

# Role of metaheuristic algorithms in healthcare: a comprehensive investigation across clinical diagnosis, medical imaging, operations management, and public health

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## Abstract

Metaheuristic algorithms have emerged in recent years as effective computational tools for addressing complex optimization problems in many areas, including healthcare. These algorithms can efficiently search through large solution spaces and locate optimal or near-optimal responses to complex issues. Although metaheuristic algorithms are crucial, previous review studies have not thoroughly investigated their applications in key healthcare areas such as clinical diagnosis and monitoring, medical imaging and processing, healthcare operations and management, as well as public health and emergency response. Numerous studies also failed to highlight the common challenges faced by metaheuristics in these areas. This review thus offers a comprehensive understanding of metaheuristic algorithms in these domains, along with their challenges and future development. It focuses on specific challenges associated with data quality and quantity, privacy and security, the complexity of high-dimensional spaces, and interpretability. We also investigate the capacity of metaheuristics to tackle and mitigate these challenges efficiently. Metaheuristic algorithms have significantly contributed to clinical decision-making by optimizing treatment plans and resource allocation and improving patient outcomes, as demonstrated in the literature. Nevertheless, the improper utilization of metaheuristic algorithms may give rise to various complications within medicine and healthcare despite their numerous benefits. Primary concerns comprise the complexity of the algorithms employed, the challenge in understanding the outcomes, and ethical considerations concerning data confidentiality and the well-being of patients. Advanced metaheuristic algorithms can optimize the scheduling of maintenance for medical equipment, minimizing operational downtime and ensuring continuous access to critical resources.

**Keywords:** metaheuristic algorithm, healthcare industry, clinical diagnosis, public health, operations management

## 1. Introduction

The problem-solving abilities of metaheuristic algorithms, a class of computational techniques motivated by natural processes and human problem-solving strategies, have attracted widespread interest and application. These algorithms have become helpful in healthcare in recent years, providing novel approaches to complex optimization and decision-making problems. Clinical treatment planning, medical condition monitoring, and healthcare logistics and resource optimization are numerous technical challenges impacting the healthcare sector. Metaheuristic algorithms present a promising method for tackling these problems, as they have the potential to enhance productivity, better patient outcomes, and provide improved data-driven decision support for clinicians. Researchers are thus actively investigating algorithms to derive valuable insights from extensive biological data in the expanding healthcare industry, which currently includes computer science, life sciences, and data science (Iqbal & Kumar, 2022). Numerous applications have been developing, including disease

diagnosis and risk assessment, individualized therapy strategies, genetic counseling (including carrier status identification), and searching for novel drugs (Calvet et al., 2023). The convergence of these field-related advancements has resulted in better medical and healthcare practices.

The healthcare sector has experienced notable progress in applying metaheuristics, evident in improved surgical procedures, extended pharmaceutical research, and instructional materials to train healthcare professionals. Although healthcare comprises many subfields, each has its unique focus, dimensions, and functions. Not only does healthcare include clinical treatment, but it also encompasses a broader range of activities and entities. Metaheuristic algorithms are frequently utilized in clinical diagnosis for diseases, including radiation therapy surgery, and for monitoring health conditions through medical images or signal processing. These algorithms additionally enhance drug development by optimizing molecular structures, improving treatment outcomes through personalized interventions, and increasing the accuracy of diagnosis in

**Received:** September 30, 2023. **Revised:** April 14, 2024. **Accepted:** April 15, 2024

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healthcare (Parihar *et al.*, 2022). Conversely, the large healthcare industry finds substantial use for metaheuristic algorithms, which handle resource allocation, clinical trial design, emergency response logistics, and telemedicine resource optimization (Do Carmo Martins, 2021). While there may be variations among healthcare applications, their primary goals are to enhance the well-being and health of the population. Both of these applications depend on metaheuristic algorithms to achieve these goals.

