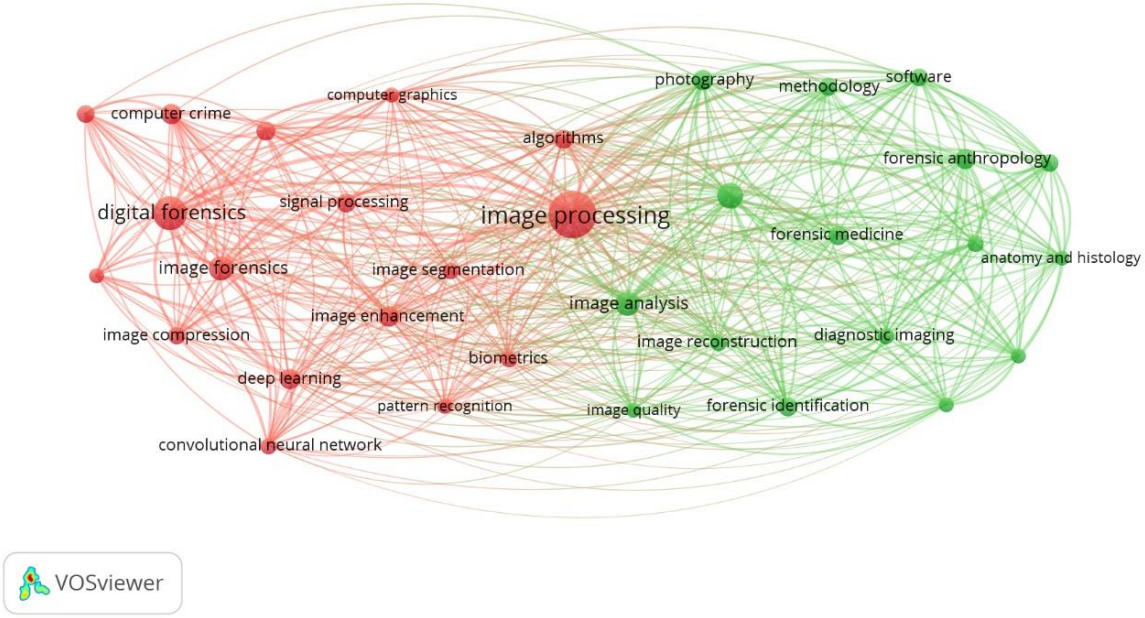

Figure. 4. (A) Network visualization of keyword mapping of forensic entomology

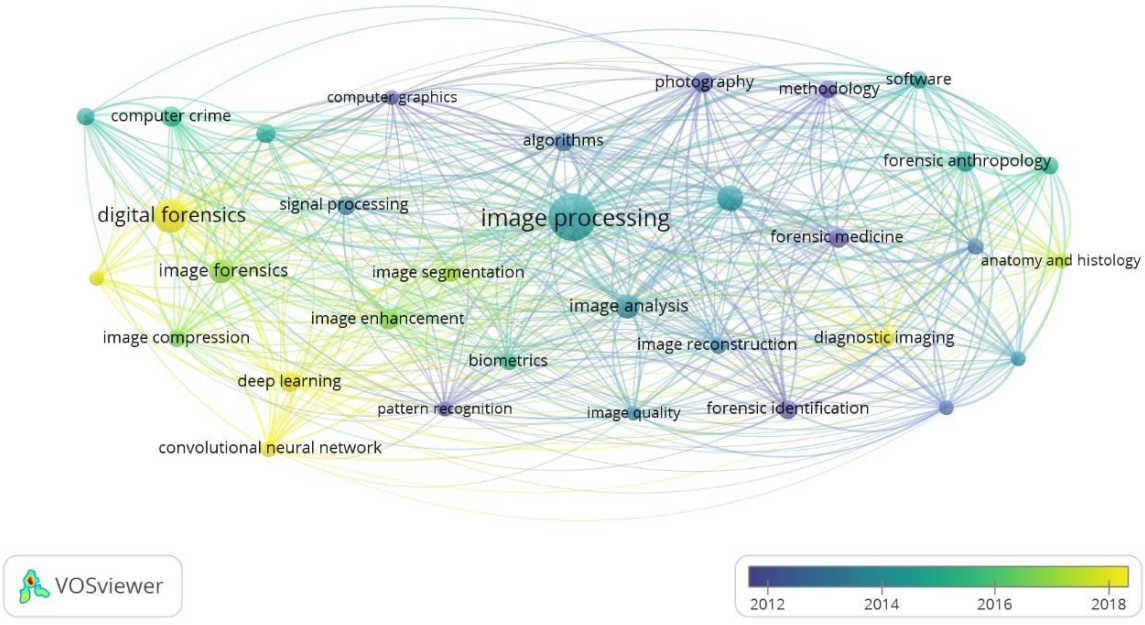

Figure. 4. (B) Overlay visualization of keyword mapping of forensic entomology

Figure. 4. (C) Cluster density visualization of keyword mapping of forensic entomology

Table 1. The most cited articles on forensic image processing.

SCR	*Article Title*	*Author*	*Journal*	*Vol (No)*	*Year*	*Citation*	*Ref*
1	Digital camera identification from sensor pattern noise	Lukáš, J., Fridrich, J., Goljan, M.	IEEE Transactions on Information Forensics and Security	1(2), pp. 205–214	2006	1113	[34]
2	Exposing digital forgeries by detecting traces of resampling	Popescu, A.C., Farid, H.	IEEE Transactions on Signal Processing	53(2 II), pp. 758–767	2005	830	[35]
3	Exposing Deep Fakes Using Inconsistent Head Poses	Yang, X., Li, Y., Lyu, S.	ICASSP, IEEE International Conference on Acoustics, Speech and Signal Processing - Proceedings	2019-May, pp. 8261–8265, 8683164	2019	779	[36]
4	Determining image origin and integrity using sensor noise	Chen, M., Fridrich, J., Goljan, M., Lukáš, J.	IEEE Transactions on Information Forensics and Security	3(1), pp. 74–90	2008	747	[37]
5	An evaluation of popular copy-move	Christlein, V., Riess, C., Jordan, J.,	IEEE Transactions on Information	7(6), pp. 1841–1854, 6301704	2012	700	[38]

	forgery detection approaches	Riess, C., Angelopoulou, E.	Forensics and Security				
6	Modern Trends in Hyperspectral Image Analysis: A Review	Khan, M.J., Khan, H.S., Yousaf, A., Khurshid, K., Abbas, A.	IEEE Access	6, pp. 14118–14129	2018	637	[39]
7	Virtopsy, a new imaging horizon in forensic pathology: Virtual autopsy by postmortem multislice computed tomography (MSCT) and magnetic resonance imaging (MRI) - A feasibility study	Thali, M.J., Ye, K., Schweitzer, W., ... Plattner, T., Dirnhofer, R.	Journal of Forensic Sciences	48(2), pp. 386–403	2005	558	[40]
