RESEARCH PAPER

Hybrid Soft Computing–Based Image Watermarking for Copyright Protection: A Systematic Review of Methods, Performance, and Security Challenges

Barkha Sahu[1*], Dr. Neeraj Kumar Rathore[2], Dr. Abhishek Bansal[3]
[1] PhD Research Scholar, Department of Computer Science, Indira Gandhi National Tribal University, Amarkantak, Anuppur, Madhya Pradesh, India. Email: barkhaigntu@gmail.com (Corresponding Author)
[2] Associate Professor, Department of Computer Science, Indira Gandhi National Tribal University, Amarkantak, Anuppur, Madhya Pradesh, India. Email: neeraj.rathore@igntu.ac.in
[3] Associate Professor, Department of Computer Science and Application, Dr. Harisingh Gour Vishwavidyalay, Sagar, Madhya Pradesh, India. Email: abhishek.bansal@igntu.ac.in

Received: 12th Mar, 2026 | **Revised:** 24th Mar, 2026 | **Accepted:** 14th Apr, 2026 | **Available Online:** 30th Apr, 2026

ABSTRACT
The rapid advancement of digital imaging technologies and widespread online multimedia sharing has intensified concerns related to copyright infringement, content authentication, and unauthorized manipulation of digital images. Ownership protection and data integrity verification can be achieved by digital image watermarking. The main challenge is to optimize imperceptibility, robustness, capacity, and security. In recent years, hybrid soft computing-based watermarking techniques have gained much attention due to their adaptive and optimization-driven capabilities. This paper presents a comprehensive systematic review of hybrid soft computing and transform-domain image watermarking methods for copyright protection, conducted in accordance with PRISMA guidelines. Transform techniques such as DWT, DCT, SVD, RDWT, contourlet, and QFT are used in the watermarking frameworks integrated with soft computing and metaheuristic optimization algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), fuzzy logic, swarm intelligence, and hybrid evolutionary approaches. Standard metrics like Peak Signal-to-Noise Ratio (PSNR), Structural Similarity Index (SSIM), Normalized Correlation (NC), Bit Error Rate (BER), and robustness under geometric and non-geometric attacks were used for performance evaluation. The studies reviewed here prove that hybrid approaches always achieve high imperceptibility (PSNR frequently over 40–60 dB), strong robustness (NC > 0.9), and improved security with reduced false positive errors. It also finds out that while hybrid intelligent watermarking frameworks are effective, computational complexity and real-time applicability present challenges for future research.

Keywords: Digital Image Watermarking, Hybrid Soft Computing, Metaheuristic Optimization, Copyright Protection, Robustness and Imperceptibility
How to cite this article: Sahu B, Rathore NK, Bansal A. Hybrid Soft Computing–Based Image Watermarking for Copyright Protection: A Systematic Review of Methods, Performance, and Security Challenges. Int J Drug Deliv Technol. 2026;16(38s): 192-217. DOI: 10.25258/ijddt.16.38s.15
Source of support: Nil.
Conflict of interest: None

1. Introduction

The rapid growth of digital technology, the Internet, and multimedia tools has changed how visual information is created, shared, and consumed. Digital images are now widely used in various fields such as social media, e-commerce, medical imaging, surveillance, education, journalism, and entertainment [1]. Unfortunately, this easy access has greatly heightened the chances of unauthorized copying, sharing, altering, and abusing digital content [2]. The fact that digital images can be copied and shared with no loss of quality has made copyright protection and the ability to prove the authenticity of the content a primary concern to the content creator and companies [3]. These issues demonstrate the relevance of effective and strong means of securing intellectual property and quality of digital visual media [4].

The digital image watermarking is a recent method that has been recognized to have potential in the area of multimedia copyright protection and authentication. Watermarking refers to the practice of embedding invisible information known as watermark on a host image so that the information can be later verified about ownership or any manipulation can be tracked [5,6]. In contrast to encryption in which the data is protected only in transit, watermarking protects the data over a long period since the data hidden in the media is saved even after the distribution [7]. The watermark can be a hidden ownership credential, authentication-code, transaction-code or a copyright ownership, hence enabling use in a wide range of applications such as copy protection, broadcast monitoring, fingerprinting, and forensic tracking [8]. The field of application of digital watermarking in different areas is illustrated in Figure 1.

Figure 1: Major application domains of digital image watermarking in multimedia security and copyright protection [9].

The basic performance requirements which an effective watermarking system requires need to include four key elements which are imperceptibility and robustness and capacity and security. The watermark needs to be embedded through imperceptibility which prevents any visual distortion from becoming detectable. The watermark remains detectable through all common signal-processing operations which include compression and filtering and noise addition and cropping and geometric transformations [10]. The system uses capacity to measure information embedding limits which maintain image quality while security protects the watermark from being removed or modified through deliberate actions [11]. The requirements present fundamental conflicts because increasing robustness decreases imperceptibility while greater capacity results in both visual quality loss and security vulnerability. The research community must solve this problem because it represents a fundamental research problem which requires resolution.

The conventional methodology of watermarking can be divided into spatial-domain and transform-domain. Spatial-domain methods, e.g. Least Significant Bit (LSB) embedding, directly alter pixel values and are simple and high-payload, but very susceptible to signal-processing and geometric attacks [12]. Transform-domain, such as “Discrete Cosine Transform (DCT), Discrete Wavelet Transform (DWT) and Discrete Fourier Transform (DFT)”, store watermark data in the frequency coefficients, which provides enhanced protection and resistance to typical distortions [13]. However, the traditional transform-based techniques usually apply predetermined embedding guidelines and handcrafted parameters optimization, which can reduce flexibility and lead to poor performance in a variety of attack cases.

To overcome these challenges, there has been a growing trend of integrating soft computing methods into watermarking schemes. Soft computing is a field of intelligent computing that includes methods such as Artificial Neural Networks (ANN), fuzzy logic systems, GA, PSO, and other evolutionary algorithms [14]. These methods are known to be able to deal with uncertainty, non-linearities, and multi-objective optimization problems, which makes them particularly useful for adaptive watermarking. For example, fuzzy logic can be used to simulate the Human Visual System (HVS) to decide on the embedding strength, while evolutionary algorithms can be used to optimize the transform coefficients to achieve robustness and imperceptibility [15]. However, more recently hybrid soft computing-based watermarking methods have received considerable interest, because they can combine the synergistic advantages of various intelligent methods. Hybrid models combine optimization programs with representation by transform domain or fuzzy logic and neural learning programs to focus on more adaptive and performance. These methods have shown enhanced resilience to compression, noise, and geometric attacks without the need to downgrade the visual quality since they combine the learning ability, uncertainty modeling, and optimization techniques.

Watermarking systems undergo performance evaluation through the application of three specific quantitative metrics which include PSNR and SSIM and NC [16]. The combination of PSNR and SSIM evaluates visual quality while NC assesses watermark extraction accuracy and robustness [17]. The hybrid soft computing-based methods demonstrate better performance results in these metrics when compared to traditional watermarking methods because of their capability to adapt and their optimization-driven functioning.

The current state of technological development has made it possible to create new solutions yet multiple obstacles still obstruct progress. The research field continues to investigate three unsolved problems which include choosing the best embedding parameters and developing lightweight hybrid systems that operate in real time and creating systems which can withstand new attack methods that include advanced geometric distortions and intelligent watermark removal techniques. The current trade-off between security and protection of content and execution efficiency results in restricted use of the system in real-world situations. The research study examines all existing hybrid soft computing–based image watermarking methods through a complete systematic evaluation method. The review process evaluates existing methods by executing two main tasks which are performance testing and capacity assessment which results in identification of research shortcomings along with future development paths for the field.

1.1 General Framework of Digital Image Watermarking

Digital images constitute primary media and the most popular type of media in contemporary digital communication systems because they are easy to store, transmit and reproduce. It is common to use grayscale images in the testing of different watermarking algorithms [18]. The grayscale image uses an 8-bit pixel intensity value, which is in the range of 0 to 255, where a particular pixel in an image is associated with a specific brightness. Grayscale images are largely employed in watermarking experiments due to the fact that they have an aspect of less computation complexity than colour images, yet and still contain sufficient information to be used in performance evaluation [19]. Thus, grayscale images have become standard benchmarks in the design and testing of watermarking techniques. Digital image watermarking refers to embedding hidden information called a watermark into a digital image known as the host or cover image [20]. The embedded watermark can carry meaningful information such as a logo, signature, authentication code, or copyright identifier; it is usually represented in the form of a grayscale image, binary image, or pseudo-random sequence [21]. The embedded watermark is designed to enable ownership identification, copyright enforcement, content authentication, and protection against illegal duplication or manipulation. In general, a digital image watermarking system operates through four fundamental stages: the embedding stage, where the watermark is inserted into the host image; the distribution stage, during which the watermarked image is transmitted or shared; the extraction stage, where the watermark is retrieved; and the decision stage, in which the extracted information is evaluated to verify authenticity or ownership, as illustrated in Figure 2.

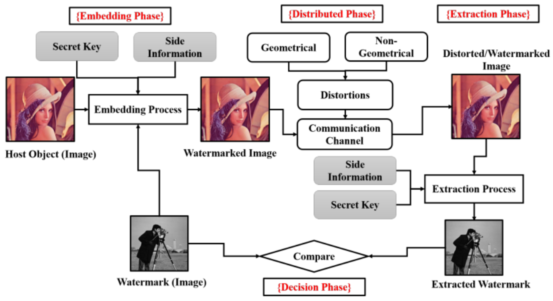

Figure 2: General model of watermarking system [22]

- **Embedding Phase:**

During this stage, the watermark is inserted into the host image using a watermark embedding algorithm. The watermark embedding algorithm may also employ a secret key and side information to improve security and prevent unauthorized detection or removal of the watermark. The result of this stage is the watermarked image, which is perceptually similar to the original host image.

- **Distribution Phase:**

After embedding, a watermarked image can be sent or stored via communication channels, e.g, the Internet, storage devices, or broadcasting systems. At this stage, the watermarked image may be exposed to both intentional and unintentional distortions. These distortions may consist of geometrical attacks such as "rotation, scaling, and cropping, and non-geometrical attacks including noise addition, filtering, and compression". Such distortions probably lower the image quality and make watermark detection difficult.

- **Extraction Phase:**

The extraction phase involves the retrieval of the watermark on the received or potentially distorted watermarked image and is performed with the help of an extraction algorithm. Depending on the type of watermarking scheme, original host image, secret key or side information may be required during this process, thus making it blind, semi-blind or non-blind. The product of this stage is the watermark that is extracted.

- **Decision Phase:**

The last stage involves comparing the extracted watermark with the original watermark as a way of confirming ownership or authenticity. The system finds out the presence or absence of the watermark based on similarity measures like NC. This step provides the provision of trustworthy copyright checks and authentication of the digital image.

1.2 Performance Requirements in Digital Watermarking

A good digital watermarking system must fulfil a list of basic performance requirements to guarantee its reliability and usefulness [23]. These requirements form the basis of how the overall quality and efficiency of a watermarking algorithm are judged. The level of priority of each performance requirement differs according to the application, which can be copyright protection, authentication, fingerprinting, or broadcast monitoring. Generally, the performance of a watermarking system is judged by a number of key characteristics, which are robustness, imperceptibility, capacity, complexity, security, and False Positive Rate (FPR). Each of these characteristics is linked to a number of specific quantitative measures that allow for the objective evaluation and comparison of different watermarking techniques. The following subsections elaborate on these basic requirements and the typical measures of evaluation for each.

1.2.1 Robustness

- **Robust watermarking:**

The watermark stays visible in strong systems because common signal processing methods and geometric attacks cannot remove it [24]. The techniques receive broad use in protecting copyright through fingerprinting and broadcast monitoring and copy control systems [25].

- **Fragile watermarking:**

Fragile watermarking shows extreme sensitivity to any changes made to the original host image [26,27]. Any small change to the system will result in complete failure of the hidden watermark. The property of fragile schemes functions as an integrity verification tool which detects any unauthorized changes. The process of authenticity verification involves comparing the extracted watermark with the original version.