Metaheuristic algorithms greatly benefit healthcare by assisting in developing complicated decision-making processes applicable across multiple sectors. The accuracy of the metaheuristic algorithm not only increases the effectiveness of the medication but also lessens side effects and improves patient outcomes. Moreover, these strategies effectively optimize resource allocation in hospitals and healthcare facilities (Fattahi *et al.*, 2023). The use of metaheuristic algorithms is predicted to experience a substantial rise in the healthcare sector in the coming years. As healthcare systems worldwide face rising challenges spurred on by resource shortages, demographic changes, and the desire for customized therapeutic approaches, metaheuristics will continue to be at the forefront, persistently solving these complex problems. Significant improvements in the quality of care and efficacy of healthcare delivery are anticipated due to the integration of machine learning (ML), artificial intelligence, and metaheuristics in clinical decision support systems, drug development, and medical research. Although metaheuristic algorithms have been the subject of extensive research, this review distinguishes itself from prior review studies in several aspects. The scope of its thorough investigation encompasses various sectors of healthcare, including public health, operations management, clinical diagnosis, and medical imaging. This ensures an in-depth understanding of the practical implementations of metaheuristic algorithms. It also incorporates state-of-the-art technologies into the healthcare domain, emphasizing its capacity to address complicated optimization challenges and improve the quality of clinical decision support. Prospective research avenues are also identified in the review, focusing on the necessity of incorporating ethical considerations and ML methodologies into algorithmic healthcare solutions. Academics, practitioners, and decision-makers will be equipped to deal with the complex landscape of healthcare and algorithmic innovation due to the exhaustive and comprehensive investigation of this research.

The paper is organized as follows: Section 2 outlines the methodology for selecting high-quality, relevant articles. Section 3 analyzes various metaheuristic algorithms employed in the healthcare sector. Section 4 explores the progress of these algorithms across multiple healthcare domains, such as clinical diagnosis and treatment, medical imaging and processing, logistics optimization and management, and public health and crisis responses. The challenges and opportunities related to applying metaheuristics in the healthcare sector are described in Section 5. Section 6 discusses the exploration of future research directions. Section 7 represents the concluding part of this study.

## 2. Methodology

This comprehensive literature review aims to provide insights into utilizing metaheuristic algorithms in the healthcare domain, including their applications and the associated challenges and openings. This review employs an integrative approach, thoroughly investigating and evaluating high-quality papers from reputable sources such as Google Scholar and Scopus and renowned publishers' journals like Nature, Elsevier, Taylor & Francis, Wiley,

Springer, IEEE, and ACM. To accomplish a comprehensive evaluation, significant contributions from publishers of lesser renowned but equivalent credibilities, such as Sage, Emerald Insight, De Gruyter, and Inderscience, are also taken into account. Thus, a well-rounded overview of the subject is produced as a result of the thorough investigation of various sources facilitated by the comprehensive methodology. The literature search was systematically carried out using a set of carefully chosen keywords relevant to the research topic. The key terms included "Metaheuristic algorithms", "Clinical diagnosis", "Logistics optimization", "Medical imaging", "Operations management", "Healthcare", and "Public health". Boolean operators, including AND, OR, and NOT, were applied to refine the search and broaden the scope of the results, which involved using combinations such as "Metaheuristic OR optimization algorithms" and "Metaheuristic algorithms AND medical imaging". Considering only studies published in English, the search was limited to articles published in the last 5 years (2019 and onwards). This review further identified relevant papers by examining the bibliographies and references of the selected publications. The papers were thoroughly assessed using the following criteria based on abstract, introduction, and conclusion, leading to the ultimate categorization:

- (i) Prioritizing peer-reviewed works primarily from the aforementioned reputable websites and equally credible publishers;
- (ii) Accumulating published materials authored by active researchers in the field;
- (iii) Maintaining an appropriate balance between recent and older studies; and
- (iv) Refer to the original sources and retrieve crucial papers referenced in subsequent research.

The literature search for this comprehensive review followed an iterative process to enhance its effectiveness. The initial findings were analyzed after a preliminary search using keywords, and the search strategy was refined based on the results. The refinement process involved adjusting search terms, incorporating additional relevant keywords, and modifying Boolean operator combinations to balance sensitivity and specificity. Specific phrases identified from the initial review were also integrated into the search strategy to capture more targeted literature. Additionally, the search was regularly revised to incorporate the latest publications and to maintain the comprehensiveness of the review. Even though they were involved in limiting and selecting the literature, the criteria for exclusion were seen as highly subjective. Scientific, peer-reviewed publications were subjected to exclusion criteria to ensure the relevance and depth of information related to the specified keywords. Publications were not considered if they did not include enough discussion of the selected keywords or did not discuss them. In addition, the review did not consider gray literature if it was determined to have redundant results or did not have the necessary references and context details. To prioritize the inclusion of more comprehensive and high-quality sources, conference proceedings were only partially taken into account. To ensure that the exclusion process was consistent and reliable, the authors employed a test-retest strategy to address potential bias. It all started with selecting studies at random from the main research pool. The random selection was essential to prevent bias and ensure that the subset chosen for reassessment represented the full range of the literature being considered. Several iterations of comprehensive checks were performed on the chosen studies, during which the relevance of the exclusion criteria was meticulously evaluated. These numerous evaluations aimed to confirm the original

