

# Scientific Landscapes of ECG Signal Processing: A Comprehensive Bibliometric Study

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## Abstract

This study presents a comprehensive bibliometric analysis of ECG signal processing research to understand its intellectual structure, growth trends, and emerging themes. The data for the study were retrieved from the Web of Science database using a structured search strategy focused on ECG and signal processing topics. After applying inclusion and exclusion criteria, a total of 1081 documents were selected for detailed analysis. The study employed bibliometric tools such as Biblioshiny, and VOSviewer to analyze publication trends, authorship patterns, sources, and collaboration networks. The findings reveal a steady growth in research output, with a significant surge observed after 2016, indicating increasing interest in the field. The analysis of authors shows a distributed pattern of contribution, with no single author dominating the domain. Leading journals such as IEEE Access and Sensors play a crucial role in disseminating research findings. The thematic analysis highlights the prominence of machine learning, deep learning, and feature extraction as core research drivers. The co-occurrence and collaboration networks indicate a strong integration of interdisciplinary approaches and global research partnerships. Overall, the study demonstrates that ECG signal processing is a rapidly evolving and impactful research area with significant potential for future advancements in intelligent healthcare systems.

**Keywords:** Electrocardiogram, ECG Signal Processing, Bibliometric Analysis, Biblioshiny, VOSviewer.

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## 1. Introduction

Electrocardiography is one of the most widely used non-invasive diagnostic techniques for monitoring cardiac activity, and its significance has grown substantially with the advancement of digital health technologies [1]. ECG signal processing refers to the application of computational methods to analyze electrical signals generated by the heart, enabling the detection of abnormalities such as arrhythmias, myocardial infarction, and other cardiovascular disorders [2]. Over the past few decades, the integration of signal processing techniques with biomedical engineering has transformed ECG analysis from manual interpretation to automated and intelligent systems [3]. This evolution has enhanced diagnostic accuracy, reduced clinical workload, and enabled real-time monitoring in both clinical and remote healthcare settings [4].

ECG signal processing involves several critical stages, including signal acquisition, preprocessing, feature extraction, and classification [5]. Raw ECG signals are often contaminated with noise such as baseline wander, power line interference, and muscle artifacts, which necessitates the use of

filtering and denoising techniques [6]. Advanced methods such as wavelet transforms, Fourier analysis, and adaptive filtering have been widely employed to improve signal quality and extract meaningful features [7]. These features, including QRS complex, P waves, and T waves, are essential for identifying cardiac conditions and assessing heart health [8]. The increasing use of wearable devices and mobile health applications has further accelerated the need for efficient and robust ECG signal processing techniques [9].

In recent years, the convergence of artificial intelligence and machine learning with ECG signal processing has opened new avenues for research and innovation [10]. Deep learning models, particularly convolutional neural networks and recurrent neural networks, have demonstrated remarkable performance in automated ECG classification and anomaly detection [11]. These approaches enable large-scale data analysis and facilitate early diagnosis of cardiovascular diseases [12]. Furthermore, the availability of large biomedical datasets and open-source tools has contributed to rapid advancements in this field. As a result, ECG

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signal processing has emerged as a multidisciplinary domain involving computer science, biomedical engineering, and healthcare analytics [13].

The scope of the present study is confined to scholarly publications indexed in the Scopus database that focus on ECG signal processing and its related applications [14]. The analysis includes peer-reviewed journal articles, conference papers, and book chapters published within a defined time frame to ensure comprehensive coverage of the research domain [15]. Documents such as editorials, notes, and errata are excluded to maintain analytical precision and relevance. The study aims to capture the intellectual structure and development of ECG signal processing research by examining publication trends, influential contributions, and collaborative networks [16].

The primary objectives of this study are to analyse the growth trajectory of publications in ECG signal processing, identify the most productive authors, institutions, countries, and journals, and evaluate the citation impact of the research output. Additionally, the study seeks to explore collaboration patterns among researchers and countries, as well as to uncover emerging research themes and trends through keyword analysis and co-citation networks. By addressing these objectives, the study intends to provide a comprehensive understanding of the evolution and current state of ECG signal processing research.

Bibliometric analysis serves as an effective methodological approach to systematically evaluate and visualize the scientific literature on ECG signal processing [17]. By employing tools such as Biblioshiny, VOSviewer, the study maps the knowledge structure, identifies research clusters, and highlights thematic developments within the field [18]. This approach not only reveals the quantitative growth of publications but also provides insights into the social and intellectual dynamics shaping the domain [19]. Consequently, the bibliometric analysis offers valuable guidance for researchers, practitioners, and policymakers in understanding existing research patterns and identifying future research directions in ECG signal processing [20].