- **Semi-fragile watermarking:**

Semi-fragile watermarking techniques integrate both robust and fragile watermarking methods. The watermark is created to be robust to acceptable manipulations (such as compression) but become useless for malicious manipulations [28,29]. This is particularly useful in content authentication. To assess the robustness of the watermarking technique, two metrics are commonly used: NC and BER.

- **Normalized Correlation (NC)**

NC measures the similarity between the original watermark and the extracted watermark. It is defined as:

$$NC = \frac{\sum_{i=1}^{X} \sum_{j=1}^{Y} W_{org}(i,j)\, W_{ext}(i,j)}{\sum_{i=1}^{X} \sum_{j=1}^{Y} W_{org}^{2}(i,j)}$$

where W_{org} and W_{ext} represent the original and extracted watermarks of size $X \times Y$, respectively. The NC value ranges between 0 and 1. Values close to 1 indicate high similarity and strong robustness. In practice, NC ≥ 0.7 is generally considered acceptable, while NC = 1 represents perfect recovery.

- **Bit Error Rate (BER)**

BER evaluates the proportion of incorrectly extracted bits relative to the total embedded bits. It is expressed as:

$$BER = \frac{N_I}{N_T}$$

where N_I is the number of incorrectly extracted bits and N_T is the total number of transmitted watermark bits. A BER value closer to 0 indicates better robustness and more accurate watermark recovery.

1.2.2 Imperceptibility

The degree of invisibility or perceptual invisibility of the concealed watermark in the host document is known as imperceptibility. At image watermarking, it is desirable that the watermark inserted must not leave visible traces or compromise the visual perception quality of the original image as viewed by the HVS [30]. The imperceptibility is necessary as the observed distortion decreases the practicability and adoption of the watermarked content. Thus, visual quality evaluation once the watermarking has been embedded is a major step towards watermarking algorithm validation. In the case of image-based watermarking, both subjective (HVS-based) and objective evaluation could be performed as an assessment of imperceptibility. Though subjective analysis is based on human analysis, objective metrics can be used to quantitatively analyze similarities in visual appearance between the original and the watermarked images.

- **Peak Signal-to-Noise Ratio (PSNR):**

PSNR serves as a common standard which researchers use to assess the visual quality of watermarked images. The test measures how closely the original image matches the watermarked image through its assessment of reconstruction errors. The definition of PSNR is presented as follows:

$$PSNR = 10\log_{10}\left(\frac{d^2}{MSE}\right)$$

where d is the maximum possible pixel value (e.g., 255 for 8-bit images), and MSE is the Mean Squared Error between the original image I_0 and the watermarked image I_w:

$$MSE = \frac{1}{M \times N} \sum (I_0 - I_w)^2$$

Higher PSNR values indicate lower distortion. Generally, PSNR values above 40 dB imply good imperceptibility, while values below 30 dB suggest noticeable degradation.

- **Structural Similarity Index (SSIM):**

SSIM evaluates perceptual similarity by considering luminance, contrast, and structural information between two images. For image patches x and y, SSIM is expressed as:

$$SSIM(x, y) = [l(x, y)]^{\alpha}[c(x, y)]^{\beta}[s(x, y)]^{\gamma}$$

The similarity between the original and the watermarked images is measured as the average SSIM value over multiple windows, known as MSSIM. The value of MSSIM lies between 0 and 1, and higher values of MSSIM indicate higher structural similarity and better visual quality.

1.2.3 Capacity

Capacity is a term used to describe the extent to which a host image can be embedded with information to an extent that it does not appear visual. That is, it dictates the extent of watermark information that can be added to a cover image without adding any obvious distortion to the image. The capacity that can be achieved greatly depends on the application needs which include copyright protection, authentication or data hiding where the volume and nature of the information embedded can differ [31]. Capacity is often measured in bits per pixel (bpp) which is the theoretical mean number of watermark bits per image pixel.

The maximum embedding capacity can be defined as:

$$\text{Maximum Embedding Capacity} = \frac{\text{Number of embeddable pixels (or peak points)}}{\text{Image length} \times \text{Image width}}$$

This formulation indicates the fraction of image components which can definitely transmit information about a watermark in comparison to the overall number of pixels in a host image. Capacity is closely associated with other performance parameters in feasible watermarking systems. Embedded data tends to be distorted more as the amount of embedded data increases, effectively decreasing the imperceptibility. Likewise, the need to increase robustness can be achieved by a more aggressive embedding that may additionally affect visual quality. Thus, a good watermarking algorithm should have a reasonable compromise between capacity, robustness, and imperceptibility. The relationship between these three basic requirements is inherent as shown in figure 3. Besides these main considerations, one should also notice other significant characteristics of the scheme including computational complexity, the level of security and FPR which need to be addressed to provide a complete assessment of the watermarking scheme.

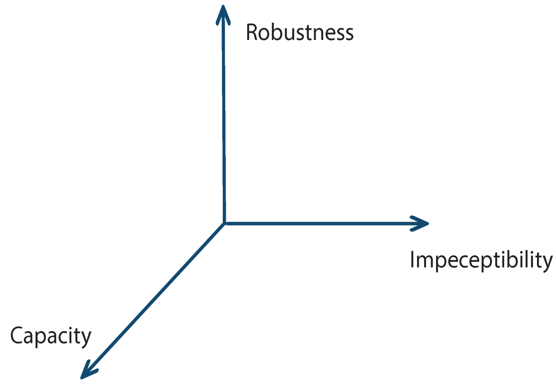

Figure 3: Constraints of digital watermarking [32].

1.2.4 Complexity

The process of creating watermarking systems needs to consider computational complexity because the system needs to handle both real-time operations and large-scale deployments. The system calculates the necessary processing resources and operational duration which the system needs to implement watermarking into a base image and later retrieve the watermark from the watermarked image. A watermarking system needs to combine security with strong protection abilities at the lowest possible resource requirement [33]. The acceptable computation duration in real-world situations depends on the specific application environment. The detection speed becomes more important than the embedding process for access control and copyright verification systems because detection needs to happen repeatedly under time constraints. Users expect to complete extraction or verification processes within one to two seconds because this time frame establishes usability and system responsiveness. The process of assessing complexity requires researchers to calculate both average embedding time and extraction time through standardized testing methods. Real-time applications become more effective when processing times decrease as long as the system maintains its performance capabilities in terms of strength and invisibility.

1.2.5 Security

Digital watermarking security: This refers to the ability of a watermarking system to resist malicious or unintentional attacks in an attempt to delete, manipulate, or forge the embedded watermark. A watermarking system can be said to be secure if the watermark is not removed, manipulated, or falsely created without compromising the visual quality of the host image or without having prior knowledge of the embedding process [34]. To improve security, various methods have been proposed to utilize encryption strategies such as DCT scrambling and chaos-based encryption methods. In these methods, the security of the encryption key plays a crucial role in determining the security of the watermarking system [35].

The Number of Pixel Change Rate (NPCR) and Unified Average Changing Intensity (UACI) serve as two common metrics which enable researchers to evaluate security against both pixel-level alterations and differential attacks. The two methods assess watermarking system performance by measuring its reaction to minimal image changes and its ability to defend against unauthorized alterations. Secure systems require NPCR values to reach 1 (or 100%) while UACI measurements need to stay near 0.33 (or 33%) because those values show strong protection against differential attacks. The combination of higher NPCR values and proper UACI levels shows that security performance has improved. Let W and W ˉ denote the original watermark and the extracted watermark respectively. The NPCR is defined as:

$$NPCR = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} D(i,j)}{M \times N} \times 100\%$$

where

$$D(i,j) = \begin{cases} 1, & \text{if } W(i,j) \neq \bar{W}(i,j) \\ 0, & \text{otherwise} \end{cases}$$

Similarly, the UACI is calculated as:

$$UACI = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} | W(i,j) - \bar{W}(i,j) |}{M \times N \times 255} \times 100\%$$

where $M$and Nrepresent the dimensions of the watermark image.

1.2.6 False Positive Rate (FPR)

The FPR measures the probability of a false positive result in the detection of a watermark, where a watermark is falsely detected when it is not actually embedded, or when a different watermark, one that was not embedded in the original image, is mistakenly identified [36]. False positives are usually encountered when the detection algorithm is highly dependent on user or reference data, which could introduce a bias or correlation during the extraction process. In an ideal watermarking system, the FPR should be as close to zero as possible to avoid any false authentication or ownership verification. The FPR can be expressed as follows:

$$FPR = \frac{FP}{TN + FP}$$

where FP denotes the total number of false positive outcomes and TN represents the total number of true negative cases observed during testing.

1.3 Hybrid Soft Computing-Based Watermarking Techniques

The techniques of spatial domain watermarking are too weak, since they are easy to manipulate. These methods are far weaker to various forms of attacks, than frequency-domain algorithms [37]. It is these disadvantages that have attracted attention to the studies of transform-domain watermarking methods that conceal information in the transform domain of a signal, as opposed to time, in a more efficient manner. The method transforms an image with a pre-determined transform with the aim of representing the image in the frequency domain [38]. Then, it watermarks the original image by modifying the transform domain coefficients of the original image with various transforms, such as the DCT, DFT, DWT, Singular Value Decomposition (SVD), Hadamard, CAT, FFT, PHT, and Fresnel transforms.

1.3.1 Discrete Cosine Transform (DCT)

The DCT is preferred in digital image watermarking because of its excellent energy compaction property and compatibility with compression algorithms such as JPEG. The DCT transforms the spatial domain image information into frequency domain coefficients represented as a linear combination of cosine basis functions. Since the DCT involves real-valued coefficients, it is computationally efficient and robust [39].

The one-dimensional (1D) DCT of a signal $x(n)$ of length N is defined as:

$$y(k) = \alpha(k) \sum_{n=0}^{N-1} x(n) \cos\left(\frac{\pi(2n+1)k}{2N}\right), k = 0,1,\dots,N-1$$

The inverse DCT (IDCT) is given by:

$$x(n) = \sum_{k=0}^{N-1} \alpha(k) y(k) \cos\left(\frac{\pi(2n+1)k}{2N}\right), n = 0,1,\dots,N-1$$

where the normalization factor $\alpha(k)$ is defined as:

$$\alpha(0) = \sqrt{\frac{1}{N}}, \alpha(k) = \sqrt{\frac{2}{N}}, 1 \leq k \leq N-1$$

Here, $x(n)$ represents the input signal, $y(k)$ denotes the DCT coefficient, and N is the number of data samples.

Block-based DCT techniques are in common use in practical watermarking applications. The host image is subdivided into non-overlapping blocks (usually 8×8 pixels) and DCT is used on the individual blocks. The watermark is introduced at the expense of adjusting the value of chosen mid-frequency coefficients to achieve a tradeoff between the strength and invisibility. Lastly, the watermarked image is reconstructed by carrying out inverse DCT (IDCT). The DCT-based watermarking is still one of the most popular transform-domain methods because it is compatible with JPEG compression and its frequency localization characteristics.

1.3.2 Discrete Fourier Transform (DFT)

The DFT serves as a fundamental method which transforms signals into the frequency domain for use in digital signal processing and image processing applications. The method transforms The DFT transforms a series of spatially and temporally distributed samples into their corresponding frequency components. The DFT uses complex exponential basis functions to represent signals which enables it to maintain both magnitude and phase information. The DFT provides a suitable solution for applications which require both geometric invariance and frequency spectrum analysis. DFT provides image watermarking with strong protection against geometric attacks which include translation and rotation and scaling operations [41]. Watermark embedding through selected magnitude coefficients enhances protection against spatial domain distortions because spatial shifts create known phase shifts in the frequency domain. DFT-based watermarking techniques find their applications in spectrum analysis and convolution processes and filtering methods and Fourier signal modelling techniques.

The one-dimensional (1D) DFT of a discrete signal $x(n)$of length $N$is defined as:

$$y(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x(n) \exp\left(-j\frac{2\pi}{N}kn\right), k = 0,1,\ldots,N-1$$

The corresponding inverse DFT (IDFT) is given by:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} y(k) \exp\left(j\frac{2\pi}{N}kn\right), n = 0,1,\ldots,N-1$$

where $j = \sqrt{-1}$, $x(n)$ represents the input sequence, $y(k)$ denotes the DFT coefficient, and $N$is the total number of samples.

