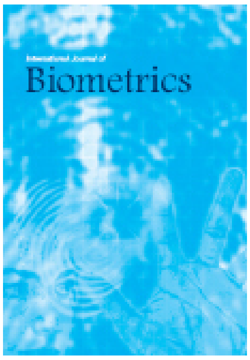


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# A systematic literature review and bibliometric analysis of signature verification spanning four decades

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# A systematic literature review and bibliometric analysis of signature verification spanning four decades

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**Abstract:** This article conducts a systematic literature review and bibliometric analysis spanning four decades of research in the field of signature verification (SV). SV holds substantial significance in practical domains like finance, law enforcement, and document authentication. The primary objective of this study is to offer a comprehensive overview of SV's evolution, pinpoint research trends, and illuminate gaps within the existing literature. The review encompasses 1,552 studies published from 1982 to the present, with analysis focusing on various SV facets such as feature extraction, classification algorithms, datasets, evaluation metrics, and applications. The findings underscore substantial growth and diversification within the field, showcasing the development and testing of diverse approaches. Nevertheless, challenges such as the absence of standardised evaluation metrics and limited accessibility to public datasets emerge. The article concludes with a discourse on prospective directions for SV, considering the potential influence of emerging technologies like deep learning and biometric authentication on the field's future.

**Keywords:** signature verification; SV; bibliometric analysis; thematic evaluation; cluster analysis.

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Dileep Kumar Singh is a seasoned academic and researcher in management with over 15 years of experience. He is holding multiple degrees including two MBAs, PhD, and numerous certifications. His research has been widely published in esteemed journals and recognised with awards like the best paper accolade. He is a proficient trainer, conducting soft skills sessions in esteemed institutions, and serves as the editor of three journals. With expertise in strategic management, he has authored books, contributed articles to newspapers, and received accolades like the Vidyabushan and Nation Builder Awards for his contributions to the field.

## 1 Introduction

The term 'biometric' refers to specific details of a person's body, such as their fingerprints, handwriting, signatures, gait, vein patterns, and eye iris patterns. Iris pattern and fingerprints are physical biometric. A physical biometric cannot be replicated or stolen. However, the other class of biometrics which is known as behavioural biometrics (Khan and Dhole, 2014a) is based on a person's behaviour and can be easily mimicked. Handwriting and signatures fall into the latter category. Automatic verification of any behavioural biometric is a crucial task.

The offline signature is a distinct handwritten depiction of a person's name or a mark that is used as identification on all legal documents, including mortgages, property deeds, and bank checks. Offline signatures are typically validated by analysing the pattern fluency discovered in the signature or by visually comparing the signature patterns to previously gathered samples. Nevertheless, manually offline verifying the signatures on several papers takes time and relies on human alertness, experience, and expertise to spot a forgery (Khan et al., 2023a).

Automatic signature verification (SV) can be classified into two categories based on the method of data acquisition namely online and offline methods (Khan and Dhole, 2014b). In contrast to the offline technique, which is known as a static SV method, the online method is also known as a dynamic SV method. Tablets, pressure-sensitive pens, and other devices are used to capture online signatures. This dynamic data includes things like pen tilt, pressure, and location. In contrast, an offline signature is obtained through scanning, or turning it into a digital image.

The need for automatic SV arises from the fact that signatures are widely used as a means of identification, authorisation, and authentication in a variety of settings such as banking, legal documents, and government agencies (Biswas and Khan, 2013). However, signatures can be easily forged or tampered with, which can lead to fraudulent activities, identity theft, and other security breaches (Deshpande et al., 2023; Mehta et al., 2022; Zaveri et al., 2019). Automatic SV provides a reliable and efficient way to detect and prevent these types of fraudulent activities. Automatic SV can improve security and reduce the risk of fraud. With automatic SV, organisations can ensure that only authorised individuals can access confidential information or perform sensitive tasks. This can help to prevent identity theft, financial fraud, and other types of security breaches (Khan et al., 2023b). Automatic SV can also provide a detailed record of SV activities, which can be useful in auditing and compliance processes.

SV has seen a wide range of techniques in classification, feature extraction, and pre-processing over the last four decades. This domain has been explored a lot and still, lots of work is going on (Khan et al., 2018). Identifying and analysing recent trends in such a field can be challenging. A bibliometric analysis is a technique that can facilitate the review of the literature and makes it easier. It enables us to explore the subtleties of a field's evolutionary history while illuminating its frontiers. It can give insights into new developments in the performance of articles and journals, collaboration patterns, research elements, and the intellectual framework of a particular area in the body of existing literature (Donthu et al., 2021).

This paper reviews the research literature on SV. Both, online and offline automatic verifiers for handwritten signatures are considered for this review purpose. The research in the area of SV started in the early 50s. But, it gained much popularity in the early 80s. This review is analysing the research pattern in SV based on the data of the last four decades. A total of 1,552 articles were taken into consideration. Two bibliometric approaches: performance analysis and science mapping (Moed, 2009), have been used to unearth the knowledge from this database. While scientific mapping (Aranda-Escolástico et al., 2020) focuses on the connections between research constituents, performance analysis takes into account the contributions of research constituents. By using performance analysis, the impact of authors, journals, countries, and articles is measured in terms of citations. However, by using science mapping, structural relationships, and intellectual interconnections among the authors, keywords, articles, and countries can be analysed. These relationships are represented using clustering algorithms and graph theory (Baker et al., 2021). This work specifically responds to the following research questions:

1 Which articles are the most impactful?

2 Which authors have carried out pertinent studies on SV?

3 Which conferences and journals have published the most articles?

4 Which issues in SV have received the most research attention?

5 What methods have been employed to address those issues?

6 How has the popular research subjects appeal changed over time?

7 Where will research in the near future be concentrated?

The rest of the paper has been structured as follows –Section 2 gives the insight into the related works which have been carried out earlier. Section 3 gives the details of the materials and methods used in the bibliometric analysis. In Section 4, the analysis and results have been reported. Lastly, the final observation and potential areas for future research have been summarised in Section 5.

## 2 Related work

There are various surveys conducted on tools and techniques associated with SV. In these reviews, a large number of papers were reviewed based on classification techniques, feature extraction techniques, datasets, etc. The performance of the systems was compared based on false acceptance rate (FAR), false rejection rate (FRR), equal error rate (EER), and average error rate (AER). None of the reviews were conducted on such a large number of papers and no bibliographic approach has been explored in this area to the best of the author's knowledge. Further, in this section, some of the classic reviews in this domain are discussed.

Some of the classic reviews in the domain of SV are published in Nalwa (1997), Jain et al. (2016), Hafemann et al. (2017) and Diaz et al. (2019). In Nalwa (1997), the author has studied the traditional method of SV which considers the whole shape of the signature and identified the core problem areas to be addressed – instead of treating the signature as a whole, dynamic properties should be extracted, etc. In Jain et al. (2016), a study of the evolution of biometric technology was published. It included the historical development of biometric verification systems by using both behavioural and physical biometrics. Iris, fingerprint, speech, face, signature, etc. were taken into consideration. This paper published how biometric technology has evolved in 50 years (till 2015). In Hafemann et al. (2017), the authors have presented a brief review of the pre-processing techniques used, learning techniques used, datasets used and feature extraction methods employed. They have analysed models based on support vector machine, neural networks, deep learning networks, hidden Markov model, etc. The authors have also discussed and reviewed the importance of different types of features like – global, local, texture, shape, shadow code, etc. In Diaz et al. (2019), authors have published a detailed review on SV which includes databases available, list of best practices for designing signature verifiers, signature verifiers for various languages like English, Japanese, Persian, Hindi, Bengali, etc., competitions on SV s, forensic applications, recent progresses in the field, etc.

Some of the reviews published are exclusively based on specific training techniques like – deep learning (Tamrakar and Badholia, 2022), neural networks (Hameed et al., 2021; O-Khalifa et al., 2013; Remaida et al., 2020), and feature selection technique review was presented in Ebrahim et al. (2018).

## 3 Materials and methods

The bibliometric technique suggested by Cobo et al. (2011) is used in this paper. To assess a research field, identify and visualise its conceptual subdomains (specific topics/themes or general thematic areas), and track its thematic evolution, this bibliometric technique blends performance analysis tools with scientific mapping tools.

### *3.1 Workflow for bibliometric analysis*

The bibliometric approach suggested in Börner et al. (2003), Cobo et al. (2012) and Moher et al. (2009) is used to analyse the database. The methodology has been divided into three phases – data retrieval, data cleansing, and data analysis. Each phase has been discussed in detail.

#### *3.1.1 Data retrieval*

It is impracticable to compile the entire population of articles that qualify for bibliometric analysis. The two most sought-after databases in technical research are Web of Science and Scopus (Burnham, 2006). To determine the breadth of this research, a comparison of the WoS and Scopus coverage was done, discovering that Scopus essentially offers a superset of the bibliographic records provided by WoS (Aghaei Chadegani et al., 2013;

Baas et al., 2020), including some additional documents. It is important to keep in mind that citation counts vary significantly between databases, therefore combining entries from various sources results in inconsistent tallies. So, the authors have chosen the Scopus database for the study.

Until a convenient balance between thoroughness and the absence of false positives was reached, a database query was refined iteratively. The query used in the Scopus database to filter out the desired documents is shown in Figure 1. The word 'signature verifi*' is a broad area to cover verification, verifier, and other similar words. The subject area taken under consideration is computer science, engineering, and mathematics. Only the articles published in the English language were included. All the publications from 1982 to till date have been considered for this study. This search string was run on the title, abstract, and keywords. The search was executed on 21 February 2023 and a total of 1,552 document results were found.