## 2. Materials and Methods

The present study adopted a bibliometric research design to analyse scholarly publications on ECG signal processing using the Web of Science database, which is widely recognized for its high-quality indexing and comprehensive citation

coverage [21]. A structured search strategy was employed using the query: “ECG Signal Processing” (Topic) OR Electrocardiogram (Topic) AND “Signal Processing” (Topic), ensuring the retrieval of relevant literature within the domain. The initial search yielded 1160 records. To maintain analytical precision and relevance, specific document types were excluded, including Review Articles (54), Editorial Materials (11), Meeting Abstracts (4), Notes (4), Early Access documents (3), Retracted Publications (3), and Letters (1). After applying these exclusion criteria, the final dataset comprised Articles (1040) and Conference Papers (41), which were considered suitable for detailed bibliometric analysis.

The refined and cleansed dataset was exported in CSV format to facilitate systematic analysis and visualization [22]. Bibliometric analysis was conducted using advanced tools such as Biblioshiny, and VOSviewer [23]. These tools enabled the exploration of publication trends, citation structures, co-authorship networks, keyword co-occurrence, and thematic evolution within the field of ECG signal processing [24]. The combined use of these software platforms ensured a comprehensive understanding of both the quantitative performance and the intellectual structure of the research domain [25].

## 3. Findings

### 3.1. Main Information of the Investigation

The main information of the investigation reveals a well-established and moderately growing research domain in ECG signal processing over the timespan from 1991 to 2025. A total of 1081 documents were published across 331 sources, indicating a wide dissemination of research across journals, books, and conference outlets. The annual growth rate of 2.53% suggests steady but not rapid expansion, while the average document age of 9.18 years reflects a mature field with sustained scholarly contributions. The average citations per document (27.52) and a substantial reference count of 29,034 highlight the strong academic impact and knowledge base of the domain. In terms of content, the presence of 1483 Keywords Plus and 3647 author keywords indicates rich thematic diversity and evolving research interests. The authorship pattern shows high collaboration, with 4,278 authors contributing and an average of 4.49 co-authors per document, while single-authored works are minimal, emphasizing the collaborative nature of the field.

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Furthermore, international co-authorship at 26.64% reflects significant global research cooperation. The dominance of articles (1040) and proceedings papers (41) confirms the field's strong orientation toward empirical research and conference-driven dissemination, collectively portraying ECG signal processing as a collaborative, impactful, and steadily advancing research area.

### 3.2. Annual Scientific Production

Figure 1 illustrates the annual scientific production of ECG signal processing research from 1991 to 2025, revealing a clear long-term upward trend with distinct phases of growth and fluctuation. During the initial period (1991–2005), the number of publications remained relatively low and stable, generally below 15 articles per year, indicating that the field was in its early developmental stage with limited research activity. A gradual increase is observed from 2006 onwards, with publications rising from 10 in 2006 to 21 in 2009, reflecting growing academic interest and technological advancements in biomedical signal processing. This trend continues into the early 2010s, where a steady rise is evident, reaching 35 publications by 2014, although a slight dip occurs in 2015. A significant surge in research output is observed from 2016 onwards, marking a period of rapid expansion in the field. Publications increased sharply from 45 in 2016 to a peak of 103 in 2025, highlighting the strong influence of emerging technologies such as artificial intelligence, machine learning, and wearable health devices in ECG analysis. Although minor fluctuations are visible between 2019 and 2023, the overall trajectory remains positive, indicating sustained research momentum. The sharp rise in recent years underscores the increasing relevance of ECG signal processing in modern healthcare and digital health ecosystems. Overall, Figure 1 reflects a transition from a nascent research area to a mature and rapidly growing domain with high scientific productivity.