In real-world image watermarking techniques, the two-dimensional (2D) DFT is used to convert the matrices of the images into their frequency domain. The watermark data is usually embedded into the magnitude spectrum to improve robustness and reduce distortions. In hybrid soft computing models, the DFT coefficients are usually optimized by evolutionary algorithms or fuzzy logic models to decide on the optimal strength and coefficients for embedding.

1.3.3 Discrete Wavelet Transform (DWT)

The DWT is a very useful time-frequency analysis tool that represents a signal in terms of scaled and shifted wavelet basis functions, unlike the sinusoidal components in the Fourier transform-based techniques (e.g., DCT and DFT) [42]. Unlike the Fourier transform-based techniques, which are only capable of representing a signal in the frequency domain, the DWT has the ability to represent a signal in both spatial (temporal) and frequency domains, which makes it very attractive for image watermarking.

In DWT, a signal is broken down into approximation and detail parts with the help of two low-pass filters and high-pass filters. The approximation coefficients are the low-frequency part of the signal and the detail coefficients are the high-frequency detail of the signal, e.g. edges and textures [43]. The key benefit of DWT is that it offers both high spatial resolution at high frequencies, and high frequency resolution at low frequencies. This adaptation resolution feature allows the model to be effective in capturing image features and increases resistance to compression and noise.

Mathematically, the DWT of a discrete signal $x[n]$can be expressed as:

$$W_\phi[j_0,k] = \frac{1}{\sqrt{M}} \sum_n x[n]\ \phi_{j_0,k}[n]$$

$$W_\psi[j,k] = \frac{1}{\sqrt{M}} \sum_n x[n]\ \psi_{j,k}[n], j \geq j_0$$

where $W_\phi[j_0,k]$ denotes the approximation coefficients and $W_\psi[j,k]$ represents the detail coefficients. The inverse DWT reconstructs the original signal as:

$$x[n] = \frac{1}{\sqrt{M}} \sum_k W_\phi\ [j_0,k]\phi_{j_0,k}[n] + \frac{1}{\sqrt{M}} \sum_{j=j_0}^{J-1} \sum_k W_\psi\ [j,k]\psi_{j,k}[n]$$

where $\phi[n]$ is the scaling function, $\psi[n]$ is the wavelet function, $M = 2^J$ represents the number of samples, and J denotes the number of decomposition levels.

The DWT breaks down a two-dimensional image into four sub-bands through its successive image processing stages which include LL (approximation) and LH and HL and HH (detail components) at each processing stage. The LL sub-band undergoes multi-level decomposition which allows researchers to conduct frequency analysis through various levels of detail. Watermarking techniques embed watermark data within specific frequency ranges that include mid and high-frequency sub-bands which consist of LH and HL and HH to create a system that protects against compression and filtering attacks while keeping visual elements undetectable. The DWT coefficients in hybrid soft computing-based systems undergo optimization through evolutionary algorithms and fuzzy logic and neural networks which enable the system to choose suitable embedding points and embedding strength parameters, thus boosting the system's defense capabilities and protection features and overall system effectiveness.

2. Review Methodology

This paper is a review of hybrid soft computing-based image watermarking techniques for copyright protection. The review covers the period from 2020 to 2025 and highlights the research that has been done on the integration of intelligent optimization algorithms such as GAs, fuzzy logic, PSO, and neural networks with transform-domain watermarking approaches. It aims at analyzing the contribution of hybrid models in enhancing robustness, imperceptibility, capacity, and security in digital image watermarking systems. The review was undertaken based on PRISMA guidelines to maintain transparency, consistency, and reproducibility.

The methodology of the research was structured and utilized five primary steps, the first of which was the planning of the research, followed by the search and screening of databases and the evaluation of eligibility and the final selection of the study. The researchers carried out an entire search procedure that used the Scopus database to obtain the findings utilizing definite keys of image watermarking and soft computing techniques that they had adopted. The researchers applied three filters that comprised of the year of publication and subject area and type of document to narrow their search results. The screening stage was used where titles and abstracts were checked to rule out the articles that did not employ hybrid watermarking techniques or those that did not involve experimental testing. The authors performed a full-text article analysis by using pre-established criteria by which they selected and discarded the studies. The study analysis done by the researchers included the classification of the chosen studies according to the soft computing methods applied and transform domains tested and application situations evaluated. This is a systematic methodology of identifying the current research trends and improving research gaps and performance of hybrid models. The research results provide the future research directions that aim at producing watermarking systems to offer the digital copyright protection in terms of increased security and adaptable features and efficient calculations.

2.1 Planning Stage

Robust, adaptive, and secure frameworks that can resist all classes of signal-processing and geometric attacks are required for digital image watermarking in copyright protection. The dynamic nature of image manipulation techniques compression, filtering, noise addition cropping as well as the deliberate destruction of the watermark makes it a great challenge to design a secure imperceptible watermarking system. The conflicting requirements of robustness capacity imperceptibility and computational efficiency multiply these challenges. Consequently, researchers have focused on hybrid soft computing approaches that integrate optimization algorithms with intelligent models using transform-domain watermarking techniques to enhance performance.

Combinative techniques, such as GA, the techniques of PSO, fuzzy logic systems, and ANNs with DCT, DWT, DFT, and SVD transforms have demonstrated greater adaptability and optimisation capability. These methods are meant to achieve optimality in the embedding strength, the coefficient selection, and the feature extraction process automatically; hence improving the resistance to attacks and improving the visual appearance of the images. This review has a planning phase that has been created to systematically analyse these hybrid approaches.

To guide the review process, the following research questions were formulated:

RQ1: Which hybrid soft computing techniques have been proposed between 2020 and 2025 for image watermarking in copyright protection?

RQ2: How do optimization-based and learning-based hybrid models improve robustness, imperceptibility, capacity, and security compared to conventional watermarking methods?

RQ3: What transform-domain combinations (e.g., DCT-DWT-SVD) are most commonly integrated with soft computing techniques, and how do they influence performance metrics such as PSNR and NC?

RQ4: What are the primary technical challenges and limitations in implementing hybrid watermarking systems in practical copyright protection applications?

The main source of literature was the Scopus Database. Studies were fetched using specific keyword combinations such as "image watermarking," "hybrid watermarking," "soft computing," "genetic algorithm," "fuzzy logic," "particle swarm optimization," and "neural network." The search was limited to appropriate subject areas that include Computer Science and Engineering and peer-reviewed journal articles. This structured planning approach ensured a focused, transparent, and reproducible selection process, enabling the identification of research trends methodological advancements existing gaps in hybrid soft computing-based image watermarking.

2.2 Review Stages

A review was also performed as a predetermined quality and exclusion criteria were applied in order to choose only the relevant and high-quality research articles. These criteria were so in order to make the screening process transparent, consistent and methodologically rigorous. The inclusion and exclusion criteria are as follows:

i. Only publications indexed in the Scopus database between January 2020 and December 2025 were considered.
ii. Only peer-reviewed journal articles were included in the review.
iii. Conference papers, book chapters, editorials, notes, and other non-article document types were excluded.
iv. Studies were included only if they focused on image watermarking techniques integrating soft computing or hybrid intelligent approaches. Articles not directly related to hybrid soft computing–based watermarking were excluded.
v. Only studies providing sufficient experimental validation and quantitative performance evaluation (e.g., PSNR, NC, SSIM, BER) were considered eligible.

The screening process and a full-text evaluation based on the above criteria were followed by screening out irrelevant studies using titles and abstracts. This methodical approach to selection was done to guarantee that the best research studies that are technically pertinent and methodologically correct were incorporated to be subject to qualitative and comparative analysis. The inclusion and exclusion strategy to be used in the article selection is illustrated in Table 1.

Table 1: Inclusion and Exclusion Criteria

Criterion	Inclusion	Exclusion
Keywords	Image Watermarking, Hybrid Watermarking, Soft Computing, Genetic Algorithm, Fuzzy Logic, Particle Swarm Optimization, Neural Network, Copyright Protection	Records not related to image watermarking or not involving hybrid/soft computing techniques
Document Type	Article	Conference papers, reviews, editorials, book chapters, erratum, notes
Source Type	Peer-reviewed journals	Book series, books, conference proceedings, trade publications
Timeframe	2020–2025	Publications before 2020
Subject Area	Computer Science, Engineering	Irrelevant subject areas
Methodological Scope	Studies with experimental validation and performance evaluation (e.g., PSNR, NC, SSIM, BER)	Studies lacking quantitative evaluation or experimental results

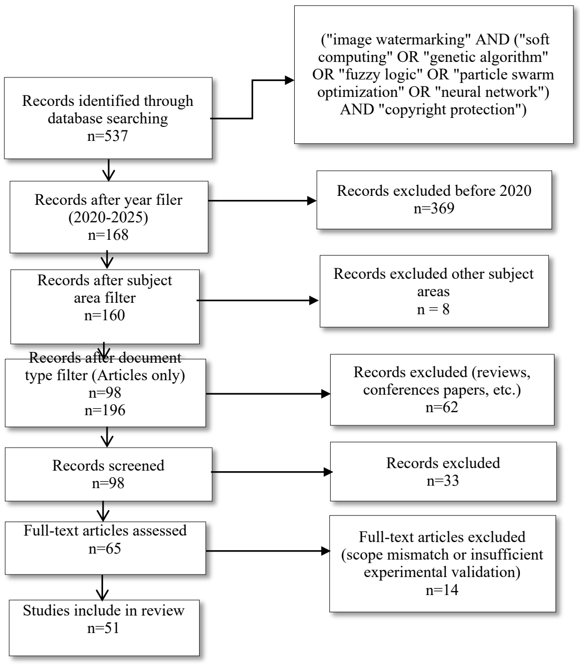

Figure 4: PRISMA Model

The researchers employed their established criteria for study inclusion and exclusion to assess retrieved studies. The study used structured keyword combinations to search the database which resulted in 537 records. The record count reached 168 after applying the publication year filter which excluded studies published before 2020 and included studies from 2020 to 2025. The subject area filter for Computer Science and Engineering reduced the record count to 160 while removing studies from other academic fields. The document type filter that permitted only journal articles resulted in 98 articles because it removed conference papers and reviews and all other types of publications. The screening process involved evaluating the titles and abstracts of 98 articles which led to 33 studies being excluded because they did not match hybrid soft computing-based image watermarking. The researchers selected 65 articles for full-text evaluation. The researchers excluded 14 studies after conducting their assessment because the studies did not match research boundaries or they lacked sufficient experimental support. The researchers selected 51 studies which met all inclusion criteria for their qualitative analysis and review process. The PRISMA flow diagram in figure 4 shows how the first search results were systematically reduced until only the eligible studies remained. The structured filtering process established methodological excellence which increased research transparency while selecting valuable studies that related to hybrid soft computing-based image watermarking used for copyright protection.

3. Hybrid Soft Computing and Metaheuristic Optimization–Based Watermarking Methods

Digital image watermarking has increasingly turned to soft computing and metaheuristic optimization approaches to efficiently handle the trade-off between imperceptibility, robustness, capacity, and security. Traditional watermarking techniques tend to use predefined embedding parameters or predefined rules, which are less adaptable to different image characteristics and attack models. In contrast, soft computing approaches such as GA, PSO, fuzzy logic, swarm intelligence, and hybrid evolutionary algorithms provide adaptability in parameter selection and multi-objective optimization. These approaches are more effective in optimizing the strength of embedding, choosing proper transform coefficients, and overcoming common problems such as the false positive problem (FPP), thus improving the efficacy of copyright protection systems.

Recent research has focused on hybrid metaheuristic models, in which a combination of different optimization strategies is used to take advantage of their complementary qualities. A detailed experimental study on hybrid metaheuristics in form of sequential, interleaved, and parallel hybrid combinations of GA, differential evolution, PSO, firefly algorithm, and artificial bee colony optimization was performed by Melman et al. (2025) [44]. Their results show that the shape and structure of the hybrid optimization schemes have a large impact on the watermark imperceptibility and robustness, and interleaved hybridization produces the most overall performance. In a similar study, Melman et al. (2025) [45] also suggested the hybrid spatial frequency watermarking framework using multiple embedding, GA-based adaptive block selection, with high resistance against image processing attacks, and additional extraction is not necessary of the original image or the watermark. The frequency of the usage of the soft computing and meta heuristic optimization methods in the research of hybrid digital image watermarks is represented in this figure 5.