**Figure 1** Search string used to extract corpus from Scopus (see online version for colours)

```
TITLE-ABS-KEY ( ( ( "signature verifi*"  OR  "signature recognition" )
AND NOT  ( "on-line"  OR  "online" )  AND NOT  ( "offline"  OR  "off-line" ) ) )
AND  ( LIMIT-TO ( SUBJAREA ,  "COMP" )  OR  LIMIT-TO ( SUBJAREA ,  "ENGI" )  OR  LIMIT-TO ( SUBJAREA ,  "MATH" ) )
AND  ( LIMIT-TO ( LANGUAGE ,  "English" ) )
```

### *3.1.2 Data cleansing*

Since bibliometric data is frequently retrieved in a raw state and also the source databases are not specifically designed for bibliometric analysis, they must be cleaned and prepared. Duplicates and inconsistent data should be pruned out. Sometimes there are inconsistencies and typos in bibliographic data that need to be clarified. The data is prepared in the format in which chosen bibliometric technique can work (Aranda-Escolástico et al., 2020). There are various keywords which were alike but no standards have been imposed and thus creating two different keywords. Such keywords were identified and grouped manually. For example, 'online' and 'on-line' both keywords were grouped to get a clear thematic analysis.

### *3.1.3 Data analysis*

The cleaned and standardised data is then analysed using recognised bibliometric techniques, performance analysis, and science mapping (Noyons et al., 1999).

## *3.2 Performance analysis*

The numeric measure of research performance is provided by performance analysis. It is the quantitative measure, that examines the productivity of the identified themes and thematic areas. It includes the number of articles, authors, or countries involved. It encompasses the measure of citations, h-index or other bibliometric indices (Cobo et al., 2011). It can be used to evaluate the performance of researchers, institutions, and journals based on their publication and citation records. Bibliometric performance analysis is often used to evaluate research impact, productivity, and influence. Some of the commonly used metrics in bibliometric performance analysis are citation count, h-index, impact factor, field-weighted citation impact, etc. In this paper, following two metrics have been used:

- Citation count: This metric counts the number of times a particular publication has been cited by other publications. Citation counts can be used to evaluate the impact and influence of individual publications, authors, or institutions.
- H-index: This metric is based on both the number of publications and the number of citations received by an individual author or institution. The h-index is defined as the number h of publications that have received at least h citations.

## *3.3 Science mapping*

Science mapping is a methodology used to visualise and analyse the structure and dynamics of scientific research. It involves using bibliometric data (i.e., data related to publications and citations) to create maps or networks that show the relationships between different research areas, disciplines, authors, and institutions. In this paper, science mapping has been implemented through an open-source software – SciMAT (Cobo et al., 2012).

Common techniques used in science mapping include bibliometric analysis, co-citation analysis, co-authorship analysis, keyword analysis, and network analysis. These techniques can be used separately or in combination to identify the most prolific authors, institutions, and journals in a particular field or research area, to identify the most influential articles or authors, to identify research groups or communities, and to identify the most important research topics or emerging research topics. In this paper, thematic networks (TNs) and strategic diagrams are used to show the evolution of SV in the last four decades.

a To identify the themes of the study – compute the co-occurrence matrix by making the assumption that the frequency of two keywords occurring together is derived from the corpus of documents by counting the number of documents in which they do. The second step is to calculate the equivalence index ($e_{ij}$) between keywords (Callon et al., 1991).

$$e_{ij} = \frac{c_{ij}^2}{c_i \cdot c_j}$$

where $c_{ij}$ is the number of documents in which the keywords $i$ and $j$ co-occur and $c_i$ and $c_j$ stand for the number of documents in which each keyword appears separately. The simple centres algorithm is used to group keywords into topics or themes at the conclusion of this stage, and as it automatically produces labelled clusters, no additional labelling step is required. With the help of this clustering technique, we may identify keyword networks that are closely related to one another and that correspond to research difficulties or interest areas where scientists have invested a lot of time and effort (Coulter et al., 1998).

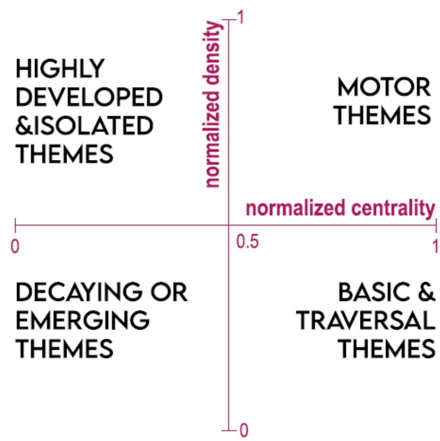
b To build strategic diagrams – A set of interconnected networks or themes throughout the clustering phase. So, each keyword network or topic in this context can be described by two factors (Muñoz-Leiva et al., 2012).

- Centrality – It gauges how closely a network interacts with other networks. The degree of external linkages to other themes is measured by centrality. It can also be characterised as a measurement of the significance of a theme in the growth of the overall study area under consideration. Centrality ($c$) is calculated as

  $$c = 10.\sum e_{kh}$$

  where $k$ is the keyword that belongs to a theme and h is the keyword that belongs to another theme.
- Density – It gauges the network's inherent fortitude. The degree of correlation between each keyword characterising the study theme is measured by density. This measure might be seen as an indicator of the progress of the theme. Density ($d$) is calculated as – $d = 100.\sum {e_{ij}}/{w}$ with $i$ and $j$ denoting keywords belonging to the theme and w the number of keywords in the theme.

**Figure 2** Quadrants in the strategic diagram (see online version for colours)




*Source:* Extracted from Ruiz-Parrado et al. (2022)

Using these two criteria, a research field can be described as a collection of concepts for future study that can be divided into four groups as shown in Figure 2 (Callon et al., 1991):

- Topics in the top-right quadrant are both well-developed and crucial for a study field's organisation. The fact that they exhibit strong centrality and high density has earned them the moniker 'motor themes of the specialty.'
- Themes in the upper-left quadrant have strong internal connections but weak exterior linkages, making them of only sporadic significance for the field. These topics are extremely niche and tangential.
- The lower-left quadrant's themes are minimal and poorly developed. Low density and low centrality characterise the themes in this quadrant, which primarily indicate motifs that are either emerging or dissipating.

- Although they are poorly developed, the themes in the lower-right quadrant are crucial for a research field. Hence, this quadrant groups universal and fundamental concepts.

### *3.4 Limitation of the study*

This research has been carried out on the Scopus database only. Any researches published out of Scopus database has not been included in the study. All the thematic maps and network clusters were generated using software tools, which, at times, resulted in the cropping or overlapping of node titles. While efforts were made to ensure clarity and readability, the automated nature of the generation process constrained the author's ability to fully control the layout of these elements.

## 4 Results and discussion

In this section, a detailed analysis of influential documents, authors, and journals has been presented. Additionally, a longitudinal analysis has also been presented in this section. It shows the evolution of SV over the decades and the prevalent themes in each decade. Also, starting from 1982 till date, four periods have been created. Period 1 – from 1982 to 1991, period II from 1992 to 2001, period 3 from 2002 to 2011, period 4 from 2012 till date. These periods have been discussed in detail concerning the themes and evolution of SV. The data extracted from the Scopus database has been analysed. The main information of the extracted corpus is shown in Figure 3. A total of 1,552 documents were analysed spanning over the period of 1982 to 2023.

**Figure 3** Main information of the extracted corpus (see online version for colours)


### *4.1 Most cited papers*

The most influential papers are identified based on the number of citations. The top ten documents with their number of citations have been shown in Figure 4. Table 1 shows the details of the same. Plamondon and Lorette (1989) is the highest-cited document and has received 749 citations.

**Figure 4** Most globally cited documents (see online version for colours)

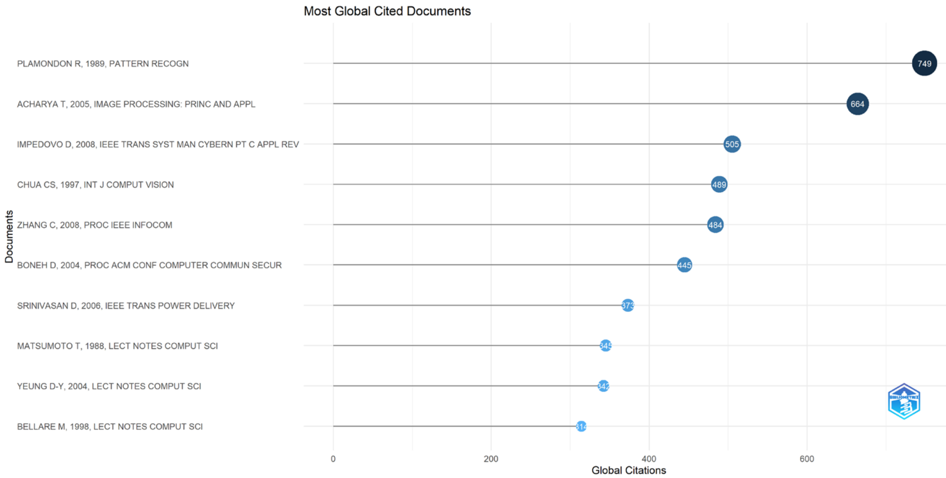



**Table 1** Most globally cited documents

| *Document title* | *Source title* | *Total citations* | *TC per year* |
|---|---|---|---|
| Automatic signature verification and writer identification – the state of the art (Plamondon and Lorette, 1989) | *Pattern Recognition* | 749 | 21.4 |
| Image Processing: Principles and Applications (Acharya and Ray, 2005) | *Image Processing: Principles and Applications* | 664 | 34.94 |
| Automatic signature verification: The state of the art (Impedovo and Pirlo, 2008) | *IEEE Transactions on Systems, Man, and Cybernetics Part C: Applications and Reviews* | 505 | 31.56 |
| Point signatures: a new representation for 3D object recognition (Chua and Jarvis, 1997) | *International Journal of Computer Vision* | 489 | 18.11 |
| An efficient identity-based batch verification scheme for vehicular sensor networks (Zhang et al., 2008) | *Proceedings – IEEE INFOCOM* | 484 | 30.25 |
| Group signatures with verifier-local revocation (Boneh and Shacham, 2004) | *Proceedings of the ACM Conference on Computer and Communications Security* | 445 | 22.25 |
| Neural-network-based signature recognition for harmonic source identification (Srinivasan et al., 2006) | *IEEE Transactions on Power Delivery* | 373 | 20.72 |
| Public quadratic polynomial tuples for efficient signature verification and message encryption (Matsumoto and Imai, 1988) | *Lecture Notes in Computer Science (*including subseries *Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* | 345 | 9.58 |

**Table 1** Most globally cited documents (continued)

| *Document title* | *Source title* | *Total citations* | *TC per year* |
|---|---|---|---|
| SVC2004: First international signature verification competition (Yeung et al., 2004) | *Lecture Notes in Computer Science (*including subseries *Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* | 342 | 17.1 |
| Fast batch verification for modular exponentiation and digital signatures (Bellare et al., 1998) | *Lecture Notes in Computer Science (*including subseries *Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* | 314 | 12.07 |

## *4.2 Most prolific authors*

The corpus extracted has 1,552 papers co-authored by 3,271 authors. About 78% of authors are sporadic and only 21% contributed in five or more documents. This observation is consistent with the pattern predicted by Lotka's (1926) law. Lotka's law states that a small proportion of individuals (about 20%) in a given field or domain tend to be responsible for the majority of the output or productivity, while the vast majority of individuals contribute only a small amount. In this case, out of the 3271 authors, 2,572 (about 78.6%) have produced only one document, indicating that the vast majority of authors in this field are not highly productive. On the other hand, 699 authors (about 21.4%) have produced five or more documents, indicating that a small proportion of highly productive authors are responsible for the majority of the output.