8	Imaging spectroscopy using tunable filters: A review	Gat, Nahum.	Proceedings of SPIE - The International Society for Optical Engineering	4056, pp. 50–64	2000	590	[41]
9	Exposing digital forgeries in color filter array interpolated images	Popescu, A.C., Farid, H.	IEEE Transactions on Signal Processing	53(10 II), pp. 3948–3959	2005	558	[42]
10	CASIA image tampering detection evaluation database	Dong, J., Wang, W., Tan, T.	2013 IEEE China Summit and International Conference on Signal and Information Processing	ChinaSIP 2013 - Proceedings, pp. 422–426, 6625374	2013	554	[43]

Based on the data in table 1, the most cited article in the field of forensic image processing is "Digital camera identification from sensor pattern noise" written by Lukáš, J., Fridrich, J., and Goljan, M. This article was published in the IEEE journal Transactions on Information Forensics and Security in 2006, in volume 1 number 2, with 1,113 citations. This large number of citations shows the importance of this article in developing research related to digital camera identification based on sensor patterns.

The article that ranks second in number of citations is "Exposing digital forgeries by detecting traces of resampling" by Popescu, A.C., and Farid, H. This article was published in IEEE Transactions on Signal Processing in 2005, with a total of 830 citations. Furthermore, the article in third place is "Exposing Deep Fakes Using Inconsistent Head Poses" written by Yang, X., Li, Y., and Lyu, S., and published in the ICASSP conference proceedings in 2019. This article has been

cited as many times 779 times, reflecting increasing academic attention to the issue of digital forgery using deepfake technology.