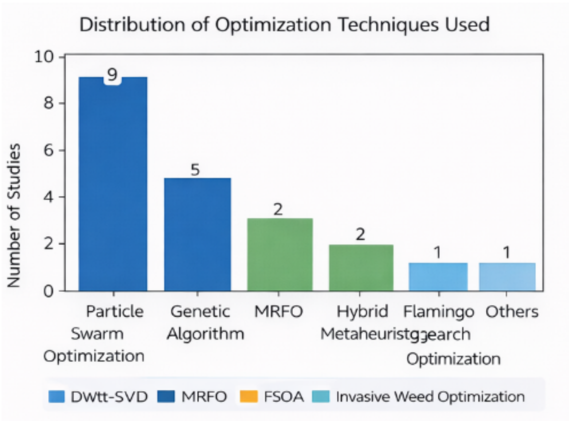

Figure 5: Distribution of optimization techniques used in hybrid watermarking methods.

An important direction is in the optimization of transform-domain watermarking, especially those methods based on the SVD which are highly stable and susceptible to false positive attack. Teoh et al. (2025) [46] have overcome this constraint by suggesting a hybrid SVD-based watermarking algorithm that combines the properties of HVS, DWT, and PSO to scale effectively the factor of scalability. They were successful in lowering FPP and keeping visual quality and resistance to geometric and signal-processing attacks at high levels. Amiri et al. (2024) [47] suggested a watermarking structure that is built on contourlet-SVD and embedding strength is optimized based on PSO-generated embedding strength (delta parameter). Their strategy gave them better values of NC especially with salt-and-pepper noise attacks, and it removes false positive detection errors. Denoising in the extraction using DnCNN also increased robustness without the image quality deterioration. Equally, Tiwari et al. (2025) [48] used Integer Wavelet Transform (IWT) with Schur decomposition and optimized embedding gain based on PSO and Manta Ray Foraging Optimization (MRFO), and achieved significant increase in PSNR (around 40 dB) and NCC (over 0.99), and MRFO surpassed PSO in enhancing its robustness.

Some studies have utilized multi-transform and adaptive optimization techniques to improve the robustness of watermarking. Babu et al. (2025) [49] presented a LWT-SVD based approach optimized by PSO to produce multiple scaling factors, which demonstrated better imperceptibility and robustness in cryptographic, medical, and multimedia images. Barlaskar et al. (2025) [50] presented an adaptive LWT-DCT based watermarking technique using entropy and edge-based region selection, optimized by PSO gain factor optimization with non-geometric distortion correction, which demonstrated PSNR values of approximately 48 dB in different attack scenarios. To counteract the degradation of robustness due to error correction coding, Wei et al. (2025) [51] presented a multi-technique fusion approach integrating spline interpolation, polar coding, DWT-DCT, SURF features, and Linear PSO (LPSO), which demonstrated high robustness (NC > 0.93) and imperceptibility (PSNR > 41 dB) even in combined attacks. Figure 6 illustrates the reported PSNR values of some exemplary hybrid watermarking techniques.

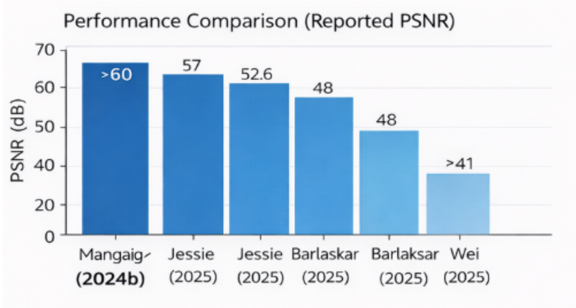

Figure 6: Performance comparison of hybrid watermarking methods in terms of PSNR.

The use of entropy-driven and adaptive embedding methods has become more common in recent times. Jessie et al. (2025) [52] proposed two hybrid methods—Entropy-Guided Singular Embedding (EGSE) and Entropy-Guided Hybrid Embedding (EGHE)—that automatically select high-entropy regions and dynamically adjust embedding strength using PSO. Their results demonstrated exceptional hidden quality which reached 52.6 dB PSNR value while proving their system could withstand geometric distortions because of their entropy-based optimization approach. Lakshmi et al. (2024) [53] used entropy-based block selection together with PSO and moth-flame optimization (MFO) to control adaptive scaling in their IWT–DCT–SVD framework which led to stronger protection and better recovery capabilities with encrypted watermark integration.

Optimization in color and multi-watermarking has also been a topic of interest. The AMEF algorithm proposed by Shen et al. (2022) [54] used a hybrid PSO–Grey Wolf Optimizer for multiple embedding factors. Their method which combines DWT, SVD, and encrypted multi-watermark embedding achieved an effective trade-off between invisibility robustness as well as capacity for color images. Experimental results demonstrated improved resistance to various attacks with high visual quality maintained at the same time. Figure 7 shows the percentage of transform domains used in hybrid soft computing-based watermarking frameworks.

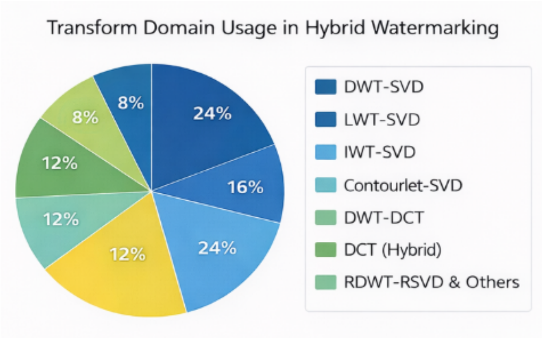

Figure 7: Transform domain usage in hybrid image watermarking approaches.

Nature-inspired and evolutionary algorithms have been extensively used in optimizing the embedding parameters under complicated attack conditions. Zhou et al. (2024) [55] applied the invasive weed optimization algorithm to choose the embedding strength in watermarking on wavelet-domain adaptively, and it showed better resistance to noise, compression, and geometric attacks than PSO and differential evolution. Dwivedi et al. (2024) [56] suggested further watermarking marking schemes based on Flamingo Search Optimization, MRFO and RDWT -RSVD frameworks to solve false positive problems and capacity-robustness trade-offs with PSNR values of more than 60 dB and NC values of over 0.99. These findings demonstrate the usefulness of more recent bio-inspired optimizers in multi-objective watermarking. On the same note, Mangaiyarkarasi et al. (2024) [57] introduced a color image watermarking model based on Flamingo Search Optimization Algorithm (FSOA) to overcome issues of robustness loss and false-positive with hybrid wavelet-SVD watermarking models. Thousands of MATLAB-based simulations showed large PSNR gains of up to 35 percent over current optimization-based watermarking schemes, and higher values of SSIM and NCC.

Further, hybrid intelligent systems that combine fuzzy logic and neural learning have improved the adaptability of watermarks. Rai et al. (2022) [58] proposed an efficient watermarking scheme that integrates HVS, fuzzy inference systems (FIS), backpropagation neural networks (BPNN), and shark smell optimization (SSO), which outperformed traditional PSO- and ABC-optimized schemes in terms of robustness and imperceptibility. Multi-objective optimization models were also adopted by Hatami et al. (2023) [59] to design a contourlet transform-based watermarking scheme that uses PSO-optimized dynamic scaling factors to attain high imperceptibility (PSNR ≈ 57 dB), high capacity, and resistance to false positive detection. Likewise, Sivananthamaitrey et al. (2022) [60] and Zhu et al. (2022) [61] proved that GA-, IWO-, and TLBO-optimized schemes can greatly enhance robustness and imperceptibility in multi-watermarking and block-based IWT-SVD schemes. Figure 8 illustrates the major research goals that have been addressed by the hybrid soft computing approaches to watermarking.

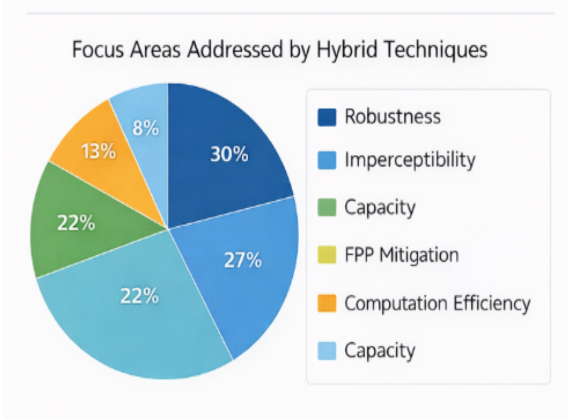

Figure 8: Focus areas addressed by hybrid soft computing–based watermarking methods.

The studied literature shows that hybrid soft computing together with metaheuristic optimization methods serve as essential elements which advance digital image watermarking technology used for copyright protection. The methods succeed in solving historical problems through their ability to choose parameters automatically and identify regions and their capability to solve multiple competing objectives. The existing methods deliver effective results yet they introduce extra computational demands which prevent their use in real-time situations thus creating a requirement for lightweight hybrid solutions. The research priority should establish efficient computational hybrid optimization systems which would integrate learning-based adaptability to strengthen the security and usability of watermarking technologies used in actual digital scenarios. The table 2 provides a summary of recent research which uses hybrid soft computing together with metaheuristic optimization methods to study image watermarking through different transform domains and optimization methods while showing their main contributions and results.

Table 2: Summary of hybrid soft computing and metaheuristic optimization–based image watermarking methods.

Author (Year)	Domain / Transform Used	Soft Computing / Optimization Technique	Key Contribution	Performance Highlights

Melman et al. (2025)	DCT-based spatial–frequency domain	Hybrid GA, DE, PSO, FA, ABC (sequential/interleaved/parallel)	Comparative analysis of hybrid metaheuristic compositions	Interleaved hybridization gives best imperceptibility–robustness trade-off
Melman et al. (2025)	Hybrid spatial–frequency domain	GA	Multiple embedding with adaptive block selection	High imperceptibility; resistant to image processing attacks; blind extraction
Teoh et al. (2025)	DWT–SVD with HVS	PSO	FPP mitigation via optimized scaling factor	Improved robustness to geometric & signal-processing attacks
Amiri et al. (2024)	Contourlet–SVD	PSO + DnCNN	Delta-optimized embedding to eliminate FPP	Improved NC, strong resistance to salt-and-pepper noise
Tiwari et al. (2025)	IWT–Schur Decomposition	PSO, MRFO	Gain factor optimization for robustness–imperceptibility balance	PSNR ≈ 40 dB, NCC > 0.99; MRFO outperforms PSO
Babu et al. (2025)	LWT–SVD	PSO (Multiple Scaling Factors)	Robust watermarking for multimedia & medical data	Higher PSNR and NCC under multiple attacks
Barlaskar et al. (2025)	LWT–DCT	PSO + entropy & edge-based selection	Adaptive region selection with non-geometric distortion correction	PSNR ≈ 48 dB under non-geometric attacks
Wei et al. (2025)	DWT–DCT with coding & features	Linear PSO (LPSO)	Multi-technique fusion for robustness–imperceptibility balance	PSNR > 41 dB, NC > 0.93 under combined attacks
Jessie et al. (2025)	IWT–SVD / IWT–DCT–SVD	PSO + entropy-based embedding	EGSE & EGHE for adaptive high-entropy embedding	PSNR ≈ 52.6 dB; strong resistance to geometric attacks
Lakshm	IWT–	PSO, MFO	Revers	Improv

i et al. (2024)	DCT–SVD		ible watermarking with encrypted watermark	ed robustness and imperceptibility
Shen et al. (2022)	DWT–SVD (Color images)	Hybrid PSO–GWO	AMEF-based multi-watermark embedding	Balanced invisibility, robustness, and capacity
Zhou et al. (2024)	Wavelet domain	Invasive Weed Optimization (IWO)	Adaptive embedding strength selection	Superior robustness vs PSO & DE
Mangaiyarkarasi et al. (2024)	ATQWT–FRT–AT–TSVD	Flamingo Search Optimization (FSOA)	FPP-resistant color watermarking	PSNR improvement up to 35%; high SSIM & NCC
Dwivedi et al. (2024)	RDWT–RSVD (YCbCr)	MRFO, Henon mapping	High-capacity encrypted dual watermarking	PSNR > 60 dB; NC > 0.99
Rai et al. (2022)	HVS-based transform domain	FIS, BPNN, Shark Smell Optimization	Intelligent hybrid embedding parameter selection	Outperforms PSO & ABC in robustness
Hatami et al. (2023)	Contourlet–SVD	PSO (dynamic scaling)	Multi-objective watermarking with FPP elimination	PSNR ≈ 57 dB; high capacity
Sivananthamaitrey et al. (2022)	SWT–SVD + LSB	GA, IWO, TLBO	Dual watermarking for ownership & tamper detection	Improved NPCR, robustness, and imperceptibility
Zhu et al. (2022)	Block-based IWT–SVD	GA	Optimized robustness–imperceptibility trade-off	Higher PSNR & NC under noise and compression