**Figure 5** Most productive authors (see online version for colours)

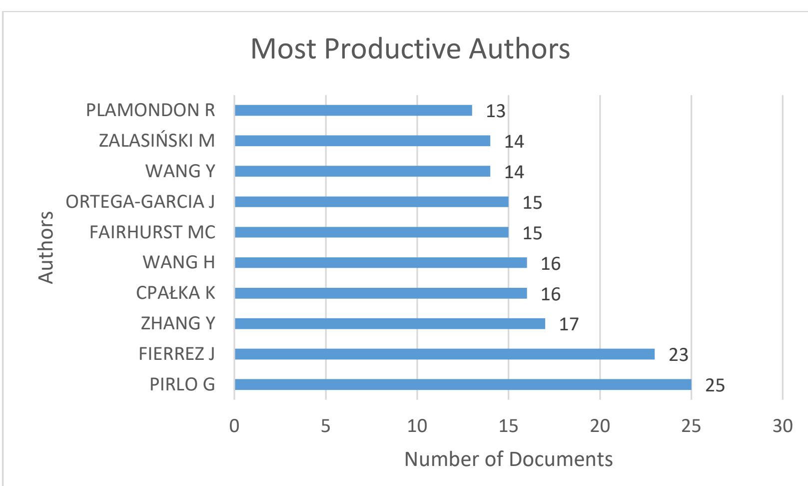
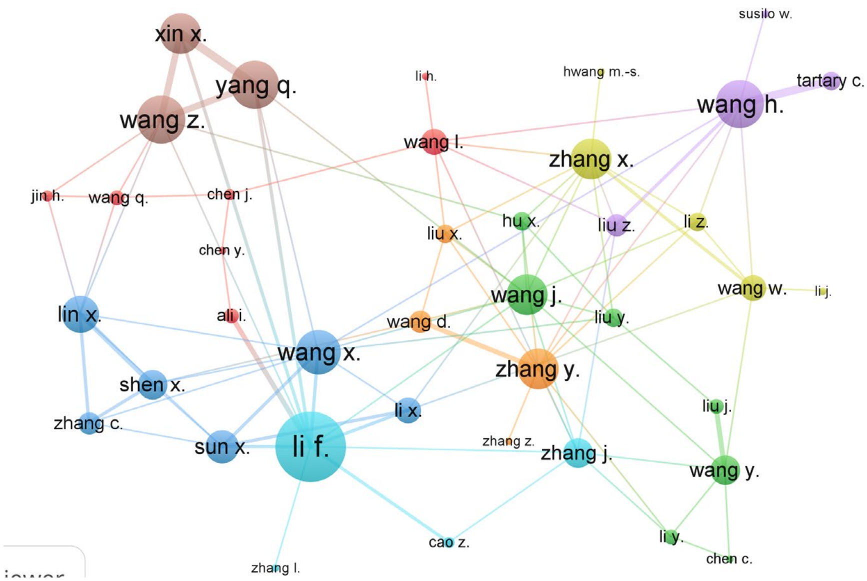



Figure 5 shows the ten most productive authors with the number of documents they contributed to in this research field. Figure 6 shows the collaboration network between the most productive authors. The threshold criteria set for identifying the most productive authors is the minimum number of documents and the minimum number of citations should be four. Out of all the authors, only 89 met the criteria, out of which only 40 are connected. So the largest connected network is shown in Figure 5. The network has eight clusters with 94 links and total link strength of 124. The method used is the association strength. The network is created by VOSviewer (van Eck and Waltman, 2013).

**Figure 6** Co-authorship network of the most productive authors (see online version for colours)



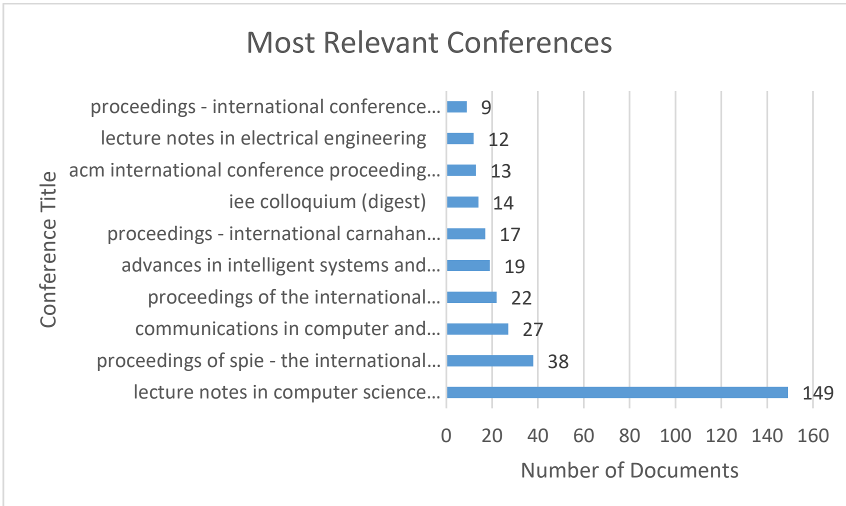

## 4.3 *Most relevant sources*

Figure 7 shows the most relevant sources that publish most articles in the 'SV' research field with highest number of documents, i.e., 149 articles, published in *Lecture Notes in Computer Science* (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics). In journals, *Pattern Recognition* stands out with 17 articles.

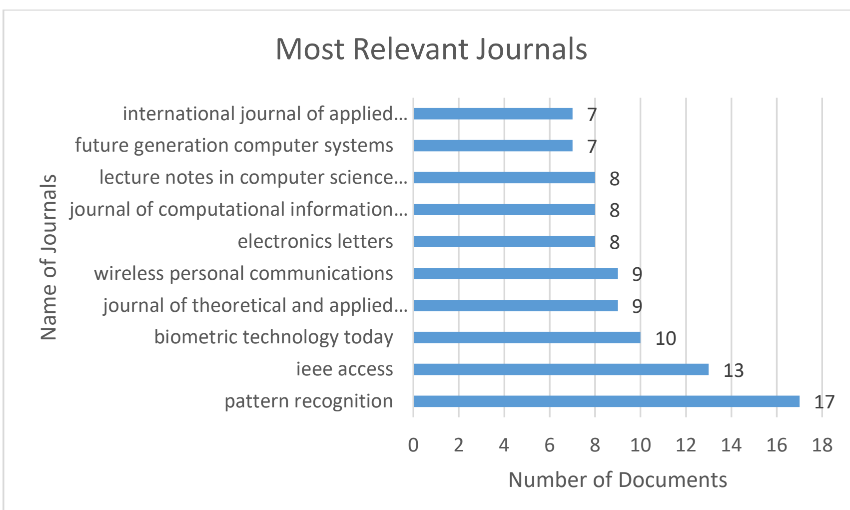
## 4.4 *Longitudinal analysis*

Figure 8 shows the number of articles published over the years from 1982 to 2023 in the area of SV. The number of articles increased gradually from 1982 to 1999 and remained relatively stable from 1999 to 2010, with some fluctuations. However, since 2010, the number of articles published has steadily increased. There are fluctuations in the number of articles published from year to year, which may be attributed to different factors, including funding, research trends, and political changes. The highest number of articles published in a single year was 102 in 2019, followed by 100 in 2021. On the other hand, the year with the lowest number of articles published was 1987 with only one article. Overall, there is a clear upward trend in the number of articles published over time, with some exceptions, such as significant increases in 1994, 1995, 2000, and 2006. The document sample into four periods of ten years each, to evaluate the temporal evolution of the area.

**Figure 7** Most relevant (a) conferences (b) journals (see online version for colours)




(a)




(b)

### *4.4.1 Thematic networks*

The science mapping method we used to determine the subjects that have received the most investigation is based on examining the relationships between paper keywords. Figure 9 represents the evolution of keywords over four decades. The four periods are divided as- from 1982 to 1991, 1992 to 2001, 2002 to 2011, and 2012 to date.