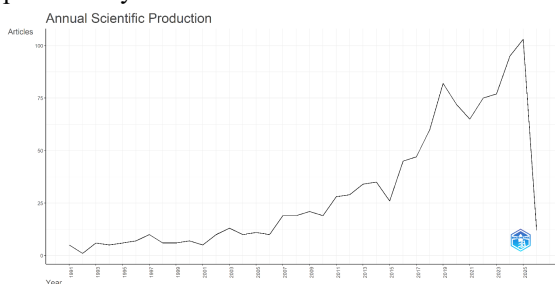
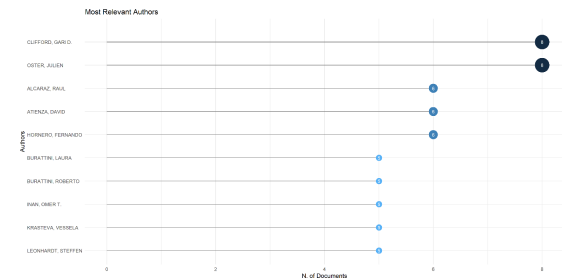


Figure 1. annual scientific production

### 3.3. Most Relevant Authors

Figure 2 presents the most relevant authors in the field based on their number of publications, highlighting a relatively dispersed authorship pattern. Gari D. Clifford and Julien Oster emerge as the most productive contributors, each with 8 publications, indicating their significant influence and sustained research involvement in the domain. They are followed by Raul Alcaraz, David Atienza, and Fernando Hornero, each contributing 6 publications, reflecting a strong but slightly lower level of research output. Additionally, a group of authors including Laura Burattini, Roberto Burattini, Omer T. Inan, Vessela Krasteva, and Steffen Leonhardt each have 5 publications, demonstrating moderate yet consistent contributions to the field. Overall, the figure indicates that no single author overwhelmingly dominates the research landscape; instead, the domain is characterized by a collaborative and distributed authorship structure, where multiple researchers contribute comparably to the advancement of ECG signal processing.



### 3.4. Most Relevant Sources

Table 3 presents the most relevant sources contributing to ECG signal processing research, highlighting the dominance of high-impact journals in engineering, biomedical sciences, and interdisciplinary healthcare technologies. IEEE Access leads with 61 publications, closely followed by Sensors with 60 articles, indicating strong research activity in open-access and sensor-based applications of ECG analysis. Biomedical Signal Processing and Control (55 articles), IEEE Transactions on Biomedical Engineering (52 articles), and Physiological Measurement (50 articles) further demonstrate the central role of specialized biomedical and signal processing journals in disseminating research findings. The second tier of sources includes IEEE Transactions on Instrumentation and Measurement and Journal of Electrocardiology, each contributing 23 articles, followed by IEEE Journal of Biomedical and Health Informatics (22 articles). Scientific Reports (19 articles) and IEEE Sensors Journal (17 articles) also

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make notable contributions. Overall, the distribution of sources reflects a strong interdisciplinary orientation, with a significant concentration in IEEE publications and biomedical journals, indicating that ECG signal processing research is primarily driven by advancements in engineering, instrumentation, and healthcare analytics.

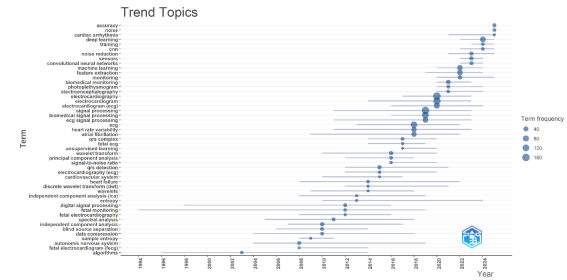
Sources	Articles
IEEE Access	61
Sensors	60
Biomedical Signal Processing And Control	55
IEEE Transactions On Biomedical Engineering	52
Physiological Measurement	50
IEEE Transactions On Instrumentation And Measurement	23
Journal Of Electrocardiology	23
IEEE Journal Of Biomedical And Health Informatics	22
Scientific Reports	19
IEEE Sensors Journal	17

### 3.5. Trend Topics

Figure 4 illustrates the trend topics in ECG signal processing research, highlighting the temporal evolution and prominence of key research themes based on their frequency and duration of occurrence. The figure shows that core topics such as ECG, ECG signal processing, and heart rate variability have consistently remained central over time, indicating their foundational importance in the field. These themes appear with high frequency and extended timelines, reflecting sustained research interest and their critical role in both clinical and technological advancements. Additionally, topics like atrial fibrillation and QRS complex analysis are prominently featured, demonstrating continued focus on cardiac abnormality detection and diagnostic accuracy.

In contrast, more specialized and emerging topics such as fetal ECG appear with shorter timelines and relatively lower frequency, suggesting niche but growing areas of research. The visualization also indicates a shift in recent years toward more application-oriented and data-driven themes, likely influenced by advancements in artificial intelligence, wearable devices, and real-time health monitoring systems. Overall, Figure 4 reveals a dynamic research landscape where traditional signal

processing concepts coexist with emerging innovations, highlighting both the maturity and evolving nature of ECG signal processing research.