4. Hybrid Transform-Domain Image Watermarking Frameworks

Hybrid transform-domain image watermarking systems have proved to be a powerful tool to overcome the increasing needs to secure a copyright, detect tampering, authenticate, and maintain data integrity in the digital multimedia space. Contrary to single-domain methods, hybrid systems apply several transforms, including DWT, DCT, SVD, RDWT, NSCT, QFT, contourlet-based methods, and projection-based models, to take advantage of their complementary benefits with respect to frequency localization, robustness and imperceptibility. These schemes are being more and more combined with optimization schemes, encryption schemes, and intelligent decision schemes to provide better resistance to geometric and signal-processing attacks whilst preserving visual quality. Recent studies show that this fusion makes it remarkably better to achieve the performance of watermarking in various applications such as social media, medical imaging, IoT, multimedia transmission, and copyright enforcement systems. This figure 9 demonstrates the frequency of the hybrid transform-domain combinations that are used in present image watermarking framework.

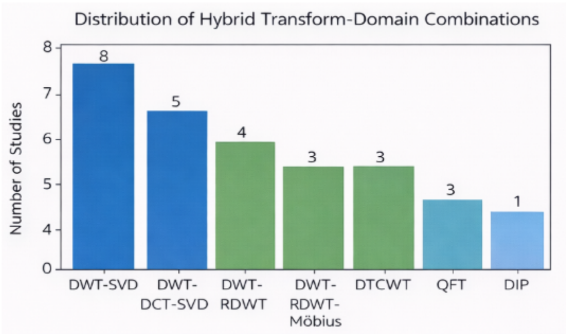

Figure 9: Distribution of hybrid transform-domain combinations in image watermarking.

The research community dedicates its main research efforts toward developing authentication systems which utilize fragile and semi-fragile hybrid frameworks to detect tampering and restore original content. Jana et al. (2025) [62] designed a DCT–LBP–Fuzzy Logic watermarking system which automatically identifies different image areas to achieve better authentication and restoration results. The system successfully reduced false tamper detection while maintaining high capabilities to detect and restore content during extreme attacks. Botta et al. (2020) [63] developed a reversible fragile watermarking technique which employs Karhunen–Loève Transform (KLT) and GA optimization to achieve precise tamper detection and complete image restoration. Singh et al. (2023) [64] advanced this field through the combination of NSCT RDWT and SVD with fuzzy inference-based scaling factor selection which produced highly secure dual watermarking that remained invisible to observers. Hemamalini et al. (2020) [65] proposed a DWT-based medical image watermarking framework which used dragonfly optimization and ENeGW-based pixel selection to achieve better security and reliability against PSO and GA methods. This figure 10 shows the distribution of soft computing and metaheuristic optimization techniques used in hybrid watermarking methods.

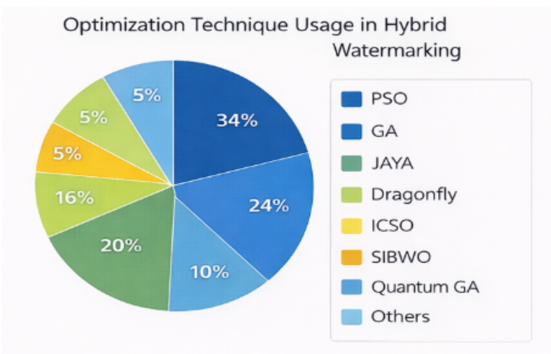

Figure 10: Usage of optimization techniques in hybrid watermarking frameworks.

Another important area of research focuses on strong hybrid watermarking systems improved by optimization and encryption techniques. Gorbal et al. (2025) [66] proposed a DWT-based robust watermarking method that uses chaotic encryption (the Arnold map and the Gingerbread Man map) and Self-Improved Beluga Whale Optimization (SIBWO) to optimize keys, showing great strength against noise, rotation, and filtering attacks. Alam et al. (2024) [67] created a dual-security robust watermarking system using RI-DWT and advanced cat swarm optimization in IoT perception layers, providing high robustness and secure embedding. Likewise, BAAGYERE et al. (2024) [68] introduced a nested watermarking method that combines GA-based encryption with DWT-based image-video watermarking for better ownership protection of multimedia content while keeping acceptable perceptual quality. In another optimization-driven system, Darwish et al. (2020) [69] proposed a GA-based dual watermarking scheme that optimally selects embedding locations and scaling factors in color images using wavelet features and SVD to enhance robustness significantly as well as imperceptibility by overcoming limitations set by expert-defined parameters. This figure 11 gives the robustness performance metrics obtained from hybrid transform-domain watermarking frameworks.

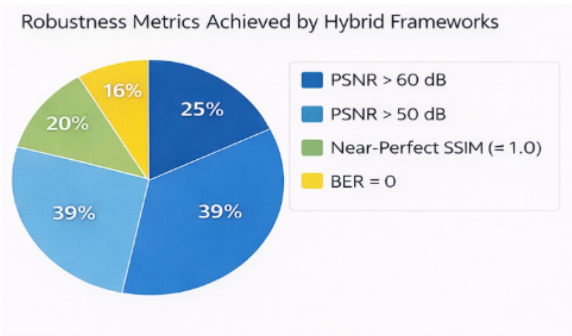

Figure 11: Robustness performance metrics reported by hybrid watermarking methods.

Multi-transform hybrid frameworks with imperceptibility-robustness trade-offs have been studied in several studies. The Dual-Tree Complex Wavelet Transform (DTCWT) with PSO-based coefficients selection was used by Bsoul et al. (2025) [70] and attained a high PSNR and NCC value without compromising the visibility of the watermark. The proposed hybrid framework is sophisticated (DWT, RDWT, and Mobius) with optimisation by GA, with exceptional imperceptibility (PSNR > 68 dB), near-perfect SSIM, and zero BER on a variety of attacks Alrammahi et al. (2025) [71]. Devi et al. (2022) [72] proposed an RDWT-SVD model using JAYA-Firefly optimization to protect social media images, which has a high capacity, strong and high robustness, and no false positive errors. Awasthi et al. (2022) [73] also compared DWT-DCT-SVD and LWT-DCT-SVD models which are optimized with PSO and JAYA and they show resistance to first- and second-generation attacks. Moreover, Belkebir et al. (2023) [74] suggested a projection-based hybrid watermarking scheme, which combines Direct Image Projection (DIP) with classical and Quantum Genetic Algorithms (QGA), which is much more resistant to histogram analysis and steganalysis and leads to significant PSNR and MSE improvements on benchmark data. This figure 12 demonstrates the main areas of application covered by the research on hybrid image watermarking.

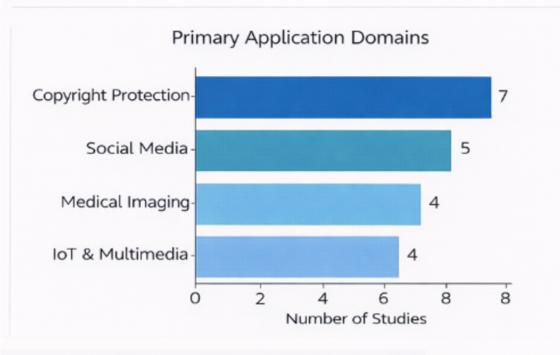

Figure 12: Application domains of hybrid transform-domain image watermarking studies.

Lastly, state-of-the-art hybrid and color watermarking systems have utilized higher-dimensional transforms, statistical models and smart optimization. Laxmanika et al. (2023) [75] used a combination of DWT, BEMD, DCT, SVD, and PSO to become more resilient to non-geometric and complicated attacks. Kumari et al. (2021) [76] stated that they developed a FrFT-PSO-based watermarking scheme of multi-parameter that uses an adaptive selection of the best fractional domain. In Niu et al. (2021) [77], a statistical color watermarking framework based on QPCET and parameter estimation by GA was presented to achieve the correct detection. Bhatti et al. (2021) [78] and Bhatti et al. 2020) [79] and Ahmadi et al. (2021) [80] took advantage of quaternion fourier transform, chaotic encryption, and hybrid robust-fragile embedding methods to enhance copyright defense on color photographs. Together, they show that hybrid transform-domain watermarking systems, when coupled with optimization, encryption, projection, and intelligent decision systems, offer more robustness, security, flexibility, and resistance to attacks, and can be considered a backbone to current research on the subject of digital image copyright protection. This table 3 gives a comparative overview of hybrid transform-domain image watermarking structures, their transform mixes, optimization methods, their important contributions, and their reported performance measures.

Table 3: Summary of hybrid transform-domain image watermarking frameworks.

Author (Year)	**Hybrid Transform / Domain**	**Optimization / Security Technique**	**Key Contribution**	**Performance Highlights**
Jana et al. (2025)	DCT–LBP–Fuzzy Logic	Similarity matrix via FL	Fragile self-embedding for tamper detection & restoration	High TDR & TRR; improved PSNR, SSIM
Gorbal et al. (2025)	Multi-level DWT	SIBWO + Arnold & Gingerbread chaotic maps	Robust watermarking with optimized encryption key	Strong resistance to noise, rotation, filtering
Bsoul et al. (2025)	DTCWT	PSO	Optimized coefficient selection for imperceptibility	Mean PSNR ≈ 80.50%, NCC ≈ 92.51%
Alrammahi et al. (2025)	DWT–RDWT–Möbius Transform	GA	Multi-resolution hybrid framework with parameter optimization	PSNR > 68 dB; SSIM ≈ 1.0; BER = 0
Alam et al.	RI-DWT	ICSO (Cat	Dual-security	High robustnes

(2024)		Swarm Optimization)	robust watermarking for IoT	s under multiple attacks
BAAGYERE et al. (2024)	DWT (Image–Video)	GA + RNS encryption	Nested watermarking for multimedia copyright	Improved perceptibility & robustness
Singh et al. (2023)	NSCT–RDWT–SVD	Fuzzy Inference System	Dual watermarking with entropy-based embedding	Strong robustness & secure extraction
Belkebir et al. (2023)	Direct Image Projection (DIP)	GA & Quantum GA	Projection-based hybrid watermarking	PSNR & MSE improvement (~90%)
Laxmanika et al. (2023)	DWT–BEMD–DCT–SVD	PSO	Multi-transform robust watermarking	Resistant to geometric & non-geometric attacks
Devi et al. (2022)	RDWT–SVD	JAYA–Firefly Optimization	Social media image protection with high capacity	High PSNR & NC; FPP elimination
Awasthi et al. (2022)	DWT–DCT–SVD / LWT–DCT–SVD	PSO + JAYA	Comparative hybrid transform study	Robust against 1st & 2nd generation attacks
Darwish et al. (2020)	Wavelet–SVD + WHT	GA	Dual watermarking with optimized embedding factors	Enhanced robustness & imperceptibility
Kumari et al. (2021)	FrFT	PSO	Multi-parameter fractional domain watermarking	Optimized RMSE; improved robustness
Niu et al. (2021)	QPCET	GA (MLE estimation)	Statistical color watermarking model	Improved detection accuracy & robustness
Bhatti et al. (2021)	QFT + Chaotic Encryption	Arnold Scrambling	Secure color watermarking framework	High PSNR, SSIM under attacks
Ahmadi et al. (2021)	DWT–HVS–SVD	PSO	Blind dual watermarking (robust + fragile)	High capacity & tamper localization accuracy
Botta et al. (2020)	KLT	GA	Reversible fragile watermarking	Accurate tamper localization & full recovery
Hemamalini et al. (2020)	DWT	Dragonfly Optimization	Medical image watermarking with ENeGW selection	Superior robustness vs PSO & GA
Bhatti et al. (2020)	QFT + Chaotic Encryption	Arnold Transform	Color image watermarking with geometric resistance	Strong robustness & imperceptibility

5. Security, Authentication, and Performance Analysis in Intelligent Image Watermarking

With the rapid growth of digital multimedia transmission in the healthcare, social media, and copyright-protected domains, it has become a high priority to ensure the security, authenticity, robustness, and performance reliability of intelligent image watermarking systems. The latest watermarking systems are no longer restricted to copyright labeling but have evolved to incorporate authentication, tampering localization, encryption, and performance enhancement techniques. Intelligent optimization algorithms, machine learning, and cryptographic processing are being increasingly leveraged to overcome the challenges of imperceptibility-robustness, false positives, computational complexity, and geometric/signal processing attacks.