**Figure 8** Articles published per year (see online version for colours)

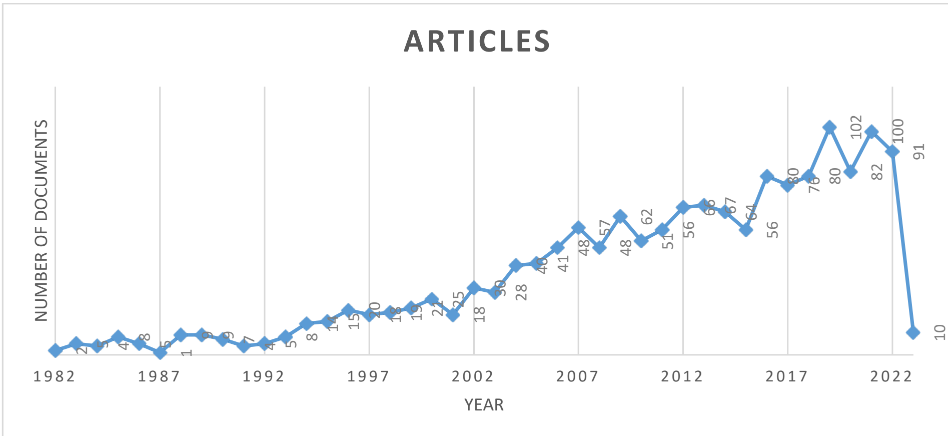
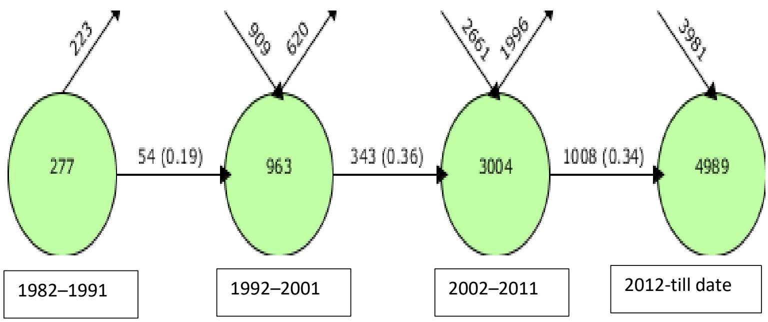



**Figure 9** Keyword overlapping map (see online version for colours)



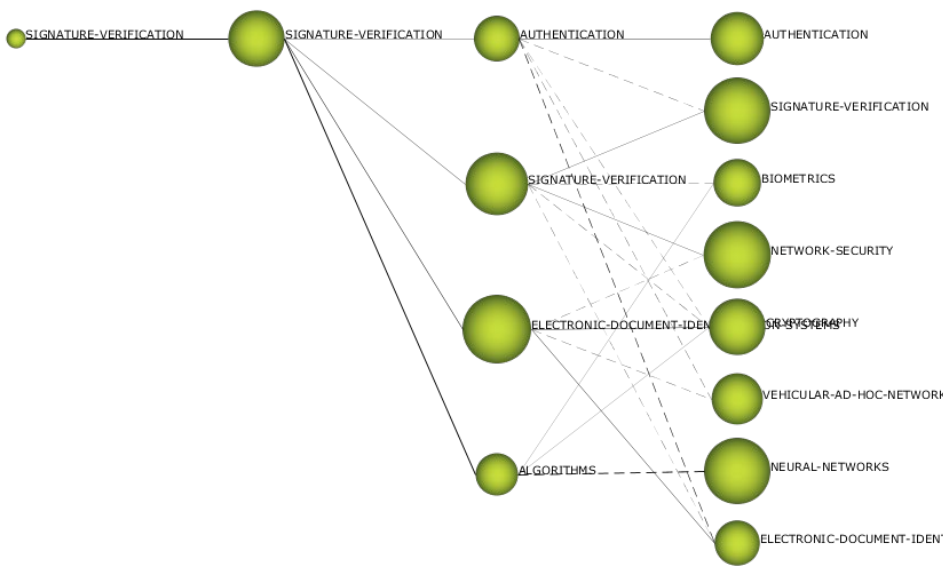

In Figure 9, the nodes represent the number of keywords prevailing in a particular period. The arrows connecting the two periods show the number of shared keywords and inclusion index in parenthesis. The numbers shown in the outgoing arrows show the outdated keywords and the incoming arrows show the inclusion of new keywords. The statistical information of the corpus extracted is given in Table 2. One of these measures is ‘units,’ which simply refers to the total number of times a word group appears in the analysed corpus. Another important measure is ‘min,’ which represents the smallest number of times a word group appears in a single publication within the corpus. ‘Max,’ on the other hand, represents the largest number of times a word group appears in a single publication within the corpus. Variance is a statistical measure that quantifies how much the word group frequency data varies from the mean. A high variance indicates that the data is spread out, while a low variance indicates that the data is tightly clustered around the mean. Standard deviation, on the other hand, is the square root of variance, and it measures the amount of variation or dispersion of the word group frequency data from the mean. A high standard deviation indicates that the data is widely spread out, while a low standard deviation indicates that the data is tightly clustered around the mean (Cobo et al., 2012).

**Table 2** Word group statistical information

| *Period* | *No. of documents* | *Units* | *Max* | *Min* | *Mean* | *Median* | *Standard deviation* | *Variance* |
|---|---|---|---|---|---|---|---|---|
| 1982–1991 | 54 | 278 | 15 | 0 | 7.07 | 7 | 3.11 | 9.69 |
| 1992–2001 | 163 | 956 | 30 | 0 | 10.93 | 11 | 4.5 | 20.24 |
| 2002–2011 | 461 | 2960 | 43 | 0 | 13.03 | 12 | 7.25 | 52.51 |
| 2012–2023 | 874 | 4981 | 65 | 0 | 13.24 | 14 | 6.08 | 36.91 |

Simple centres algorithm has been used to identify TNs. For each period, a different strategic diagram is created which shows the clusters placement in the spatial representation of the thematic diagram with centrality and density as axes. For each cluster thus formed, a cluster network is created which shows the relevance of prevalent themes in that period. Figure 10 represents the thematic linkage between the periods and gives the evolution of the field over the years.

**Figure 10** TN conceptual linking between the networks over the years (see online version for colours)




Each node represents a theme and the size of the node represents the number of papers in that theme. It is created using the keywords. Edges in the network represent the conceptual linkage between the themes. Solid edges represent a high degree of shared keywords whereas dashed edges represent a lesser degree. The strategic diagrams for all the periods and their cluster network has been discussed in detail in the subsequent sub-sections. The strategic diagrams have been represented in the spatial space of centrality and density. The values of both the variables for each cluster have been given in Table 3. The 'centrality' column denotes the relative importance of nodes in the network, while the 'centrality range' column illustrates the span of centrality scores observed. Whereas, the 'density' column signifies the connectedness of nodes within the network, with higher values indicating denser networks. The 'density range' column displays the range of density values observed in the dataset. Together, these metrics offer insights into the structural characteristics and connectivity patterns of the analysed network. While creating the TNs the threshold for frequency reduction for each period was kept to 3 and the edge reduction value was kept to 5. Simple centres algorithm is used which labels the TN according to the most central keyword.

**Table 3** Centrality and density values for each cluster

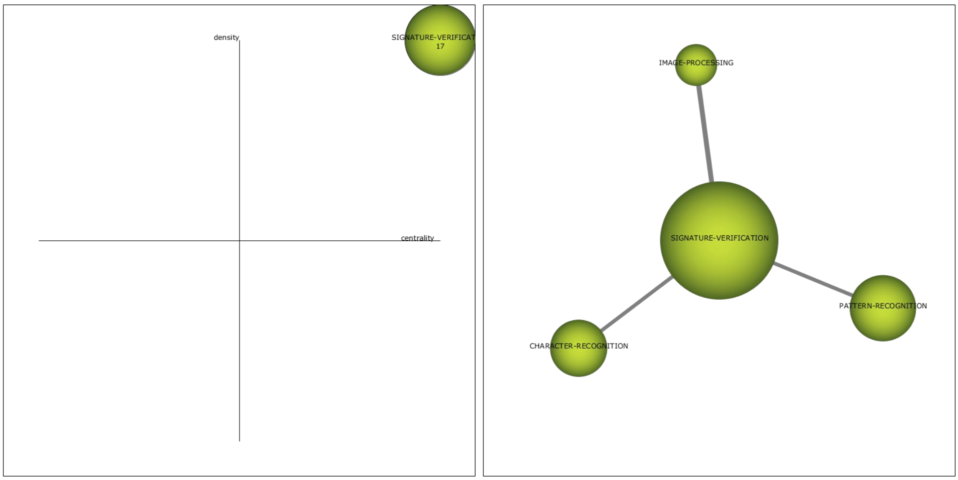
| *Period* | *Cluster* | *Centrality* | *Centrality range* | *Density* | *Density range* |
|---|---|---|---|---|---|
| 1982–2001 | Signature-verification | 0 | 1 | 52.81 | 1 |
| 1992–2001 | Signature-verification | 83.96 | 1 | 106.7 | 1 |
| 2002–2011 | Authentication | 305.28 | 0.75 | 98.85 | 1 |
| | Signature-verification | 373.65 | 1 | 90.51 | 0.75 |
| | Electronic-document-identification-systems | 229.06 | 0.5 | 90.32 | 0.5 |
| | Algorithms | 150.07 | 0.25 | 84.74 | 0.25 |
| 2012–2022 | Authentication | 999.99 | 0.88 | 95 | 0.62 |
| | Signature-verification | 1,101.25 | 1 | 93.51 | 0.5 |
| | Biometrics | 179.82 | 0.12 | 106.21 | 1 |
| | Network-security | 616.64 | 0.62 | 67.74 | 0.25 |
| | Cryptography | 459.6 | 0.5 | 81 | 0.38 |
| | Vehicular-ad-hoc-networks | 639.88 | 0.75 | 99.99 | 0.75 |
| | Neural-networks | 189.17 | 0.25 | 101.32 | 0.88 |
| | Electronic-document-identification-systems | 356.64 | 0.38 | 38.47 | 0.12 |

### *4.4.2 Period 1: 1982–1991*

Figure 11(a) shows the strategic diagram for period 1: 1982–1991 and Figure 11(b) shows the cluster network for the same period. The strategic diagram shows that there was only one motor theme in the period I. There were 17 documents with an h-index of 7. To solve the SV problem in this decade, image processing, pattern recognition, and character recognition were used. Table 4 shows the top 10 most cited papers of the cluster ‘SV’ along with the cluster keywords, h-index, and the number of documents associated with the theme. The number of citations has been given in the subscript of each paper.