In the bottom three positions, there is the article "Exposing digital forgeries in color filter array interpolated images" which was also written by Popescu and Farid in 2005, as well as "Virtopsy, a new imaging horizon in forensic pathology" by Thali et al. published in the same year, each received 558 citations. The last article on the list is "CASIA image tampering detection evaluation database" written by Dong, J., Wang, W., and Tan, T., published in 2013, with a total of 554 citations.

Table 2. The top ten authors on forensic image processing research.

SCR	***Author***	***Document Number***
1	Tubaro, S.	39
2	Liu, K.J.R.	35
3	Barni, M.	33
4	Bestagini, P.	32
5	Piva, A.	31
6	Stamm, M.C.	30
7	Li, C.T.	27
8	Huang, J.	26
9	Zhao, Y.	25
10	Ni, R.	25

Based on the data in table 2, the author with the highest number of publications in forensic image processing is Tubaro, S., with a total of 39 documents. In second place is Liu, K.J.R., who has published 35 documents, followed by Barni, M., with 33 documents. Meanwhile, in the bottom three positions are Huang, J., with 26 documents, and Zhao, Y. and Ni, R., who have each published 25 documents.

Table 3. The most contributed journal on forensic image processing.

SCR	Journal	Document Number
1	Forensic Science International	270
2	Journal Of Forensic Sciences	190
3	Proceedings Of SPIE The International Society For Optical Engineering	184
4	Lecture Notes In Computer Science Including Subseries Lecture Notes In Artificial Intelligence And Lecture Notes In Bioinformatics	157
5	Multimedia Tools And Applications	96
6	International Journal Of Legal Medicine	91
7	Proceedings International Conference On Image Processing Icip	90
8	IEEE Transactions On Information Forensics And Security	84
9	ICASSP IEEE International Conference On Acoustics Speech And Signal Processing Proceedings	73
10	Advances In Intelligent Systems And Computing	51

Table 3 highlighted the top 10 sources of publications contributing to the field of forensic image processing, emphasizing the pivotal role of leading journals and conferences in disseminating research and advancements. Among these, Forensic Science International (FSI) stood out as the most significant contributor, with an impressive 270 documents, solidifying its position as the premier journal in forensic science research. The most affiliation in FSI was the Netherlands Forensic Institute (NFI) with 15 documents. Although not listed in the top 10 cited journals, FSI had a journal with 373 citations [44].

Following FSI, the Journal of Forensic Sciences secured the second rank with 190 publications, reflecting its importance in covering a wide range of topics within forensic investigations. Meanwhile, Proceedings of SPIE: The International Society for Optical Engineering occupies the third position with 184 documents, showcasing the integration of optical engineering technologies in forensic applications [41,45]. In fourth place was Lecture Notes in Computer Science, including its subseries in Artificial Intelligence and Bioinformatics, with 157 publications. This highlighted the growing impact of computational methods and artificial intelligence in advancing forensic research [46]Click or tap here to enter text..

Multimedia Tools and Applications, ranked fifth (n=96), followed by The International Journal of Legal Medicine (n=91), Proceedings of the International Conference on Image Processing (ICIP) (n=90), IEEE Transactions on Information Forensics and Security, ranked eighth with (n=84), IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)

(n=73), and Advances in Intelligent Systems and Computing (n=51). Fostering collaborations across these journals and conferences and encouraging interdisciplinary research will be essential in advancing the field of forensic image processing. By promoting cross-disciplinary partnerships, researchers can integrate insights from forensic science, engineering, computer science, and signal processing to develop innovative tools and techniques. Such collaborations will not only enhance the understanding of forensic image processing but also pave the way for novel applications in legal investigations, ultimately strengthening the reliability and effectiveness of forensic analyses in handling complex visual evidence [47,48].