**Table 1:** Criteria for identifying appropriate literature.

Inclusion guidelines	Exclusion guidelines
<ul style="list-style-type: none"> <li>– Research should prioritize the utilization of metaheuristic algorithms in healthcare domains, encompassing clinical diagnosis, medical imaging, operations management, and public health, among others.</li> <li>– To encompass recent developments and progress in the field, the literature should be published recently, usually no later than the last 5 year.</li> <li>– Selected publications for this study should be scientific, peer-reviewed, and able to address the research inquiries effectively.</li> <li>– Extensive research is conducted on gray literature due to its potential value and significance.</li> <li>– An in-depth understanding of the topic is typically achieved by including numerical and experimental studies, meta-analyses, and systematic reviews.</li> </ul>	<ul style="list-style-type: none"> <li>– In order to mitigate the potential influence of bias in literature reviews, we exclude studies that do not deal with clinical diagnosis, medical imaging, operations management, or public health, as well as those that do not specifically mention the use of metaheuristic algorithms in healthcare.</li> <li>– To prioritize current developments and prevent the inclusion of outdated information, literature published before the specified period is excluded.</li> <li>– Despite being scientific and peer-reviewed, publications that excluded or inadequately discussed information related to the specified keywords are not considered.</li> <li>– Gray literature that contains repetitive results or lacks appropriate references and contexts is not included. In addition, conference proceedings were only considered in this analysis to a limited extent.</li> </ul>

exclusion decisions and minimize the influence of subjective assessments. Table 1 outlines the main criteria for including and excluding papers that served as the foundation for this research.

Although involved in the literature selection and limitation process, the exclusion criteria appeared judgmental. A test–retest procedure was utilized to ensure accuracy, where the retrieved data were tested for accuracy multiple times after a random selection from primary research. Figure 1a provides a summary of the primary content of this investigation, using a pre-exploratory mapping approach to assist readers in understanding the article selection overview. A thorough outline was put together by utilizing the pre-existing publication classification system. Figure 1b illustrates the accumulation of 918 publications for analysis since the year 2019. However, only 106 were considered suitable for inclusion in this review paper, as evidenced by the chronological arrangement of publications shown in Fig. 1a.

### 3. Metaheuristic algorithms

Metaheuristic algorithms are mostly robust problem-solving approaches extensively used in search and optimization domains (Osaba et al., 2021). They are divided into different categories (Fig. 2): swarm-based algorithms, evolutionary algorithms, physics-inspired algorithms, and human-inspired algorithms (Bhattacharyya et al., 2020). Among different types of algorithms, one of the frequently used algorithms that facilitates the healthcare industry and improves the well-being of people is the genetic algorithm (GA), developed by J. H. Holland and first published in 1992. This optimization is based on the biological theory of evolution, specifically the Darwinian concept of “survival of the fittest”; it has been distinguished by essential elements like chromosome representation, fitness selection, and biologically inspired operators (Almufti et al., 2023). Then, the whale optimization algorithm (WOA) incorporates two main predatory strategies to imitate the foraging behavior of humpback whales whereas the first technique involves hunting prey using the most effective search agent or at random, while the second technique imitates the tactical use of bubble nets during hunting (Mohammed et al., 2019).

Gray wolf optimization (GWO) (Makhadmeh et al., 2024) focuses on three main phases – prey encirclement, hunting, and prey capture, which emulate the social organization and hunting method of gray wolves in their natural habitat. The cuckoo search

optimization algorithm (CSOA) is a population-based metaheuristic optimization method stimulated by the breeding habits of cuckoo birds, where each solution in the search space is symbolized by a cuckoo egg (Jawad et al., 2023). The spider monkey optimization algorithm was formed by the behaviors of primates living in hierarchical “parent groups” whose dynamics are affected by the availability of food, exhibit adaptability whereby it split into smaller groups during times of food scarcity (fission) and coalesces into larger ensembles in times of food abundance (fusion), corresponding to their foraging instincts (Sharma et al., 2019). Again, the lion optimization algorithm is based on the complex social interactions and collaborative instincts of lions, which include prey hunting, mating rituals, territorial marking, and defensive tactics (Al-Janabi & Alkaim, 2022). The other techniques such as ant lion optimization, dragon-fly optimization algorithm (DFOA, Ali et al., 2023), moth flame optimization (Haseena et al., 2022), harmony search algorithm (Bhattacharyya et al., 2020), and many more are assisting in resolving optimization issues in numerous industries, including healthcare and medicine.