One of the major research directions is the focus on medical image security and the region-of-interest (ROI) protection. Awasthi et al. (2025) [81] suggested a watermarking scheme based on ROI involving MSER segmentation to retain diagnostically vital areas whilst imprinting a hybrid biometric watermark based on Aadhaar and fingerprint information. The best scaling factor was identified with the help of the Gaussian quantum-behaved PSO (GQ-PSO) algorithm where imperceptibility (57.42%) and robustness (11.10%) were significantly improved, and the execution time decreased. Similarly, Awasthi et al. (2024) [82] proposed a watermarking scheme using fuzzy-logic and Henon map encryption, DnCNN denoising, blockchain authentication, and hybrid watermarking to increase their security. Likewise, Cheema et al. (2020) [83] investigated the problem of security and false positivity in color images based on the FRT -DWT-SVD and PSO-optimized scaling factors and Arnold transform based scrambling. All these studies prove that smart optimization and encryption systems reinforce authentication and data integrity in medical and secure multimedia setting. This figure 13 shows the shares of smart and soft computing methods that are utilized in the research on security- and authentication-based image watermarking.

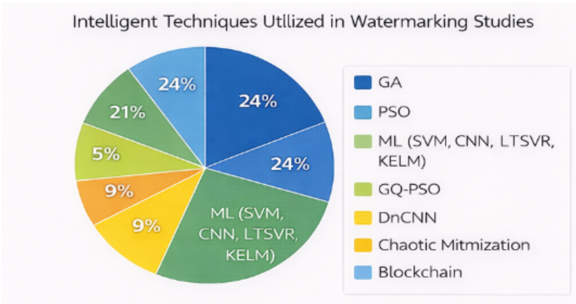

Figure 13: Distribution of intelligent techniques used in image watermarking studies.

Another major research stream revolves around dual watermarking and evolutionary optimization for copyright protection and tamper localization. Sivananthamaitrey et al. (2022) [84] proposed a dual watermarking framework using SWT–SVD with GA-based optimization to embed robust and fragile watermarks simultaneously for ownership verification and tamper detection. Darwish et al. (2020) [85] introduced an intelligent dual watermarking model for color images wherein GA help in finding optimal embedding locations as well as scaling factors while Walsh transform is used to enhance the encryption of the watermark. In the same vein, Kang et al. (2020) [86] presented a hybrid DWT–DCT–SVD watermarking scheme which was optimized by a variant of PSO and secured through the combination of logistic chaotic maps achieving more robustness and imperceptibility than previous schemes. Bagheri et al. (2021) [87] improved embedding capacity by indirectly inserting watermark bits into SVD components through HVS-guided region selection with PSO-driven dynamic scaling factors that do not produce false positive detection errors. These works bring out how important adaptive optimization is in balancing security, robustness, and visual fidelity. This figure 14 shows the application domains that intelligent image watermarking techniques have worked on, which proves their importance to medical security, copyright protection, and IoT-based systems.

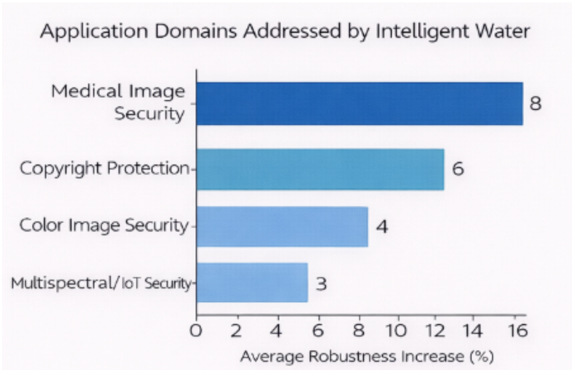

Figure 14: Application domains of security- and authentication-focused image watermarking methods.

Recent watermarking research has seen optimization-driven hybrid frameworks become the leading approach. Mohan et al. (2021) [88] combined PSO and Firefly optimization with selective encryption and transform-domain embedding, achieving high PSNR (55.14 dB) and strong robustness indicators (NC ≈ 0.9956). The researchers used PSO and Arnold transform to enhance DWT-SVD watermarking which Thakkar et al. (2021) [89] improved through their work. Sisaudia et al. (2021) [90] integrated PSO with Kernel Extreme Learning Machine (KELM) to predict optimal embedding strengths in multispectral images. Mehta et al. (2020) [91] proposed a machine learning-driven watermarking scheme which used fuzzy entropy for region selection and LWT transform and LTSVR regression modeling and GA-based scaling factor optimization. The blind color watermarking scheme developed by Hsu et al. (2020) [92] used quaternion DFT and PSO-optimized modulation parameters to enhance both imperceptibility and attack resistance. The research demonstrates how intelligent parameter tuning processes lead to improved watermark performance metrics across various attack methods. The performance improvements from different intelligent optimization techniques are shown in figure 15 which measures both robustness and imperceptibility.

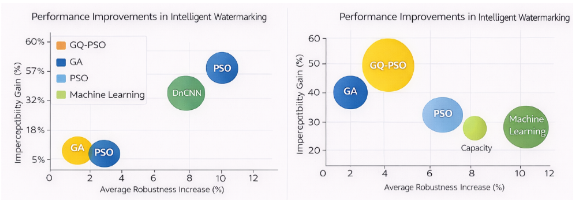

Figure 15: Comparative performance analysis of intelligent watermarking techniques.

Lastly, analytical and survey-based researches give holistic perspectives of performance. Rai et al. (2025) [93] introduced a systematic literature review of digital watermarking schemes based on the combination of machine learning and evolutionary algorithms, pointing out the benefits of hybrid ML-EA systems in improving robustness and reducing false positive challenges. In a survey, Singh et al. (2021) [94] reviewed the watermarking methods based on soft computing and highlighted the opportunities of optimization and intelligent systems to enhance embedding capacity and imperceptibility in different application fields.

These studies together show that intelligent watermarking frameworks involving evolutionary optimization, machine learning, chaotic encryption, blockchain authentication, and hybrid transform-domain techniques provide better security, robustness, and authentication than traditional methods. However, issues concerning computational overhead and real-time implementation are still open research directions for future intelligent watermarking systems. This table 4 presents recent intelligent image watermarking studies that have addressed security, authentication mechanisms, and performance evaluation metrics.

Table 4: Security, authentication, and performance-oriented intelligent image watermarking studies.

Author (Year)	Domain / Transform Used	Soft Computing / Intelligent Technique	Security & Authentication Strategy	Performance Highlights
Awasthi et al. (2025)	ROI–RONI, Redundant domain	GQ-PSO, MSER, BRISK	Hybrid biometric watermark, SHA-384, IoT-based authentication	+57.42 % imperceptibility, +11.10% robustness, reduced execution time
Rai et al. (2025)	Spatial & Frequency domains (DCT, DWT, SVD)	ML (SVM, CNN), PSO, GA, SSO	Review of hybrid ML–EA watermarking security	Identifies robustness–imperceptibility optimization gaps
Awasthi et al. (2024)	Fuzzy-based transform domain	Fuzzy Logic, DnCNN, Blockchain	Henon map encryption, blockchain authentication	+3.4% robustness, +1.49% imperceptibility
Sivananthamaitrey et al. (2022)	SWT–SVD + LSB	GA	Dual watermarking for copyright & tamper localization	Improved robustness, embedding capacity, NPCR
Mohan et al. (2021)	Wavelet-based hybrid domain	PSO–Firefly Optimization	Selective encryption, watermark scrambling	PSNR ≈ 55.15 dB, NC ≈ 0.9956
Singh et al. (2021)	Soft computing environments	Soft computing survey	Security & robustness evaluation framework	Comparative analysis of soft computing watermarking
Thakkar	DWT–	PSO,	Artifact	Improve

et al. (2021)	SVD	Arnold Transform	removal & robustness enhancement	d PSNR and NSR under noise attacks
Sisaudia et al. (2021)	DCT-based multispectral	PSO, KELM	Intelligent embedding strength prediction	Outperforms state-of-the-art watermarking schemes
Bagheri et al. (2021)	DWT–SVD with HVS	PSO	HVS-guided embedding, FPP elimination	Higher capacity, robustness, no false positives
Mehta et al. (2020)	LWT + QR factorization	GA, LTSVR (ML)	Arnold transform–based watermark security	Improved robustness against image processing attacks
Hsu et al. (2020)	Quaternion DFT (QDFT)	PSO	Blind watermarking with optimized modulation	Superior imperceptibility & robustness
Kang et al. (2020)	DWT–DCT–SVD	Variant PSO, Chaotic map	Logistic-map-based security	Enhanced robustness & imperceptibility
Darwish et al. (2020)	Wavelet–SVD	GA	Walsh transform encryption, dual watermarking	Improved PSNR and NCC under attacks
Cheema et al. (2020)	FRT–DWT–SVD	PSO	Arnold scrambling, FPP mitigation	High robustness under geometric & non-geometric attacks
	(Color images)			

6. Discussion

The systematic review points out that the hybrid soft computing approach to image watermarking has emerged as a prominent area of research owing to its potential to efficiently resolve the long-standing conflict between imperceptibility, robustness, capacity, and security. The combination of metaheuristic optimization algorithms like PSO, GA, MRFO, FSOA, and hybrid swarm intelligence with transform domain techniques (DWT, DCT, SVD, RDWT, contourlet transform, QFT, and others) helps in making a flexible choice of embedding parameters and coefficients. As made evident by the various studies reviewed, optimization-assisted approaches always report higher values of PSNR and SSIM metrics while ensuring high NC even under geometric and non-geometric attacks. Moreover, the use of entropy-based region selection, HVS models, and multi-transform domains has been found to minimize the false positive issues, especially in SVD-based image watermarking schemes.

Intelligent watermarking systems now use encryption and blockchain authentication and machine learning and ROI-based techniques to protect sensitive medical imaging and IoT-based systems. The approaches effectively defend against attacks while they increase authentication precision and they safeguard essential image areas without damaging diagnostic or visual assessment quality. The combination of different methods produces better results but it makes systems harder to run because it creates extra computing needs which stop systems from working in real time and operating at scale. The absence of standardized evaluation methods and datasets makes it difficult to conduct fair comparisons between different studies. Future research should therefore focus on developing lightweight hybrid optimization models and creating unified benchmarking systems and incorporating learning-based adaptability systems which will help achieve better performance results and operational efficiency. The successful implementation of these requirements will enable the transition of intelligent watermarking methods from research environments to effective real-world systems which protect copyrights and ensure security.

7. Future Scope

Future research should focus on developing computationally efficient hybrid watermarking frameworks which will decrease system complexity while preserving their ability to detect unaltered content. The developed framework should handle both real-time processing and operation in environments with limited resources.

The combination of deep learning models with soft computing and optimization methods could facilitate adaptive watermarking embedding and extraction in dynamic and novel attack situations.

Common benchmark datasets, attack models, and evaluation protocols should be established for fair comparison and reproducibility of watermarking techniques.

Cryptographic integration, blockchain-based authentication, and secure key management can significantly enhance trust and traceability in sensitive applications such as healthcare and IoT.

The researchers need to investigate advanced multi-objective optimization frameworks which enable them to assess all four critical components of their study.