Table 4. The institution with the top publication of forensic image processing

SCR	***Institution***	***Country***	***Document Number***
1	Sun Yat-Sen University	China	58
2	Chinese Academy of Sciences	China	52
3	Università degli Studi di Firenze	Italy	44
4	Politecnico di Milano	Italy	43
5	Netherlands Forensic Institute – NFI	Netherlands	42
6	A. James Clark School of Engineering	United States	40
7	CNRS Centre National de la Recherche Scientifique	France	39
8	Hunan University	China	39
9	Ministry of Public Security of the People's Republic of China	China	39
10	Università degli Studi di Siena	Italy	37

Table 4 presented a quantitative overview of the top ten institutions actively contributing to the field of forensic image processing. The ranking is based on the number of scientific publications, a key indicator of research productivity and academic impact within this discipline. The data reveals that Sun Yat-Sen University from China occupies the top position with 58 publications, followed by the Chinese Academy of Sciences in second place with 52 publications, thereby confirming China's dominant role in this research area [49,50]. Italy also emerges as a key player, with three institutions—Università degli Studi di Firenze (44 publications), Politecnico di Milano (43 publications), and Università degli Studi di Siena (37 publications)—all positioned within the top ten. This indicates that Italy possesses a robust academic framework for forensic science and a high level of expertise in image processing techniques [51-53].

The involvement of the Netherlands Forensic Institute – NFI, with 42 publications, highlights the importance of practical applications and collaboration within forensic science.

Meanwhile, the A. James Clark School of Engineering from the United States, with 40 publications, demonstrates that engineering departments are also significant contributors, particularly emphasizing the technological aspects of forensic image processing. Three institutions share the seventh position with 39 publications each: the CNRS Centre National de la Recherche Scientifique (France), Hunan University (China), and the Ministry of Public Security of the People's Republic of China, showcasing a cluster of institutions with comparable research output. The global nature of forensic image processing research highlighted the contributions of both academic and governmental actors from around the world. This suggested that progress in the field was not confined to specific regions or institutions but rather represented a collaborative global endeavor [54,55].

Table 5. The top ten country on forensic image processing research.

SCR	***Country***	***Document number***	***Collaborating country number***
1	China	791	24
2	United States	739	42
3	India	649	24
4	United Kingdom	342	44
5	Italy	313	26
6	Germany	222	24
7	Australia	141	33
8	France	130	22
9	Spain	116	26
10	Brazil	99	15

Table 5 shows an overview list of the ten leading countries contributing to forensic image processing research, ordered by the number of documents produced. China leads with 791 documents, followed by the United States (n = 739), and India (n = 649). These three countries dominate the field, producing a large amount of research publicaton. The United Kingdom ranks fourth with 342 documents, demonstrating its significant contribution to the field despite a lower total compared to the top three. The list is completed by Italy (n = 313), Germany (n = 222), Australia (n = 141), France (n = 130), Spain (n = 116). Brazil contributing the fewest publications on that list (n = 99).

The United Kingdom is the most active country collaborating with researchers from 44 countries, followed by United States (n = 42), Australia (n = 33), Italy (n = 26) and Spain (n = 26) in a similar number, China (n = 24), India (n = 24) and Germany (n = 24) in similar number, France (n = 22). The fewest country collaborating number on that list is Brazil (n = 15). Although China and India have a very large number of documents, each has a relatively limited collaborative network, with 24 countries.

DISCUSSION

Figure 1

There are many factors contribute, such as technological limitation and lack of digital tools for the image analysis [31,32]. Digital revolution happen in the early of 1990s make a transition from analog to digital method which triggered many articles to be uploaded. Significant technology advantages such as digital cameras, image processing software and incrased storage capacities make the researcher easier to capture and analyzing the images [32]. Interdisciplinary collaboration between expert in computer, forensic medicine, and the other discipline also make the published article increased year by year in early 1990s [56]. The year 2017 marked a peak publication, as the application of deep learning techniques to digital image forensics (DIF) began to gain traction around this time [57]. Digital image forensics is a specialized branch of digital forensics that focuses on the analysis and verification of digital images to determine their authenticity and origin. This field involves various techniques to detect image forgeries, identify the source of an image, and ensure the integrity of digital content [58]. On the other hand, the decline in publication trend on forensic image processing is multifaced, involving increased complexity in Image Forensics, technological limitaions, and research focus shifting to genetics and pathology [59,60]. The complexity in image forensics has increased significantly since 2017 due to several factors, leading to a decrease in publications. The rise of sophisticated image editing tools and the widespread availability of high-quality image manipulation software have made it easier to create doctored images, complicating the detection process [61]. Additionally, the integration of deep learning techniques, while promising, has introduced challenges related to the interpretability and robustness of these methods [62]. Moreover, the emergence of adversarial attacks on forensic models has added another layer of complexity, making it harder to develop reliable detection systems [62]. These challenges, combined with the necessity for interdisciplinary collaboration and the slow adoption of automated tools in practical applications, have contributed to a decline in the rate of new publications in the field [63].