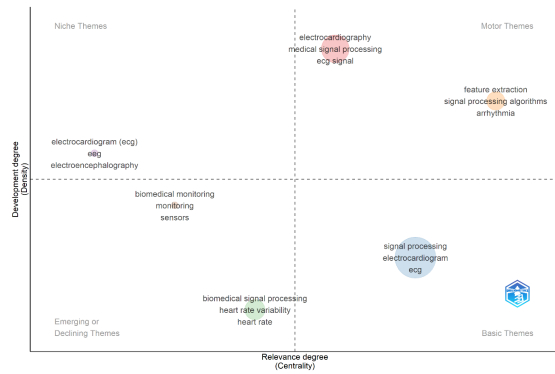


### 3.5. Thematic Map

Figure 5 presents the thematic map of ECG signal processing research, categorizing key themes based on their centrality and density, which reflect their importance and level of development within the field. The upper-right quadrant, representing motor themes, includes highly developed and influential topics that drive the research domain. In ECG signal processing, themes such as deep learning, machine learning, and feature extraction are typically positioned here, indicating their strong relevance and maturity in advancing automated diagnosis and intelligent healthcare systems. These themes are both well-developed and widely connected to other research areas, making them central to current scientific progress.

The upper-left quadrant, representing niche themes, consists of specialized and well-developed topics with limited external connections. Themes such as wavelet transform, independent component analysis, and entropy-based methods often fall into this category, reflecting their technical depth and methodological significance, although they may not be broadly integrated across the entire field. The lower-right quadrant, known as basic themes, includes fundamental and transversal topics such as ECG, signal processing, and biomedical monitoring, which are essential to the domain but still evolving in terms of development. Finally, the lower-left quadrant, representing emerging or declining themes, includes topics like fetal ECG or traditional spectral analysis techniques, which may either be gaining new attention or gradually losing prominence. Overall, Figure 5 highlights the structural organization of research themes in ECG signal processing, illustrating a balance between foundational concepts, advanced analytical methods, and emerging innovations.

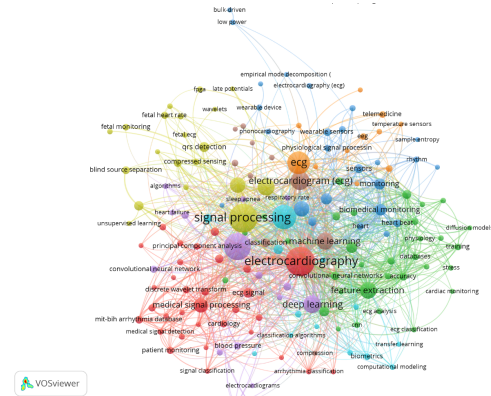
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### 3.6. Co-occurrence of author keywords

Figure 6 illustrates the co-occurrence network of author keywords in ECG signal processing research, revealing the conceptual structure and interconnections among key research themes. The network is dominated by central nodes such as electrocardiography, signal processing, ECG, and electrocardiogram (ECG), which appear as the largest and most connected nodes, indicating their fundamental role in the domain. These core terms are closely linked with important methodological and application-oriented keywords such as machine learning, deep learning, feature extraction, and classification, highlighting the strong integration of advanced computational techniques in ECG analysis. The dense interlinkages among these nodes suggest a highly interconnected research landscape where traditional signal processing methods are increasingly combined with artificial intelligence approaches.

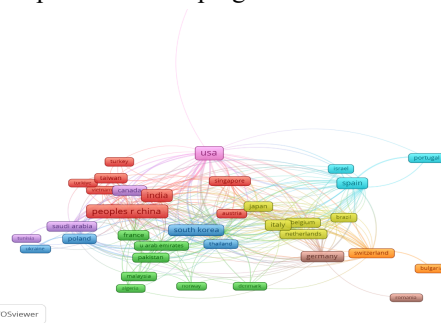
The network also reveals several thematic clusters representing distinct research directions. One cluster focuses on machine learning and deep learning applications, including terms such as convolutional neural networks, classification algorithms, and ECG classification, emphasizing the growing role of AI-driven diagnostics. Another cluster is centered on biomedical monitoring and healthcare applications, with keywords like biomedical monitoring, heart rate, physiology, and cardiac monitoring. A third cluster highlights signal processing techniques, including wavelet transform, principal component analysis, and independent component analysis, reflecting methodological advancements. Additionally, niche areas such as fetal ECG, wearable devices, and telemedicine indicate emerging and specialized research directions. Overall, Figure 6 demonstrates that ECG signal processing research is highly multidisciplinary, integrating engineering, data science, and healthcare to advance diagnostic and monitoring technologies.