The top cited article, Plamondon and Lorette (1989) gave an insight into various tools and techniques used back then for solving SV problems. It also summarised various datasets and benchmarks used in the field. The article discusses the promising prototypes developed for SV and writer identification but notes that improvements are needed for practical use, particularly in terms of interface, system, and social issues. It raised various issues related to the pattern recognition approach to solving the problem. In Plamondon and Parizeau (1988), the authors presented a comparison of the performance of different machine learning models in SV using position, velocity, and acceleration signals. The results showed that the random forest model achieved the highest accuracy of 97.5%, outperforming other models such as support vector machines and multi-layer perceptron. The extension of this work has been presented in Parizeau and Plamondon (1990), the authors compared three different pattern recognition approaches for SV namely – regional correlation, dynamic time warping, and skeletal tree matching. The authors found that the highest performance was achieved using skeletal tree matching, followed by dynamic time warping and regional correlation.

**Figure 11** (a) Strategic diagram (b) Cluster network of cluster 'SV' for the period 1982–1991 (see online version for colours)




(a) (b)

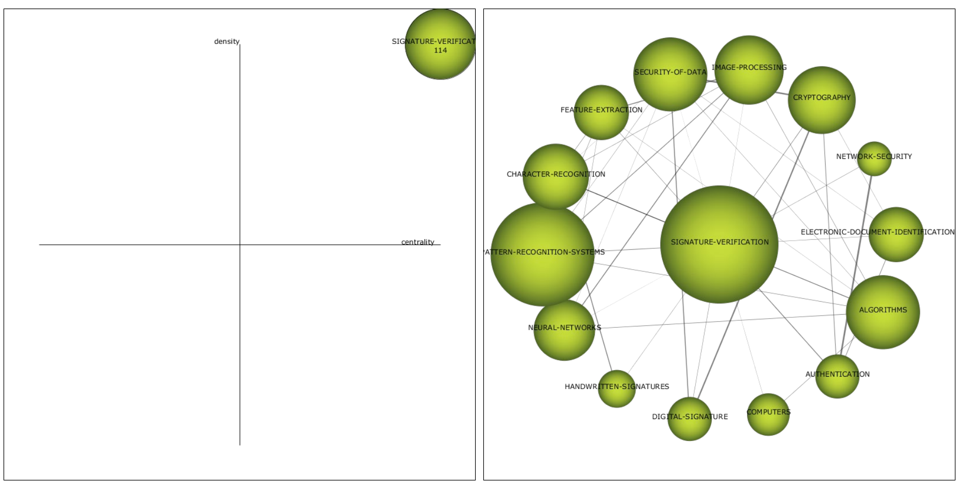
**Table 4** TN's performance analysis for period I-1982–1991

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Signature verification | Signature-verification pattern-recognition image-processing character-recognition | 17 | 7 | 1 | Plamondon and Lorette (1989)#749 |
| | | | | 2 | Parizeau and Plamondon (1990)#103 |
| | | | | 3 | Plamondon and Parizeau (1988)#41 |
| | | | | 4 | Baron and Plamondon (1989)#40 |
| | | | | 5 | Lam and Kamins (1989)#39 |
| | | | | 6 | Sabourin and Plamondon (1986)#21 |
| | | | | 7 | Wilkinson and Goodman (1991)#9 |
| | | | | 8 | de Bruyne and Forre (1986)#7 |
| | | | | 9 | Impedovo et al. (1989)#4 |
| | | | | 10 | Lucas and Damper (1990)#4 |

### *4.4.3 Period 2: 1992–2001*

Figure 12(a) shows the strategic diagram for period 2: 1992–2001 and Figure 12(b) shows the cluster network for the same period. The strategic diagram shows that there was only one motor theme in the period 1. There were 96 documents with an h-index of 26. To solve the SV problem in this decade various techniques have been used. Pattern recognition and character recognition were the two themes that were carried forward from period 1 to period 2. Other significant themes in period 2 are – security of data, cryptography, neural networks, feature extraction, electronic document identification systems, digital signature, authentication, network security, computational methods, and handwritten signatures. Specifically, signatures were used for authentication in this era and researchers paid high attention to this theme. Apart from that, the security of data was the major concern regarding SV and is one of the prominent themes of period 2. Table 5 shows the top 10 most cited papers of the cluster 'SV' along with the cluster keywords, h-index, and the number of documents associated with the theme. The number of citations has been given in the subscript of each paper.

**Figure 12** (a) Strategic diagram (b) Cluster network of cluster 'SV' for the period 1992–2001 (see online version for colours)




(a) (b)

The top cited document, Bellare et al. (1998) proposed a batch verification scheme that was much faster than others and has potential applications in information security and authentication. However, it left security and scalability as open research problems. In Harn (1994), the authors propose a practical and secure method for achieving threshold digital signatures and multi-signatures with a reduced number of keys and communication overhead. The article presents a useful contribution to the field of cryptography and digital signatures, with potential applications in various areas of information security and authentication. In Said et al. (2000), the authors propose a feature extraction and recognition approach based on various handwriting characteristics such as pen pressure, direction, and speed. The article presents a useful contribution to the field of biometrics and personal identification, with potential applications in various areas such as forensic science and handwriting recognition technology. Thus, in period 2, various novel methods based on neural networks, pattern recognition, cryptography, etc. have been proposed which proved to have potential applications in information security, authentication, biometric technology, and forensic science. However, the open research problems were security and scalability which were addressed in the period 3.

**Table 5** TN's performance analysis for period 2-1992–2001

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Signature verification | Algorithms, authentication, character-recognition, computational-methods, cryptography, digital-signature, electronic-document, identification-systems, feature-extraction, handwritten-signatures, network-security, neural-networks, pattern-recognition, security-of-data, signature-verification | 114 | 27 | 1 | Bellare et al. (1998)#314 |
| | | | | 2 | Harn (1994)#264 |
| | | | | 3 | Said et al. (2000)#264 |
| | | | | 4 | Ye and Chen (2001)#177 |
| | | | | 5 | Bao and Deng (1998)#171 |
| | | | | 6 | Bajaj and Chaudhury (1997)#135 |
| | | | | 7 | Munich and Perona (1999)#117 |
| | | | | 8 | Zhu et al. (2000)#105 |
| | | | | 9 | Brault and Plamondon (1993)#98 |
| | | | | 10 | Qi and Hunt (1994)#84 |

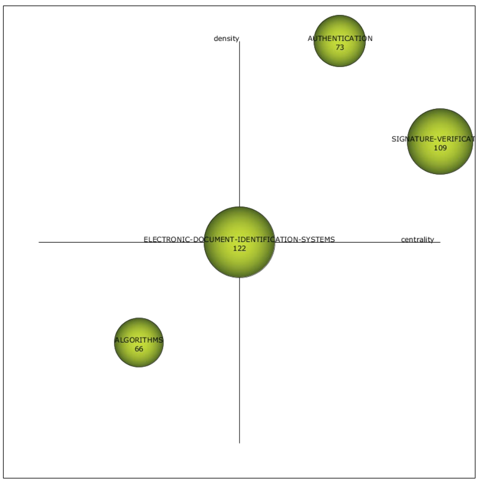
### *4.4.4 Period 3: 2002–2011*

Figure 13(a) shows the strategic diagram for period 3: 2002–2011 and Figures 13(b)–13(e) shows the cluster network for the same period. The strategic diagram shows that there are four themes identified in period 3 namely – authentication, SV, electronic document identification systems, and algorithms. Among these, SV has been carried from period I and period 2. Three hundred seventy documents contributed to these themes. 'authentication' and 'SV' were identified as motor themes, 'algorithms' as emerging themes, and 'electronic document verification systems (EDIS)' as the central theme of the period.

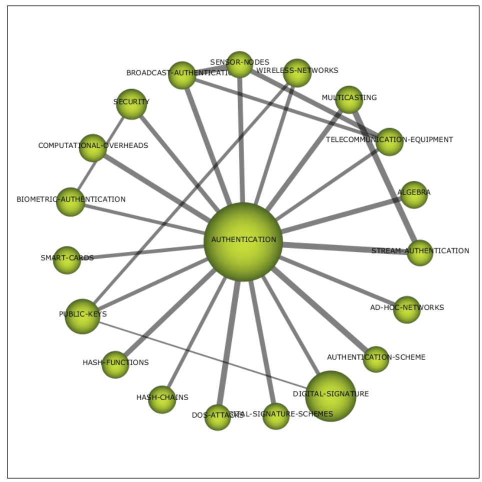
Digital signatures, public key cryptosystems, and DOS attacks were the most relevant areas which were explored concerning the authentication cluster. In Lu and Liao (2003), structural digital signatures were used and were encrypted using public key cryptosystems. The authors show that the proposed method is more robust to these types of distortions compared to other existing methods. Another TN 'signature-verification' has been carried forward from periods 1 and 2. In this TN, network security, access control, and signature generations were different applications of SV which were explored. Hidden Markov model and Bayesian networks were widely used for the implementation of SV. The TN which is identified as the central theme of SV is EDIS. The major concerns identified in this theme were the security of data. Cryptography, discrete algorithms, group signatures, and multi-signatures were used to address this issue. The fourth TN identified in this period is 'algorithms'. This is an emerging theme and is present in the fourth quadrant of the strategic diagram. Various types of algorithms including biometrics, pattern recognition, character recognition, and artificial intelligence were used to implement signature verifiers.

Table 6 shows the top 10 most cited papers of each cluster along with the cluster keywords, h-index, and number of documents associated with the theme. The number of citations has been given in the subscript of each paper.