The development of future watermarking systems will address the specific security and performance requirements that exist in social media platforms, telemedicine applications, autonomous systems, and digital forensics.

8. Conclusion

In this systematic review, the authors investigated the current developments in hybrid soft computing-based image watermarking methods used to protect copyright, authentication, and secure enhancement of image. The literature review shows that transform-domain watermarking techniques including DWT, DCT, SVD, RDWT, contourlet and quaternion-based transforms, with a watermarking system using soft computing and metaheuristic optimization algorithms have potential to enhance the performance of the watermarking process to a significantly greater level. Such techniques as the PSO, GA, fuzzy logic, swarm intelligence, and hybrid evolutionary models allow using adaptive selection of parameters, intelligent detection of regions, and mitigation of false positive issues. As demonstrated in various works, hybrid structures have always been very imperceptible, robust against geometric and non-geometric attacks, and are more secure due to encryption, authentication, and smart decision-making processes. With these encouraging results, however, there are still a number of challenges. Most hybrid strategies add more computational complexity, potentially restricting their use in real time and resource-constrained systems. Moreover, due to the lack of standardized evaluation protocols as well as benchmark datasets, it is hard to compare study results objectively across studies. Future work ought to be on developing lightweight and scalable hybrid designs, incorporation of learning to adapt dynamic attack cases and development of single benchmark frameworks. The need to deal with these issues will help in the pragmatic implementation of the intelligent watermarking systems and further enhance their role in safeguarding the copyrights of digital images in contemporary multimedia and data intensive settings.

References

1. George, A. Shaji. "The evolution of digital and social media communications: Opportunities, challenges, and the road ahead." *Partners Universal Multidisciplinary Research Journal (PUMRJ)* 2, no. 2 (2025): 35-49.
2. Razak, Muhammad Isma Farhan Bin Mohd, Mazlina Abdul Majid, Husnul Ajra, Md Shohidul Islam, and Aziman Abdullah. "An Evaluation of Security Features for Preventing Illegal Distribution of Digital Content Using Quantitative Methods." In *2025 4th International Conference on Computing and Information Technology (ICCIT)*, pp. 84-91. IEEE, 2025.
3. Widjaja, Gunawan. "Advantages of Copyright Law in the Digital Age: Challenges and Opportunities for Content Creators." *Journal of Intellectual Property Rights (JIPR)* 30, no. 5 (2025): 574-582.
4. Gupta, Malaika. "Intellectual property rights: a comprehensive review of concepts, challenges, and implications." *Challenges, and Implications (May 27, 2024)* (2024).
5. Ray, Arkadip, and Somaditya Roy. "Recent trends in image watermarking techniques for copyright protection: a survey." *International Journal of Multimedia Information Retrieval* 9, no. 4 (2020): 249-270.
6. Begum, Mahbuba, and Mohammad Shorif Uddin. "Digital image watermarking techniques: a review." *Information* 11, no. 2 (2020): 110.
7. Qureshi, Amna, and David Megias Jimenez. "Blockchain-based multimedia content protection: Review and open challenges." *Applied Sciences* 11, no. 1 (2020): 1.
8. Sinhal, Rishi, Irshad Ahmad Ansari, and Om Prakash Verma. "A Review of Digital Watermarking Approaches for Forensic Applications." *Current Forensic Science* 1, no. 1 (2023): e020223213376.

9. Ben Jabra, Saoussen, and Mohamed Ben Farah. "Deep learning-based watermarking techniques challenges: a review of current and future trends." *Circuits, Systems, and Signal Processing* 43, no. 7 (2024): 4339-4368.
10. Kusuma, Muhammad Romadhona, and Supriadi Panggabean. "Robust digital image watermarking using DWT, hessenberg, and SVD for copyright protection." *IJACI: International Journal of Advanced Computing and Informatics* 2, no. 1 (2026): 41-52.
11. Sharma, Sunpreet, Ju Jia Zou, Gu Fang, Pancham Shukla, and Weidong Cai. "A review of image watermarking for identity protection and verification." *Multimedia Tools and Applications* 83, no. 11 (2024): 31829-31891.
12. Riddhi, Preeti Garg, and Vineet Sharma. "A Comprehensive Review of Digital Video Watermarking Techniques in Spatial, Frequency, and Compressed Domain." *Archives of Computational Methods in Engineering* (2025): 1-37.
13. Kadian, Poonam, Shiafali M. Arora, and Nidhi Arora. "Robust digital watermarking techniques for copyright protection of digital data: A survey." *Wireless Personal Communications* 118, no. 4 (2021): 3225-3249.
14. Abdolrasol, Maher GM, SM Suhail Hussain, Taha Selim Ustun, Mahidur R. Sarker, Mahammad A. Hannan, Ramizi Mohamed, Jamal Abd Ali, Saad Mekhilef, and Abdalrhman Milad. "Artificial neural networks based optimization techniques: A review." *Electronics* 10, no. 21 (2021): 2689.
15. Trigka, Maria, and Elias Dritsas. "A comprehensive survey of deep learning approaches in image processing." *Sensors* 25, no. 2 (2025): 531.
16. Jasim, Ali Nasif, and Sadiq H. Abdulhussain. "A Comprehensive Review of Digital Watermarking techniques: Applications, Characteristics, Classification, and Related Aspects." (2025).
17. Chaudhary, Himanshi, and Virendra P. Vishwakarma. "A Survey: Digital Image Watermarking-robustness and Imperceptibility." *Recent Advances in Electrical & Electronic Engineering* 18, no. 8 (2025): 1157-1175.
18. Dixit, Anuja, and Rahul Dixit. "A review on digital image watermarking techniques." *International Journal of Image, Graphics and Signal Processing* 9, no. 4 (2017): 56.
19. Bistroń, Marta, Jacek M. Żurada, and Zbigniew Piotrowski. "Deep Learning for Image Watermarking: A Comprehensive Review and Analysis of Techniques, Challenges, and Applications." *Sensors (Basel, Switzerland)* 26, no. 2 (2026): 444.
20. M. Ali, C. W. Ahn, and M. Pant, "A robust image watermarking technique using svd and differential evolution in dct domain," Optik-International Journal for Light and Electron Optics, vol. 125, no. 1, pp. 428–434, 2014.
21. R. B. Wolfgang and E. J. Delp, "A watermark for digital images," in Proceedings of 3rd IEEE International Conference on Image Processing, vol. 3. IEEE, 1996, pp. 219–222
22. Zainol, Zurinahni, Je Sen Teh, Moatsum Alawida, and Abdulatif Alabdulatif. "Hybrid SVD-based image watermarking schemes: a review." *IEEE Access* 9 (2021): 32931-32968.
23. Pal, P.; Singh, H.V.; Verma, S.K. Study on watermarking techniques in digital images. In Proceedings of the 2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli, India, 11–12 May 2018; pp. 372–376.
24. Fares, K.; Khaldi, A.; Redouane, K.; Salah, E. DCT & DWT based watermarking scheme for medical information security. *Biomed. Signal Process. Control* **2021**, *66*, 102403.
25. Verma, V.S.; Jha, R.K. An overview of robust digital image watermarking. *IETE Tech. Rev.* **2015**, *32*, 479–496.
26. Qin, C.; Ji, P.; Zhang, X.; Dong, J.; Wang, J. Fragile image watermarking with pixel-wise recovery based on overlapping embedding strategy. *Signal Process.* **2017**, *138*, 280–293.
27. Zhang, H.; Wang, C.; Zhou, X. Fragile watermarking for image authentication using the characteristic of SVD. *Algorithms* **2017**, *10*, 27.
28. Feng, B.; Li, X.; Jie, Y.; Guo, C.; Fu, H. A novel semi-fragile digital watermarking scheme for scrambled image authentication and restoration. *Mob. Netw. Appl.* **2020**, *25*, 82–94.
29. Qi, X.; Xin, X. A singular-value-based semi-fragile watermarking scheme for image content authentication with tamper localization. *J. Vis. Commun. Image Represent.* **2015**, *30*, 312–327.
30. Zhou, N.R.; Hou, W.M.X.; Wen, R.H.; Zou, W.P. Imperceptible digital watermarking scheme in multiple transform domains. *Multimed. Tools Appl.* **2018**, *77*, 30251–30267.

31. Wang, C.; Zhang, H.; Zhou, X. A self-recovery fragile image watermarking with variable watermark capacity. *Appl. Sci.* **2018**, *8*, 548.
32. Boujerfaoui, Said, Rabia Riad, Hassan Douzi, Frederic Ros, and Rachid Harba. "Image watermarking between conventional and learning-based techniques: A literature review." *Electronics* 12, no. 1 (2022): 74.
33. Sutojo, T.; Rachmawanto, E.H.; Sari, C.A. Fast and efficient image watermarking algorithm using discrete tchebichef transform. In Proceedings of the 2017 5th International Conference on Cyber and IT Service Management (CITSM), Denpasar, Bali, Indonesia, 8–10 August 2017; pp. 1–5.
34. Bhalerao, S.; Ansari, I.A.; Kumar, A. A secure image watermarking for tamper detection and localization. *J. Ambient. Intell. Humaniz. Comput.* **2021**, *12*, 1057–1068.
35. Zhou, N.R.; Luo, A.W.; Zou, W.P. Secure and robust watermark scheme based on multiple transforms and particle swarm optimization algorithm. *Multimed. Tools Appl.* **2019**, *78*, 2507–2523.
36. Makbol, N.M.; Khoo, B.E.; Rassem, T.H. Security analyses of false positive problem for the SVD-based hybrid digital image watermarking techniques in the wavelet transform domain. *Multimed. Tools Appl.* **2018**, *77*, 26845–26879.
37. Naem, Saif Aldeen S., and Sarab M. Hameed. "Digital watermarking techniques, challenges, and applications: A review." *Mesopotamian Journal of CyberSecurity* 5, no. 2 (2025): 453-476.
38. Domain, W. T. I. S. "A review and open issues of diverse text watermarking techniques in spatial domain." *Journal of Theoretical and Applied Information Technology* 96, no. 17 (2018): 5819-5840.
39. Tanwar, Lavi, and Jeebananda Panda. "Review of different transforms used in digital image watermarking." In *2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, pp. 1165-1171. IEEE, 2018.
40. Li, ChunWang, JiaLin Guo, and Min Zhi. "A Review of Frequency-Domain Transformers in Image Processing Applications." In *2025 4th International Conference on Image Processing, Computer Vision and Machine Learning (ICICML)*, pp. 406-411. IEEE, 2025.
41. Palafox, M. Alcolea. "DFT computations on vibrational spectra: Scaling procedures to improve the wavenumbers." *Physical Sciences Reviews* 3, no. 6 (2018): 20170184.
42. Joseph, Emerson Raja, Hossen Jakir, Bhuvaneswari Thangavel, Azlina Nor, Thong Leng Lim, and Pushpa Rani Mariathangam. "Tool-emitted sound signal decomposition using wavelet and empirical mode decomposition techniques—A comparison." *Symmetry* 16, no. 9 (2024): 1223.
43. Kumar, Mahendra, and Satyarth Tiwari. "2-D Discrete Wavelet Decomposition using Low Pass and High Pass Sub-band: A Review." *International Journal of Research & Technology* 12, no. 3 (2024): 27-31.
44. Melman, Anna, and Oleg Evsutin. "Hybrid metaheuristic algorithms for image watermarking: An experimental study." Swarm and Evolutionary Computation 99 (2025): 102163.
45. Melman, Anna Sergeevna, Oleg Olegovich Evsutin, and Olesya Evgenievna Senyukova. "Multiple embedding of watermarks into a spatial-frequency domain of images based on a genetic algorithm." Computer Optics 49, no. 2 (2025): 273-281.
46. Teoh, Yuan Ju, Huo-Chong Ling, Wei Kitt Wong, Ing Ming Chew, Thomas Anung Basuki, and Hezerul Abdul Karim. "A robust SVD-based watermarking scheme using orthogonal vectors and PSO-enhanced scaling factor." Cluster Computing 28, no. 13 (2025): 850.
47. Amiri, Ali, and Bahram Kimiaghalam. "Robust watermarking with PSO and DnCNN." Signal, Image and Video Processing 18, no. Suppl 1 (2024): 663-676.
48. Tiwari, Anurag, Divyanshu Awasthi, and Vinay Kumar Srivastava. "RFPPFMark: robust and false positive problem free image watermarking scheme with its performance comparison by PSO and MRFO in Schur domain." Signal, Image and Video Processing 19, no. 3 (2025): 199.
49. BABU, P., and G. KASINATHAN. "PSO-OPTIMIZED WATERMARKING USING LIFTING WAVELET TRANSFORM AND SVD FOR ENHANCED IMAGE SECURITY." JOURNAL OF MACHINE AND COMPUTING Учредители: Anapub Publications (2025): 131-139.
50. Barlaskar, Saharul Alom, Anish Monsley Kirupakaran, Rabul Hussain Laskar, and Taimoor Khan. "A robust digital image watermarking technique in LWT-DCT domain using particle swarm optimization and statistical distortion

correction." Multimedia Tools and Applications 84, no. 3 (2025): 1429-1461.