### 3.7. Co-authorship of Countries

Figure 7 illustrates the co-authorship network of countries in ECG signal processing research, revealing a highly interconnected global collaboration structure. The United States appears as the most central and influential node, maintaining strong collaborative links with multiple countries, including India, China, Spain, and South Korea. The prominent position of these countries indicates their significant contribution to research output and their active participation in international collaborations. China and India also form strong collaborative clusters, particularly with Asian and developing countries, reflecting their growing influence in the field.

The network further reveals distinct regional clusters, such as the European cluster led by Germany, Italy, Netherlands, and Belgium, and another cluster involving France, Poland, and Middle Eastern countries such as Saudi Arabia and United Arab Emirates. Additionally, countries like Portugal, Switzerland, and Romania appear as smaller yet connected nodes, indicating emerging or moderate collaboration roles. Overall, Figure 7 highlights that ECG signal processing research is globally collaborative, with strong intercontinental linkages and increasing participation from both developed and developing nations.



## 4. Discussions

The findings of this bibliometric study reveal that ECG signal processing has evolved into a mature and steadily expanding research domain with strong

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scientific impact and collaborative intensity. The consistent growth in annual scientific production, particularly the sharp increase after 2016, indicates a paradigm shift driven by technological advancements such as artificial intelligence, machine learning, and wearable healthcare devices. The high average citations per document and extensive reference base further confirm the intellectual richness and academic relevance of the field. Moreover, the dominance of multi-authored publications and a significant level of international collaboration highlight the interdisciplinary and global nature of ECG signal processing research, where expertise from engineering, medicine, and data science converges to address complex healthcare challenges.

Another key insight emerging from the analysis is the distributed yet impactful authorship and source structure. The absence of a single dominant author suggests a decentralized knowledge production system, where multiple researchers contribute significantly to the advancement of the field. At the same time, the concentration of publications in leading journals such as IEEE Access, Sensors, and Biomedical Signal Processing and Control underscores the critical role of high-impact and specialized outlets in shaping the research landscape. This pattern reflects the interdisciplinary orientation of the field, bridging biomedical engineering, signal processing, and clinical applications, while also emphasizing the importance of open-access platforms in disseminating knowledge widely.

Furthermore, the thematic and conceptual analyses highlight a dynamic and evolving research structure characterized by the integration of traditional signal processing techniques with emerging artificial intelligence methodologies. Thematic map results indicate that machine learning, deep learning, and feature extraction function as motor themes driving current research, while foundational topics like ECG and signal processing remain essential yet evolving. The co-occurrence network reinforces this transition by showing strong linkages between core biomedical concepts and advanced computational approaches. Additionally, the global co-authorship network demonstrates that countries such as the United States, China, and India play central roles in fostering international collaboration, supported by strong regional clusters in Europe and Asia. Collectively, these findings suggest that ECG signal processing is progressing toward more intelligent,

data-driven, and globally collaborative research paradigms, with significant implications for future innovations in digital healthcare and real-time cardiac monitoring systems.

## 5. Conclusion

This bibliometric study demonstrates that ECG signal processing has evolved into a mature, impactful, and steadily growing research domain driven by technological advancements and interdisciplinary collaboration. The increasing publication trends and strong citation impact highlight the growing academic and practical importance of the field in modern healthcare systems. The study also reveals that research contributions are widely distributed among authors and institutions, reflecting a collaborative and globally connected knowledge structure. Furthermore, the integration of machine learning and deep learning techniques has emerged as a major driving force shaping current and future research directions. It is recommended that future research should focus on developing more robust and explainable artificial intelligence models to enhance the reliability of ECG-based diagnostics. Researchers are also encouraged to explore underrepresented areas such as fetal ECG and low-resource healthcare applications to ensure inclusive technological development. Additionally, strengthening international collaborations, particularly between developed and developing countries, can further accelerate innovation and knowledge exchange in this field. Overall, ECG signal processing is poised to play a critical role in advancing intelligent, real-time, and accessible cardiac healthcare solutions.

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