Figure 2

According to Figure 2, the purple cluster—which includes Swaminathan Ashwin, Stamm Matthew C., and Liu K. J. Ray—had the most publications in the early years of 2014–2016. The cluster made a significant contribution by doing groundbreaking research that subsequently inspired other academics to contribute to the development of forensic image processing, as evidenced by the preponderance of publications during this time. The formation of a new red cluster, with scholars like Zeng Hui, Shi Yun-Qing, Luo Xiangyang, and Kang Dangui, is an advancement of earlier studies. Digital image processing techniques are among the emerging

methods in digital forensic investigation that have become the focus of this group's discussions. Digital image processing is integrated into forensic programs to maximize information extraction from crime scenes and improve the quality of evidence. The preservation of the legal value of findings depends on methods including picture enhancement, restoration, and authentication [30,32,64].

These clusters were created through institutional cooperation and shared research topics. It is clear that research has evolved from basic manipulation to the use of artificial intelligence for more intricate analysis. As a result, this visualization offers detailed information about the dynamics of collaboration and current trends in research on forensic image processing.

Figure 3

China and india leading in publication of new articles acoording to increasing awareness and research focus to the application on deep learning technique in digital image forensic[65,66]. Both countries have seen support from various funding agencies and institutions, which has facilitated extensive research and development in image processing and forensics[65].The National Natural Science Foundation of China (NSFC) funded 352 projects in forensic science from 2000 to 2019, with a total funding of 174.69 million yuan [66,67]. India has a lower overall funding ratio compared to China, with 58.2% of research publications being funded, this indicates that while there is support for research, it may not be as extensive as in China but comparing with the other these two countries have the most funding for the research [68]. The collaboration between the top ten countries in publishing image processing forensic articles is robust, with the USA and European countries leading the way [69]. There is a growing trend of international cooperation, particularly with China, and emerging contributions from countries like India and Italy[65].

Figure 4

In the data visualization generated using VOSviewer in Fig.4.A-B, the division into two main clusters is clearly visible. These clusters are identified based on the interconnection of keywords that support research, providing insights into the evolution of research topics and future development directions.

The red cluster includes topics such as digital forensics, image forensics, deep learning, convolutional neural network, and pattern recognition. The primary focus of this cluster is on digital image processing technology and the application of artificial intelligence in forensics. Keywords such as signal processing, image compression, and image enhancement reflect an emphasis on optimizing digital data to support investigations and analyses. On the other hand, the green cluster includes topics such as forensic medicine, diagnostic imaging, image analysis, forensic anthropology, and image reconstruction. This cluster focuses on forensic applications in

the medical field, including image-based identification techniques and the development of improved diagnostic methods.

The evolution of keywords from 2010 to 2020 indicates significant shifts in trends (Fig.4.C) In the early phase, keywords such as forensic medicine and anatomy and histology dominated, indicating a primary focus on traditional aspects of forensic science, particularly those related to biological and medical analysis. Forensic medicine traditionally relied on methods from chemistry, biology, and optical technologies like microscopy for examining evidence [70]. Techniques such as autopsies, toxicology, DNA analysis, and forensic anthropology were pivotal in criminal investigations [71].

During the period from 2015 to 2017, keywords such as image analysis, image segmentation, and biometrics emerged, reflecting a shift toward the integration of image processing technologies. This development enhanced the efficiency of forensic identification. The integration of radiology and imaging techniques, such as CT and MRI, became more prevalent in forensic examinations [72,73]. Digital pathology and forensic radiology also emerged, utilizing imaging for diagnostics and legal investigations [74,75].