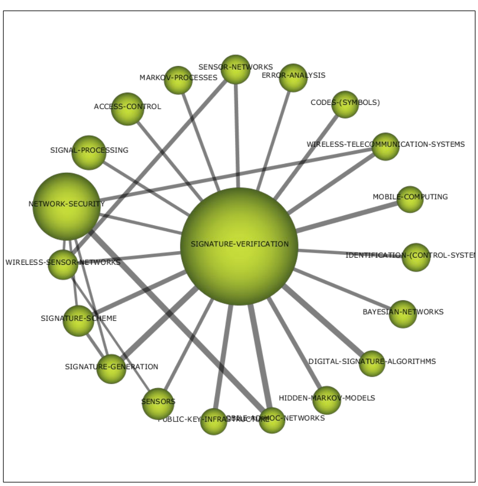
**Figure 13** (a) Strategic diagram (b) Cluster network of cluster 'authentication' (c) Cluster network of cluster 'SV' (d) Cluster network of cluster 'electronic document identification systems' (e) Cluster network of cluster 'algorithms' for the period 2002–2011 (see online version for colours)



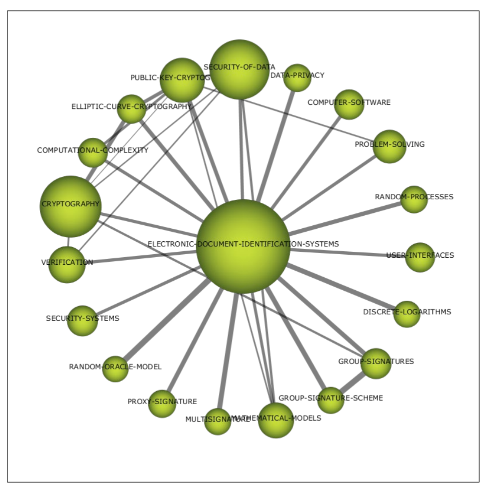

(a)




(b)

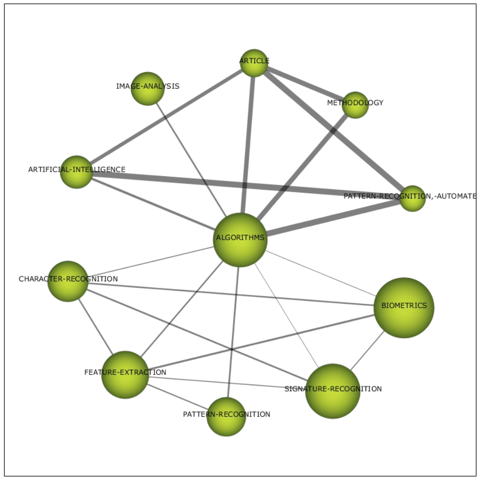



(c)




(d)

**Figure 13** (a) Strategic diagram (b) Cluster network of cluster ‘authentication’ (c) Cluster network of cluster ‘SV’ (d) Cluster network of cluster ‘electronic document identification systems’ (e) Cluster network of cluster ‘algorithms’ for the period 2002–2011 (continued) (see online version for colours)




(e)

**Table 6** TN’s performance analysis for period 3-2002–2011

| *Thematic network* | *Network’s keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Authentication | Authentication, digital-signature, public-keys, security, biometric-authentication, wireless-networks, broadcast-authentication, computational-overheads, hash-chains, multicasting, smart-cards, telecommunication-equipment, ad-hoc-networks, algebra, hash-functions, digital-signature-schemes, sensor-nodes, authentication-scheme, dos-attacks, stream-authentication | 73 | 14 | 1 | Lu and Liao (2003)#301 |
| | | | | 2 | Lin et al. (2008)#152 |
| | | | | 3 | Ning et al. (2008)#136 |
| | | | | 4 | Hsiao et al. (2011)#77 |
| | | | | 5 | Sun et al. (2002)#57 |
| | | | | 6 | Chang et al. (2009)#57 |
| | | | | 7 | Dong et al. (2008)#45 |
| | | | | 8 | Wang et al. (2011)#43 |
| | | | | 9 | Wu et al. (2011)#29 |
| | | | | 10 | Gilbert and Minier (2002)#29 |

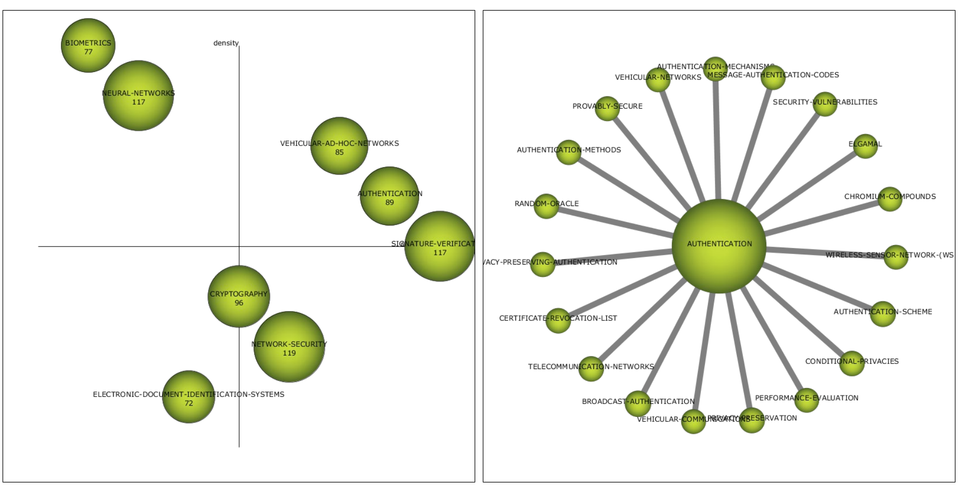
**Table 6** TN's performance analysis for period 3-2002–2011 (continued)

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | *Top 10 documents* |
|---|---|---|---|---|
| Signature verification | algorithms, biometrics, signature-recognition, pattern-recognition, feature-extraction, character-recognition, artificial-intelligence, image-analysis, article, methodology | 109 | 22 | 1 Zhang et al. (2008)#484<br>2 Guo et al. (2007)#200<br>3 Du et al. (2005)#169<br>4 Lin et al. (2008)#152<br>5 Ning et al. (2008)#136<br>6 Boldyreva et al. (2007)#129<br>7 Zhang et al. (2011)#119<br>8 Tseng (2006)#95<br>9 Hsiao et al. (2011)#77<br>10 Sun et al. (2002)#57 |
| Electronic document identification systems | Discrete-logarithms, group-signatures, group-signature-scheme, mathematical-models, multisignature, proxy-signature, random-oracle-model, security-systems, verification, cryptography, computational-complexity, elliptic-curve-cryptography, electronic-document-identification-systems, public-key-cryptography, security-of-data, data-privacy, computer-software, problem-solving, random-processes | 122 | 24 | 1 Zhang et al. (2008)#484<br>2 Boneh and Shacham (2004)#445<br>3 Lu and Liao (2003)#301<br>4 Gentry and Ramzan (2006)#254<br>5 Groth (2006)#240<br>6 Guo et al. (2007)#200<br>7 Datta et al. (2007)#154<br>8 Ning et al. (2008)#136<br>9 Dodis and Reyzin (2003)#118<br>10 Chang et al. (2009)#93 |
| Algorithms | Algorithms, biometrics, signature-recognition, pattern-recognition, feature-extraction, character-recognition, artificial-intelligence, image-analysis, article, methodology, pattern-recognition, automated | 66 | 16 | 1 Srinivasan et al. (2006)#373<br>2 Buchtala et al. (2005)#116<br>3 Tang et al. (2002)#82<br>4 Dimauro et al. (2004)#65<br>5 Ballard et al. (2007)#60<br>6 Florestal et al. (2006)#59<br>7 Sun et al. (2002)#57<br>8 Vielhauer and Steinmetz (2004)#52<br>9 Toledano et al. (2006)#49<br>10 Nel et al. (2005)#40 |

### 4.4.5 Period 4: 2012–2023

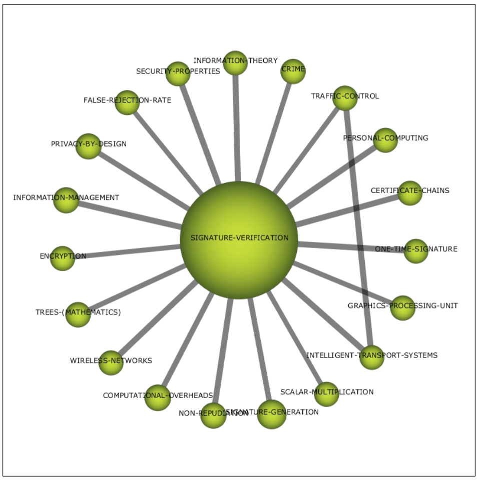
Figure 14(a) shows the strategic diagram for period 4: 2012–2023 and Figures 13(b)–13(i) shows the cluster network for the same period. The strategic diagram shows that there are eight themes identified in period 4 namely-authentication, SV, biometrics, network security, cryptography, vehicular-ad-hoc-networks, neural networks, and electronic-document-identification-systems. Seven hundred seventy-two documents contributed to these themes. 'vehicular-ad-hoc-networks', 'Authentication' and 'SV' were identified as motor themes, 'biometrics' and 'neural networks' are under the category of highly developed and isolated themes, 'network-security' and 'cryptography were characterised as basic themes and 'EDIS' as the emerging theme of the period. The noteworthy contribution was in biometrics and neural network themes. In biometrics themes, identity verification, multi-modal biometrics, bi-modal biometrics, face recognition, static signatures, and dynamic signatures were the major fields in which research have been taken place. However, this period was also identified as the major period for the evolution of neural networks in SV. Convolutional neural networks (CNNs) and deep learning were explored for implementing SV. Identity-based signatures, digital signatures, and different signature schemes are the less explored fields, and much research is needed in this field.