51. Wei, Ying, Tianqi Zhang, Debang Liu, Linhao Cui, Baoze Ma, and Zeliang An. "Robust Image Watermarking Scheme Using Error Correcting Codes and Linear Particle Swarm Optimization." Circuits, Systems, and Signal Processing (2025): 1-34.
52. Jessie, Ooi, Liew Siau Chuin, Syifak Izhar Bt Hisham, Khor Hui Liang, Khoo Bee Ee, and Jasni Mohamad Zain. "Optimized Hybrid Watermarking: Dual-Scheme Strategies for Enhanced Robustness." Iraqi Journal for Computer Science and Mathematics 6, no. 3 (2025): 30.
53. Lakshmi, H. R., and Surekha Borra. "Improved adaptive reversible watermarking in integer wavelet transform using moth-flame optimization." Multimedia Tools and Applications 83, no. 6 (2024): 17183-17215.
54. Shen, Yuxin, Chen Tang, Min Xu, Mingming Chen, and Zhenkun Lei. "A DWT-SVD based adaptive color multi-watermarking scheme for copyright protection using AMEF and PSO-GWO." Expert Systems with Applications 168 (2021): 114414.
55. Zhou, Xia, and Andrea Santos. "Digital Copyright Protection of Images Based on Invasive Weed Optimisation Algorithm." (2024).
56. Dwivedi, Ranjana, Divyanshu Awasthi, and Vinay Kumar Srivastava. "An optimized dual image watermarking scheme based on redundant DWT and randomized SVD with henon mapping encryption." Circuits, Systems, and Signal Processing 43, no. 1 (2024): 408-456.
57. Mangaiyarkarasi, P., V. Tamil Selvi, and K. Valarmathi. "Color Image Watermarking Using Adaptive Tunable Q Wavelet, Finite Ridge Let, and Arnold Transforms with TSVD." IETE Journal of Research 70, no. 7 (2024): 6382-6394.
58. Rai, Manish, and Sachin Goyal. "A hybrid digital image watermarking technique based on fuzzy-BPNN and shark smell optimization." Multimedia Tools and Applications 81, no. 27 (2022): 39471-39489.
59. Hatami, Einolah, Hamidreza Rashidy Kanan, Kamran Layeghi, and Ali Harounabadi. "An optimized robust and invisible digital image watermarking scheme in Contourlet domain for protecting rightful ownership." Multimedia Tools and Applications 82, no. 2 (2023): 2021-2051.
60. Sivananthamaitrey, P., and P. Rajesh Kumar. "Performance analysis of meta-heuristics on dual watermarking of color images based on SWT and SVD." Multimedia Tools and Applications 81, no. 1 (2022): 1001-1027.
61. Zhu, Ting, Wen Qu, and Wenliang Cao. "An optimized image watermarking algorithm based on SVD and IWT." The Journal of Supercomputing 78, no. 1 (2022): 222-237.
62. Jana, Manasi, Biswapati Jana, and Subhankar Joardar. "Self-embedding tampered image localization and restoration scheme exploiting DCT, LBP with fuzzy logic." Multimedia Tools and Applications 84, no. 40 (2025): 49071-49107.
63. Botta, Marco, Davide Cavagnino, and Victor Pomponiu. "Reversible fragile watermarking for multichannel images with high redundancy channels." Multimedia Tools and Applications 79, no. 35 (2020): 26427-26445.
64. Singh, Om Prakash, Chandan Kumar, Amit Kumar Singh, Maheshwari Prasad Singh, and Hoon Ko. "Fuzzy-based secure exchange of digital data using watermarking in NSCT-RDWT-SVD domain." Concurrency and Computation: Practice and Experience 35, no. 16 (2023): e6251.
65. Hemamalini, B., and Velmurugan Nagarajan. "Wavelet transform and pixel strength-based robust watermarking using dragonflyoptimization." Multimedia Tools and Applications 79, no. 13 (2020): 8727-8746.
66. Gorbal, Mangalagowri, Ramesh D. Shelke, and Manuj Joshi. "Robust image watermarking scheme with transform domain technique on resisting different attacks: impact of self-improved optimization algorithm." International Journal of System Assurance Engineering and Management 16, no. 3 (2025): 1163-1187.
67. Alam, Shahzad, Tanvir Ahmad, M. N. Doja, and Om Pal. "Dual secure robust watermarking scheme based on hybrid optimization algorithm for image security." Personal and Ubiquitous Computing 28, no. 1 (2024): 193-205.
68. BAAGYERE, E., PA AGBEDEMNAB, M. AKOLGO, and SA BAYITAA. "A NESTED DIGITAL WATERMARKING SCHEME USING GARN WITH DWT." JOURNAL OF COMPUTER SCIENCE 20, no. 10 (2024): 1214-1221.
69. Darwish, Saad M., and Osama F. Hassan. "A new colour image copyright protection approach using evolution-based dual watermarking." Journal of Experimental & Theoretical Artificial Intelligence 33, no. 6 (2021): 945-967.

70. Bsoul, Abed Al Raoof, and Alaa Bani Ismail. "Optimizing image watermarking with dual-tree complex wavelet transform and particle swarm intelligence for secure and high-quality protection." Applied Sciences 15, no. 3 (2025): 1315.
71. Alrammahi, Atheer, and Hedieh Sajedi. "A Robust Image Watermarking Based on DWT and RDWT Combined with Möbius Transformations." Computers, Materials & Continua 84, no. 1 (2025).
72. Devi, K. Jyothsna, Priyanka Singh, Hiren Kumar Thakkar, and Neeraj Kumar. "Robust and secured watermarking using Ja-Fi optimization for digital image transmission in social media." Applied Soft Computing 131 (2022): 109781.
73. Awasthi, Divyanshu, and Vinay Kumar Srivastava. "LWT-DCT-SVD and DWT-DCT-SVD based watermarking schemes with their performance enhancement using Jaya and Particle swarm optimization and comparison of results under various attacks." Multimedia Tools and Applications 81, no. 18 (2022): 25075-25099.
74. Belkebir, Djalila. "DIP-QGA: a secure and robust watermarking technique based on direct image projection and quantum genetic algorithm." International Journal of Information and Computer Security 20, no. 3-4 (2023): 221-247.
75. Laxmanika, and Pradeep Kumar Singh. "Robust and imperceptible image watermarking technique based on SVD, DCT, BEMD and PSO in wavelet domain." Multimedia Tools and Applications 81, no. 16 (2022): 22001-22026.
76. Kumari, Rani, and Abhijit Mustafi. "An optimized framework for digital watermarking based on multi-parameterized 2D-FrFT using PSO." Optik 248 (2021): 168077.
77. Niu, Panpan, Li Wang, Jialin Tian, Siyu Zhang, and Xiangyang Wang. "A statistical color image watermarking scheme using local QPCET and Cauchy–Rayleigh distribution." Circuits, Systems, and Signal Processing 40, no. 9 (2021): 4516-4545.
78. Bhatti, Uzair Aslam, Linwang Yuan, Zhaoyuan Yu, JingBing Li, Saqib Ali Nawaz, Anum Mehmood, and Kun Zhang. "New watermarking algorithm utilizing quaternion Fourier transform with advanced scrambling and secure encryption." Multimedia Tools and Applications 80, no. 9 (2021): 13367-13387.
79. Bhatti, Uzair Aslam, Zhaoyuan Yu, Jingbing Li, Saqib Ali Nawaz, Anum Mehmood, Kun Zhang, and Linwang Yuan. "Hybrid watermarking algorithm using Clifford algebra with Arnold scrambling and chaotic encryption." IEEE Access 8 (2020): 76386-76398.
80. Ahmadi, Sajjad Bagheri Baba, Gongxuan Zhang, Mahdi Rabbani, Lynda Boukela, and Hamed Jelodar. "An intelligent and blind dual color image watermarking for authentication and copyright protection." Applied Intelligence 51, no. 3 (2021): 1701-1732.
81. Awasthi, Divyanshu, and Vinay Kumar Srivastava. "ROI-based optimized image watermarking with real-time authentication." Cluster Computing 28, no. 7 (2025): 463.
82. Awasthi, Divyanshu, Priyank Khare, and Vinay Kumar Srivastava. "RFDB: Robust watermarking scheme with Fuzzy-DnCNN using blockchain technique for identity verification." Expert Systems with Applications 255 (2024): 124554.
83. Cheema, Adnan Mustafa, Syed Muhammad Adnan, and Zahid Mehmood. "A novel optimized semi-blind scheme for color image watermarking." IEEE Access 8 (2020): 169525-169547.
84. Sivananthamaitrey, P., and P. Rajesh Kumar. "Optimal dual watermarking of color images with SWT and SVD through genetic algorithm." Circuits, Systems, and Signal Processing 41, no. 1 (2022): 224-248.
85. Darwish, Saad M., and Layth Dhafer Shukur Al-Khafaji. "Dual watermarking for color images: a new image copyright protection model based on the fusion of successive and segmented watermarking." Multimedia Tools and Applications 79, no. 9 (2020): 6503-6530.
86. Kang, Xiaobing, Yajun Chen, Fan Zhao, and Guangfeng Lin. "Multi-dimensional particle swarm optimization for robust blind image watermarking using intertwining logistic map and hybrid domain: X. Kang et al." Soft Computing 24, no. 14 (2020): 10561-10584.
87. Bagheri Baba Ahmadi, Sajjad, Gongxuan Zhang, Songjie Wei, and Lynda Boukela. "An intelligent and blind image watermarking scheme based on hybrid SVD transforms using human visual system characteristics." The Visual Computer 37, no. 2 (2021): 385-409.
88. Mohan, Anand, Ashima Anand, Amit Kumar Singh, Ramji Dwivedi, and Basant Kumar. "Selective encryption and optimization based watermarking for robust transmission of landslide images." Computers and Electrical Engineering 95 (2021): 107385.

89. Thakkar, Falgun, and Vinay Kumar Srivastava. "An adaptive, secure and imperceptive image watermarking using swarm intelligence, Arnold transform, SVD and DWT." Multimedia Tools and Applications 80, no. 8 (2021): 12275-12292.
90. Sisaudia, Varsha, and Virendra P. Vishwakarma. "Copyright protection using KELM-PSO based multi-spectral image watermarking in DCT domain with local texture information based selection." Multimedia Tools and Applications 80, no. 6 (2021): 8667-8688.
91. Mehta, Rajesh, Keshav Gupta, and Ashok Kumar Yadav. "An adaptive framework to image watermarking based on the twin support vector regression and genetic algorithm in lifting wavelet transform domain." Multimedia Tools and Applications 79, no. 25 (2020): 18657-18678.
92. Hsu, Ling-Yuan, and Hwai-Tsu Hu. "Blind watermarking for color images using EMMQ based on QDFT." Expert Systems with Applications 149 (2020): 113225.
93. Rai, Manish, and Abhishek Kesarwani. "Image watermarking in the digital era: A review of transform, ML-based, and evolutionary methods." Circuits, Systems, and Signal Processing (2025): 1-52.
94. Singh, Om Prakash, Amit Kumar Singh, Gautam Srivastava, and Neeraj Kumar. "Image watermarking using soft computing techniques: A comprehensive survey." Multimedia Tools and Applications 80, no. 20 (2021): 30367-30398.