In subsequent years, from 2018 to 2020, keywords such as deep learning, digital forensics, and convolutional neural network became dominant. This signifies a growing interest in artificial intelligence-based technologies that enable big data analysis for forensic purposes with more accurate and rapid results. Artificial intelligence (AI) and machine learning have significantly impacted digital forensics, enhancing the efficiency and accuracy of investigations [76–78]. AI applications in forensic science include biometric analysis, image processing, and the automation of digital evidence analysis [79–81]. AI-driven tools are used for tasks such as pattern recognition, image identification, and natural language processing, aiding in the rapid analysis of large datasets [76–78].

Keywords marked in yellow, such as digital forensics, deep learning, and convolutional neural network, show great potential to become primary research focuses in the future (Fig.4.D). The future of forensic science lies in the integration of digital and medical technologies to improve forensic analysis [82–84]. Predicted developments include AI innovations for big data analysis, advancements in image processing techniques like image reconstruction and image enhancement, and the integration of digital and medical technologies enabling new approaches to resolving complex cases. AI is expected to play a crucial role in enhancing diagnostic accuracy, automating evidence processing, and providing real-time analysis [76–78].

This cluster visualization analysis illustrates the dynamic evolution of forensic research, with differing focuses between digital technologies and medical sciences. Collaboration between forensic experts and AI technologies will be essential to address challenges such as data quality, ethical considerations, and the need for explainable AI models [79,85,86]. Deep learning has revolutionized investigative techniques in forensic science, particularly in biometric analysis, digital forensics, and image processing. It has expanded the scope of forensic science beyond traditional fingerprint recognition to include facial, iris, voice recognition, and gait analysis [74]. Image-based diagnostics in forensic analysis are gradually shifting regarding computer-aided solutions, with a focus on deep learning-assisted biomedical image analysis. This approach is known for its efficiency and has the potential to improve the quality of diagnosis in forensic medicine [75].

Overall, the red cluster demonstrates the dominance of artificial intelligence-based technologies in digital forensics, while the green cluster highlights the importance of medical research in supporting biological forensics. Future trends are expected to increasingly integrate modern technologies with traditional approaches, creating significant innovations in the field of forensics. Researchers are encouraged to utilize these insights to guide their studies according to future needs and challenges.

Table 1

Table 1 shows that the study titled "Digital Camera Identification from Sensor Pattern Noise" has the highest number of citations, totaling 1,113 citations. This journal discusses a technique for identifying digital cameras based on sensor pattern noise (SPN), which is a unique fingerprint left by the camera sensor on each image. SPN is a noise pattern inherent to every camera sensor and can be used to identify the source camera of a digital image. This noise pattern acts as a fingerprint for the camera [87].

The technique involves extracting the SPN from images using denoising filters and comparing this noise pattern to a reference pattern created from multiple images taken by the same camera. The presence of the reference pattern in an image is determined using a correlation detector. The method relies on extracting SPN from images using wavelet-based denoising filters. This SPN serves as a unique identifier for each camera, similar to a fingerprint [87,88].

This technique demonstrates robustness against common image processing operations such as JPEG compression, gamma correction, and resizing, making it highly practical for forensic applications. The method's potential in forensic science has drawn significant attention. It provides a reliable way to link images to their source cameras, which is crucial for legal and investigative purposes [88,89].

The journal was published by IEEE Transactions on Information Forensics and Security (T-IFS), which is highly regarded and has a significant impact factor, contributing to its visibility and citation count [90]. The journal publisher has demonstrated the ability to adapt to the evolving landscape of information forensics and security. Over the past decade, its focus areas have been continuously updated to include emerging topics, ensuring relevance to current scientific and industrial challenges [91]. The journal also maintains rigorous publication standards. For instance, the IEEE Workshop on Information Forensics and Security (WIFS), associated with T-IFS, had a highly selective acceptance rate, with only 48 out of 160 submissions accepted in 2012. This selectivity ensures that only high-quality research is published [92].

In addition to its practical applications in forensic science, the authors of this journal, Lukás, J., Fridrich, J., and Goljan, M., are well-known in the field of digital forensics and have strong academic reputations. Their previous and subsequent works have also been highly influential, adding to the credibility and citation count of this paper [93,94].