**Figure 14** (a) Strategic diagram (b) Cluster network of cluster 'authentication' (c) Cluster network of cluster 'SV' (d) Cluster network of cluster 'biometrics' (e) Cluster network of cluster 'network-security' (f) Cluster network of cluster 'cryptography' (g) Cluster network of cluster 'vehicular ad-hoc networks' (h) Cluster network of cluster 'neural networks' (i) Cluster network of cluster 'electronic document identification systems' for the period 2012–2023 (see online version for colours)

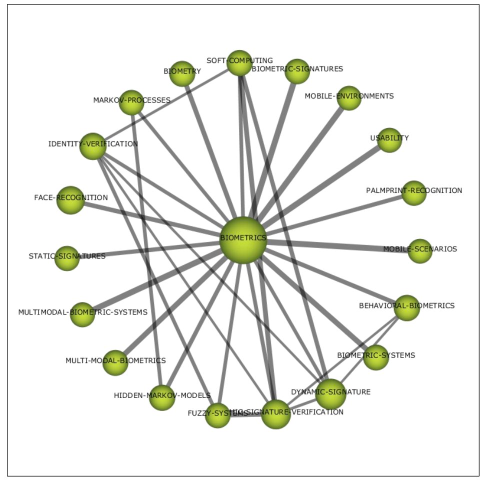



(a) (b)

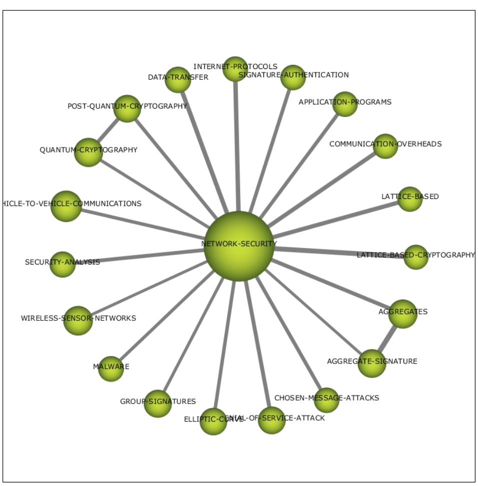
**Figure 14** (a) Strategic diagram (b) Cluster network of cluster 'authentication' (c) Cluster network of cluster 'SV' (d) Cluster network of cluster 'biometrics' (e) Cluster network of cluster 'network-security' (f) Cluster network of cluster 'cryptography' (g) Cluster network of cluster 'vehicular ad-hoc networks' (h) Cluster network of cluster 'neural networks' (i) Cluster network of cluster 'electronic document identification systems' for the period 2012–2023 (continued) (see online version for colours)



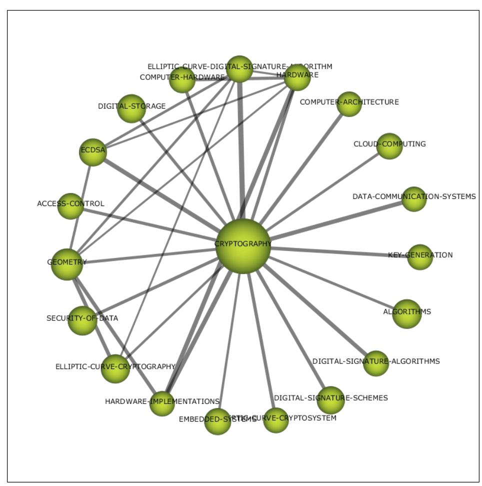

(c)




(d)

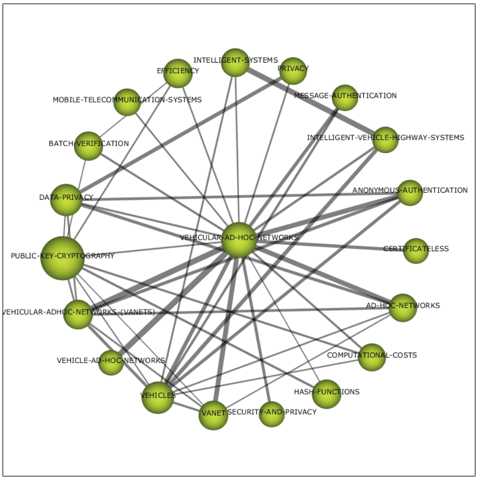



(e)

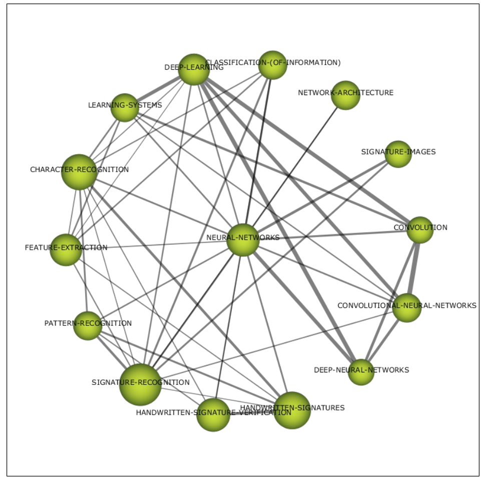



(f)

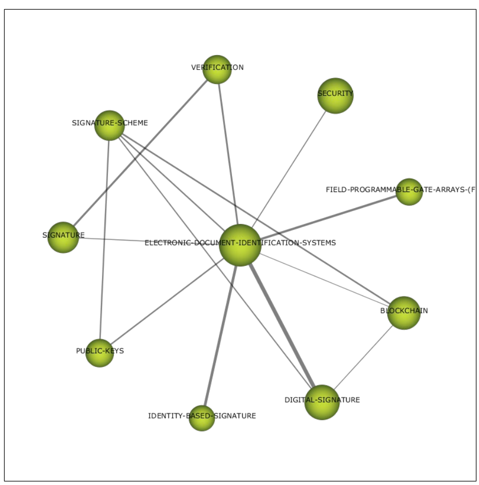
**Figure 14** (a) Strategic diagram (b) Cluster network of cluster 'authentication' (c) Cluster network of cluster 'SV' (d) Cluster network of cluster 'biometrics' (e) Cluster network of cluster 'network-security' (f) Cluster network of cluster 'cryptography' (g) Cluster network of cluster 'vehicular ad-hoc networks' (h) Cluster network of cluster 'neural networks' (i) Cluster network of cluster 'electronic document identification systems' for the period 2012–2023 (continued) (see online version for colours)




(g)




(h)




(i)

**Table 7** TN's performance analysis for period 4-2012–2023

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Authentication | Authentication, authentication-scheme, conditional-privacies, performance-evaluation, privacy-preservation, vehicular-communications, broadcast-authentication, telecommunication-networks, certificate-revocation-list, privacy-preserving-authentication, random-oracle, authentication-methods, provably-secure, vehicular-networks, authentication-mechanisms, message-authentication-codes, security-vulnerabilities | 89 | 24 | 1 | Azees et al. (2017)$_{\#268}$ |
| | | | | 2 | Jiang et al. (2016)$_{\#173}$ |
| | | | | 3 | He et al. (2012)$_{\#169}$ |
| | | | | 4 | Zhu et al. (2014)$_{\#147}$ |
| | | | | 5 | Vijayakumar et al. (2018)$_{\#131}$ |
| | | | | 6 | Catalano et al. (2014)$_{\#74}$ |
| | | | | 7 | Wang and Yao( 2017)$_{\#73}$ |
| | | | | 8 | Ali et al. (2019)$_{\#65}$ |
| | | | | 9 | Lyu et al. (2016)$_{\#65}$ |
| | | | | 10 | Benzaid et al. (2016)$_{\#64}$ |
| Signature-verification | Graphics-processing-unit, intelligent-transport-systems, scalar-multiplication, signature-generation, signature-verification, non-repudiation, computational-overheads, wireless-networks, trees-(mathematics), encryption, information-management, privacy-by-design, false-rejection-rate, security-properties, information-theory, crime, traffic-control, personal-computing | 117 | 16 | 1 | He et al. (2012)$_{\#169}$ |
| | | | | 2 | Zhao et al. (2020)$_{\#87}$ |
| | | | | 3 | Ghali et al. (2014)$_{\#73}$ |
| | | | | 4 | Liu et al. (2017)$_{\#54}$ |
| | | | | 5 | Alzubi (2021)$_{\#50}$ |
| | | | | 6 | Chen et al. (2017)$_{\#41}$ |
| | | | | 7 | Tsai et al. (2013)$_{\#30}$ |
| | | | | 8 | Crain et al. (2021)$_{\#29}$ |
| | | | | 9 | Wang et al. (2020)$_{\#28}$ |
| | | | | 10 | Nkenyereye et al. (2019) $_{\#28}$ |
| Biometrics | Behavioural-biometrics, biometrics, biometric-systems, dynamic-signature, dynamic-signature-verification, fuzzy-systems, hidden-Markov-models, multi-modal-biometrics, multimodal-biometric-systems, static-signatures, face-recognition, identity-verification, Markov-processes, biometry, soft-computing, biometric-signatures, mobile-environments, usability, \`palmprint-recognition | 77 | 15 | 1 | Diaz et al. (2018)$_{\#76}$ |
| | | | | 2 | Kuruvilla et al. (2016)$_{\#76}$ |
| | | | | 3 | Doroz et al. (2016)$_{\#38}$ |
| | | | | 4 | Blanco-Gonzalo et al. (2014b)$_{\#38}$ |
| | | | | 5 | Zalasiński et al. (2014)$_{\#33}$ |
| | | | | 6 | Pirlo and Impedovo (2013)$_{\#32}$ |
| | | | | 7 | Zalasiński et al. (2016b)$_{\#27}$ |
| | | | | 8 | Zareen and Jabin (2016)$_{\#23}$ |
| | | | | 9 | Tolosana et al. (2015)$_{\#18}$ |
| | | | | 10 | Zalasiński et al. (2016a)$_{\#17}$ |