This research is a collaboration between the three authors, who come from different institutional backgrounds. Lukás, J., is from Honeywell International Inc., a diversified technology and manufacturing company serving customers worldwide with products and services in aerospace, control technologies, sensors, and security for buildings, homes, and industries [95]. Meanwhile, Fridrich, J., and Goljan, M., are from Binghamton University, State University of New York, known for its reputation as a leading public university offering high-quality education, supported by excellent faculty, cutting-edge research opportunities in various fields such as technology, biomedicine, and digital imaging, as well as an academic environment that fosters innovation and collaboration [96].

All three authors are based in the United States, a country that has been a prolific contributor to research in digital camera identification using sensor pattern noise. This is driven by the rapid advancements in digital camera technologies, which have made digital imaging more affordable and accessible. The use of sophisticated digital image processing tools in the United States provides effective means for manipulating images, increasing the frequency and importance of digital images in forensic investigations [97].

This first journal is also supported by the second-ranked journal titled “Exposing Digital Forgeries by Detecting Traces of Resampling” by Popescu, A.C., and Farid, H., published in 2005. Both journals make significant contributions to digital forensics. The first study focuses on camera identification through the unique sensor pattern noise (SPN), while the second detects image forgery by analyzing traces of resampling, a common manipulation technique [87,98].

These two methods are complementary: SPN is effective in tracking image origins but is less robust against noise removal, while resampling detection reveals image manipulation without identifying the source device. Combining both methods enables a more comprehensive forensic analysis, both for device identification and image integrity verification [87,98].

This research serves as a cornerstone in the field of digital forensics for source camera identification.

Table 2

Table 2 provides a comprehensive overview of the scholars who are significantly engaged in research endeavors and scholarly publications pertinent to the domain of forensic image processing. Among them, Tubaro, S. emerges as the most productive author, with an impressive total of 39 publications, showcasing significant engagement in the field. In contrast, Ni, R. has made a modest contribution, with 25 publications, reflecting a comparatively lower level of research output.

Based on Scopus data, research contributions in the field of forensic image processing show the dominance of several prominent authors (table 2). Tubaro, S**.** emerges as the most productive author with a total of 39 published documents. This author hails from Italy and is a professor in telecommunications at Politecnico di Milano. He has authored over 180 scientific publications in international journals. In recent years, he has focused his interests on developing innovative techniques for detecting image and video manipulation. Tubaro's productivity can be attributed to his focus on key topics such as digital image forgery detection and sensor noise analysis for camera identification, which form the core of forensic image processing research. Although his contributions are not directly linked to the most frequently cited articles in the table, Tubaro's productivity reflects his significant role in expanding the knowledge base in this field [99].

Other authors, such as Liu, K.J.R**.**, who ranks second with 35 documents, and Barni, M**.**, with 33 documents, also demonstrate significant influence. Liu, based in the United States, has made substantial contributions to the development of signal processing algorithms for forensic applications. He was a Distinguished Scholar-Teacher at the University of Maryland, College Park, MD, USA, in 2007, where he holds the position of Christine Kim Eminent Professor of Information Technology. Meanwhile, Barni, also from Italy, a professor in the Department of Information Engineering and Mathematics, University of Siena, 53100 Siena, Italy, is known for his contributions to forgery detection and the development of innovative image processing techniques [100].

The research by Tubaro, S., Liu, K.J.R., and Barni, M. is frequently published in high-impact journals such as *IEEE Transactions on Information Forensics and Security*, one of the leading

platforms for research in this field. Their contributions reflect not only quantity but also quality, as many of their works serve as essential references in the literature.

Table 3

Forensic Science International became the most significant contributor to the field of forensic image processing. FSI boasts a significant impact factor, a key indicator of a journal's reputation and influence. According to the most recent data, FSI has an impact factor of 2.2 and a 5-year impact factor of 2.3, however, the specialized nature of the field and its unique bibliometric patterns result in comparatively lower citation rates. This is partially because forensic research, by its nature, tends to attract fewer citations compared to studies in more general or widely applicable scientific disciplines [101,102].

At the moment, The Journal of Forensic Sciences ranked field of forensic image processing through several key factors, consistently publishing a large number of articles. This high volume of publications has helped it maintain a strong presence in the field [102,103]. The journal had also contributed to the development of new image-processing methodologies that provide objective data for forensic analysis, which is crucial for tasks like bloodstain pattern analysis and wound detection [104,105].