**Table 7** TN's performance analysis for period 4-2012–2023 (continued)

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Network-security | Aggregates, aggregate-signature, chosen-message-attacks, denial-of-service-attack, elliptic-curve, group-signatures, malware, wireless-sensor-networks, network-security, security-analysis, vehicle-to-vehicle-communications, quantum-cryptography, post-quantum-cryptography, data-transfer, internet-protocols, signature-authentication, application-programs, communication-overheads | 119 | 21 | 1 | Zhang and Chen (2019)$_{\#152}$ |
| | | | | 2 | Zhu et al. (2014)$_{\#147}$ |
| | | | | 3 | Vijayakumar et al. (2017)$_{\#73}$ |
| | | | | 4 | Li et al. (2015)$_{\#68}$ |
| | | | | 5 | Ali et al. (2019)$_{\#65}$ |
| | | | | 6 | Lyu et al. (2016)$_{\#65}$ |
| | | | | 7 | Benzaid et al. (2016)$_{\#64}$ |
| | | | | 8 | Wang et al. (2016)$_{\#54}$ |
| | | | | 9 | Sun et al. (2017)$_{\#43}$ |
| | | | | 10 | Güneysu et al. (2013)$_{\#41}$ |
| Cryptography | Algorithms, digital-signature-algorithms, digital-signature-schemes, elliptic-curve-cryptosystem, embedded-systems, hardware-implementations, cryptography, elliptic-curve-cryptography, security-of-data, geometry, access-control, ECDSA, digital-storage, computer-hardware, elliptic-curve-digital-signature-algorithm, hardware, computer-architecture, cloud-computing | 96 | 13 | 1 | Li et al. (2015)$_{\#68}$ |
| | | | | 2 | Liu et al. (2017)$_{\#54}$ |
| | | | | 3 | Rao and Dutta (2016)$_{\#39}$ |
| | | | | 4 | Rao and Prema (2019)$_{\#32}$ |
| | | | | 5 | Gao et al. (2020)$_{\#32}$ |
| | | | | 6 | Ben Hamida and Javed (2016)$_{\#26}$ |
| | | | | 7 | Knezevic et al. (2016)$^{\#25}$ |
| | | | | 8 | Jin et al. (2018)$_{\#24}$ |
| | | | | 9 | Hu et al. (2015)$_{\#24}$ |
| | | | | 10 | Li et al. (2020)$^{\#18}$ |
| Vehicular-ad-hoc-networks | Ad-hoc-networks, computational-costs, hash-functions, security-and-privacy, VANET, vehicles, vehicle-ad-hoc-networks, vehicular-ad-hoc-networks, vehicular-adhoc-networks-(VANETs), public-key-cryptography, data-privacy, batch-verification, mobile-telecommunication-systems, efficiency, intelligent-systems, privacy, message-authentication, intelligent-vehicle-highway-systems, anonymous-authentication, certificateless | 85 | 22 | 1 | Azees et al. (2017)$_{\#268}$ |
| | | | | 2 | Jiang et al. (2016)$_{\#173}$ |
| | | | | 3 | He et al. (2012)$_{\#169}$ |
| | | | | 4 | Zhang and Chen (2019)$_{\#152}$ |
| | | | | 5 | Zhu et al. (2014)$_{\#147}$ |
| | | | | 6 | Vijayakumar et al. (2018)$_{\#131}$ |
| | | | | 7 | Zhao et al. (2020)$_{\#87}$ |
| | | | | 8 | Wang and Yao (2017)$_{\#73}$ |
| | | | | 9 | Vijayakumar et al. (2017)$_{\#73}$ |
| | | | | 10 | Ali et al. (2019)$_{\#65}$ |

**Table 7** TN's performance analysis for period 4-2012–2023 (continued)

| *Thematic network* | *Network's keywords* | *Number of documents* | *h-index* | | *Top 10 documents* |
|---|---|---|---|---|---|
| Neural-networks | Convolutional-neural-networks, deep-neural-networks, handwritten-signatures, handwritten-signature-verification, neural-networks, signature-recognition, pattern-recognition, feature-extraction, character-recognition, learning-systems, deep-learning, classification-(of-information), network-architecture, signature-images | 117 | 11 | 1 | Impedovo et al. (2012)$_{\#54}$ |
| | | | | 2 | Porwik et al. (2016)$_{\#43}$ |
| | | | | 3 | Blanco-Gonzalo et al. (2014b)$_{\#38}$ |
| | | | | 4 | Agrawal et al. (2021)$_{\#15}$ |
| | | | | 5 | Behera et al. (2018)$_{\#15}$ |
| | | | | 6 | Połap and Woźniak (2016)$_{\#15}$ |
| | | | | 7 | Jampour et al. (2021)$_{\#15}$ |
| | | | | 8 | Blanco-Gonzalo et al. (2014a)$_{\#15}$ |
| | | | | 9 | Tayeb et al. (2017)$_{\#13}$ |
| | | | | 10 | Xia et al. (2018)$_{\#12}$ |
| Electronic-document-identification-systems | Blockchain, digital-signature, identity-based-signature, public-keys, signature, signature-scheme, verification, electronic-document-identification-systems, security, field-programmable-gate-arrays-(FPGA) | 72 | 14 | 1 | Jiang et al. (2016)$_{\#173}$ |
| | | | | 2 | Pöppelmann et al. (2014)$_{\#80}$ |
| | | | | 3 | Ren et al. (2021)$_{\#73}$ |
| | | | | 4 | Benzaid et al. (2016)$_{\#64}$ |
| | | | | 5 | Alzubi (2021)$_{\#50}$ |
| | | | | 6 | Li et al. (2012)$_{\#43}$ |
| | | | | 7 | Seo et al. (2012)$_{\#35}$ |
| | | | | 8 | Knezevic et al. (2016)$_{\#25}$ |
| | | | | 9 | Kaga et al. (2017)$_{\#16}$ |
| | | | | 10 | Hyla and Pejaś (2020)$_{\#16}$ |

Table 7 shows the top 10 most cited papers of each cluster along with the cluster keywords, h-index, and number of documents associated with the theme. The number of citations has been given in the subscript of each paper.

## 5 Conclusions and future scope

SV is a research field that has been continuously growing since the 1980s. Various approaches used in the implementation of verifiers, image acquisition, feature extraction, etc. have been witnessed in the last four decades. The research questions proposed by the authors have resulted in the following conclusions which can be drawn from the bibliometric study of this research area.

- Plamondon and Lorette (1989) is the most cited paper in the field of SV which is written by Plamondon and Lorette. It has 749 citations.
- The most productive author in this field was found to be Pirlo with a contribution of 25 documents in this research area.
- The conference proceedings published in Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics) is the highest contributor with 149 articles whereas in journals, *Pattern Recognition* stands out with 17 articles
- Annual scientific production has seen a steady rise since the very beginning of the research. The number of documents published per year has increased every year.
- At the beginning of the research, more focus was on image processing techniques, pattern recognition, and character recognition. Eventually, different verifying techniques like neural networks hidden Markov models, support vector machines, etc were explored.
- The most studied problems of SV were authentication, security, electronic document identification systems, biometric verification, and recognition.
- The evolution of the SV theme can be seen over the periods. The inclusion of signature generation, the creation of databases, and access control mechanisms in the last two decades show the increase in applications of SV.
- Some less explored domains public keys, smart cards, and blockchains in association with SV.
- Many TNs show that pattern recognition and character recognition algorithms have significantly contributed to the field of SV.

As seen through the thematic evolution of SV over the past four decades, some future trends can be predicted. These future trends are summarised below:

- Multiscript variation systems – Typically, signatures are written in one language or illegible patterns. The majority of verifiers employ feature sets that are unique to each script. As a result, these verifiers perform poorly for signatures that contain numerous scripts or for scripts that are not included in the training set. Separate databases of different scripts are frequently used to get around this situation

(Pal et al., 2013). Das et al. (2016) gave a comparison of the single script and multiscript signatures. It also suggested a fresh method for creating a multiscript signature training database. There is still work to be done on both online and offline signature databases with several scripts.

- Acquisition methods – Typically, data is gathered either online or offline for automatic signature verifiers (Khan and Dhole, 2014). Images of signatures are scanned or shot from paper in offline mode. In online systems, signatures are collected using digital tools like digitising pens or tablets. Then, to remove noise, background effects, and distortions brought on by the data acquisition process, these digital images are put through image preprocessing. Many different kinds of digital tablets can be utilised for this. Tablets come in a variety of forms, including passive, active, optical, acoustic, capacitive, etc. Online signatures can also be obtained using digital pens. Certain standards must be followed to maintain consistency among the data collected using various devices.
- Signatures in medical applications – Researchers and psychologists have been interested in the use of handwriting and signatures to study human behaviour and medical issues. Using neuro-motor control, a signature is a complex activity (Ferrer et al., 2015). Additionally, it requires kinematic, perceptual-motor, and cognitive skills. Different activities, such as eye-hand coordination, visual motor planning, kinematic activities, muscle movement, motor planning, etc., are necessary for writing. As a result, psychiatric and neurodegenerative illnesses have an impact on handwriting (Khan and Jain, 2018; Onofri et al., 2013; Senatore and Marcelli, 2017). According to recent studies, there is a direct link between poor handwriting and conditions like Alzheimer's, Parkinson's, dysgraphia, etc. It can also be used to track how well patients respond to treatment, spot disorders like these in children at a young age, and many other things.
- Synthetic signature generation- The gathering of datasets for training purposes is one of the main drawbacks that automatic SV experiences. Data gathering for automatic signature verifiers is a particularly challenging process because of regulatory restrictions and people's reluctance to freely supply their signatures (Khan et al., 2023c). It is a time- and money-consuming process. Many researchers have suggested the use of synthetic signatures to get rid of this. Additionally, many artificial generator models can simulate both intrapersonal and interpersonal variability (Khan et al., 2023a). The production of unrealistic data is still a concern for synthetic signature generation. The most current and successful area of research for automatic verifiers is in this area.
- Deep learning methods – CNNs and recurrent neural networks (RNNs), two deep learning approaches, have demonstrated promise in the verification of digital signatures. Future studies could look into ways to further increase these techniques' accuracy (Ghosh, 2021; Parcham et al., 2021).
- Multi-modal biometrics – To increase overall accuracy, SV can be integrated with additional biometric modalities like fingerprint or facial recognition. Future studies might examine the optimal way to combine various modalities and create more reliable multi-modal biometric systems (Abualghanam et al., 2021).

- Adversarial attacks – Like other biometric systems, SV systems are vulnerable to hostile attacks. Subsequent research endeavours may investigate strategies to fortify these systems' resilience against attacks through the employment of adversarial training techniques (Bird et al., 2023).

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