The Proceedings of SPIE, The International Society for Optical Engineering, has become a significant contributor to the field of forensic image processing, ranking as the number three journal in this domain. The journal covers a diverse range of specialized topics in forensic image processing, such as the detection of image manipulations, including median filtering, which reflects its focus on practical forensic techniques. It also delves into various forensic image analysis methods, including photogrammetry, photographic comparison, content analysis, and image authentication, all of which are critical for law enforcement applications. Additionally, the journal features research on camera forensics, such as identifying cameras through sensor fingerprints and analyzing lateral chromatic aberration, providing valuable tools for forensic investigators [106–109].

Table 4

Forensic image processing research has become a global effort, with both government and academic institutions playing key roles. The progress in this field is a testament to international collaboration rather than being limited to specific regions or institutions [54,55]. Leading research institutions worldwide have significantly contributed to methodological and technological advancements in forensic image processing. Institutions from China, Italy, the Netherlands, the United States, and France stand out for their extensive contributions to this field.

At the forefront are Sun Yat-Sen University and the Chinese Academy of Sciences, with 58 and 52 publications, respectively. These institutions are highly regarded for their expertise in AI-driven forensic image analysis and digital forensics [110,111]. China's commitment to forensic technology is underscored by the collaborative efforts of institutions like Hunan University and the Ministry of Public Security. These efforts include technological integration, intelligence reforms, educational contributions, and ongoing standardization initiatives, all aimed at enhancing the effectiveness and reliability of forensic science in the country [112–115].

In Europe, Politecnico di Milano and Università degli Studi di Firenze lead with 43 and 44 publications, respectively. These universities are known for their state-of-the-art labs specializing in AI-based forensic image processing. Università degli Studi di Siena, with 37 publications, also plays a crucial role in digital forensics research. The Netherlands Forensic Institute (NFI), with 42 publications, is a key player in setting forensic imaging standards and developing methodologies. In the United States, the A. James Clark School of Engineering has contributed 40 publications, emphasizing its role in advancing forensic technology, particularly through AI and machine learning applications.

The main focus areas among these institutions include forensic image processing, digital forensic imaging, and AI integration in forensic analysis. Digital forensic imaging employs image reconstruction techniques for criminal investigations, while AI continues to enhance automation and identification accuracy. Deep learning methods are increasingly used to refine, detect, and classify forensic images affected by environmental conditions [116,117].

Table 5

China has the largest number of research publication because of a strong focus on domestic collaboration, national research priorities, and rapid internal growth. Language barriers, cultural differences, and limited international network contribute to fewer global collaboration [118]. Over the years, China and the United States have built a strong scientific partnership. Their partnership driven by common interests and mutual benefits. Their collaboration has expanded significantly since establishing formal relations in the 1970s, fuelled by China's enhanced research capacity and heavy investment in research and development. With an increasing number of high-quality publications, China has become an important partner for US scientists [119].

Brazil's low contribution to forensic image processing research is influenced by economic constraints and research priorities. Historical financial difficulties, economic recessions, and disparities in infrastructure have hindered research development and accessibility. Furthermore, Brazilian institutions, particularly the University of São Paulo (USP), have traditionally focused on fundamental biological research, often following international trends rather than prioritizing

forensic science. This focus diverts resources from specialized fields like forensic image processing, limiting progress in this area [120,121].

India could become the top three in new article publications due to increased awareness, expanded research efforts, and strong institutional support. Since 2018, more studies on digital image forensics, particularly using deep learning, have emerged. India is also a top contributor to forensic medicine research, with steady growth in publications. Additionally, the country has established forensic science institutions like the National Forensic Sciences University, which play a key role in training forensic experts. These factors collectively strengthen India's presence in this important area of research [57,122].

CONCLUSION

The bibliometric analysis of forensic image processing highlights its growing significance in forensic investigations, particularly in enhancing image-based evidence analysis. The study reveals an increasing trend in research publications, with key contributions from interdisciplinary fields such as digital forensic, deep learning, convolutional neural network, and diagnostic imaging. These findings underscore the ongoing interest and advancements in forensic image processing, highlighting its significance and diverse applications in criminal investigations. Additionally, collaborations between academic institutions and law enforcement agencies play a crucial role in driving innovation in this field.

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