Metaheuristic algorithms offer flexible and versatile techniques suitable for addressing complex problems, especially when conventional exact methods become impractical or time-consuming. When traditional exact methods are proven impractical or time-consuming, metaheuristic algorithms offer adaptable and versatile techniques to address diverse complex problems. Moreover, metaheuristics are widely considered advanced techniques that provide comprehensive guidance to heuristic procedures, enabling them to explore and navigate solution spaces effectively. Although these algorithms do not guarantee optimal solutions, they can achieve near-optimal or superior solutions. Incorporating concepts from a range of natural and artificial phenomena, including genetic evolution, simulated annealing, and ant colony behavior, the adaptability and robustness of metaheuristics render them invaluable for solving problems characterized by uncertain or ill-defined objective functions and constraints (Agrawal et al., 2021).

In recent years, there have been significant advancements and refinements in metaheuristic algorithms. The general trend of metaheuristic algorithm development for healthcare is illustrated in Fig. 3. The researchers have been consistently investigating and exploring how to enhance the efficiency, convergence rates, and applicability of metaheuristic algorithms across different domains. Lately, the practice of hybridization,

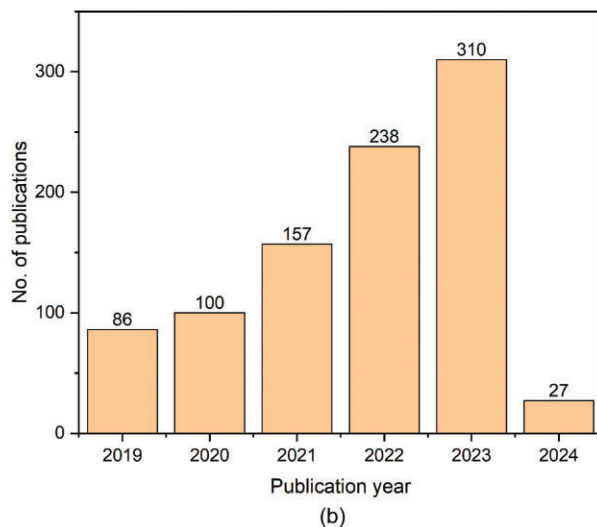
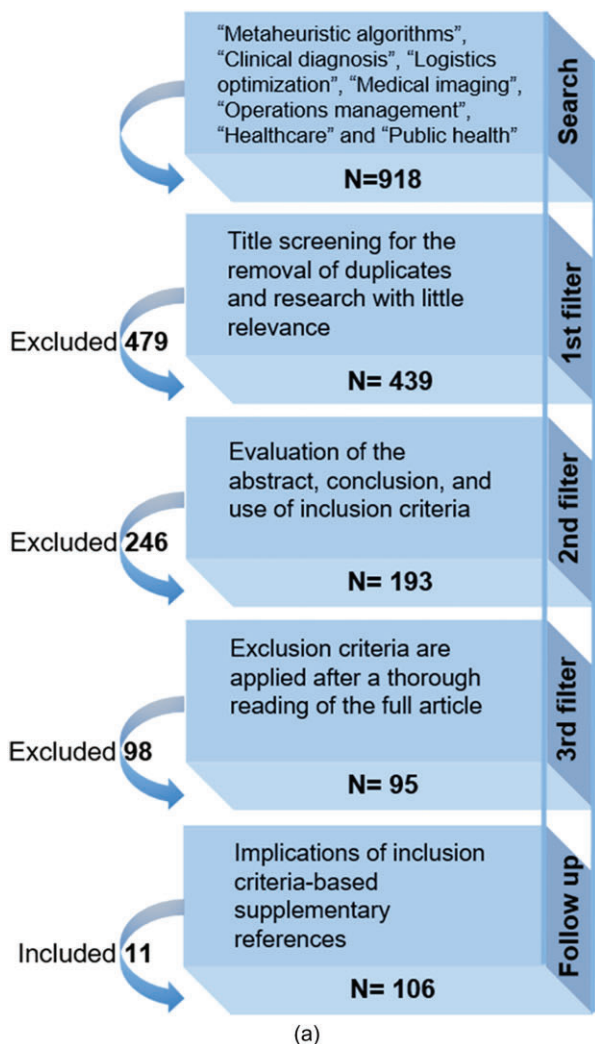


Figure 1: (a) Flowchart illustrating the process of selecting and filtering literature, with N representing the total number of publications. (b) Distribution of yearly publications since 2019.

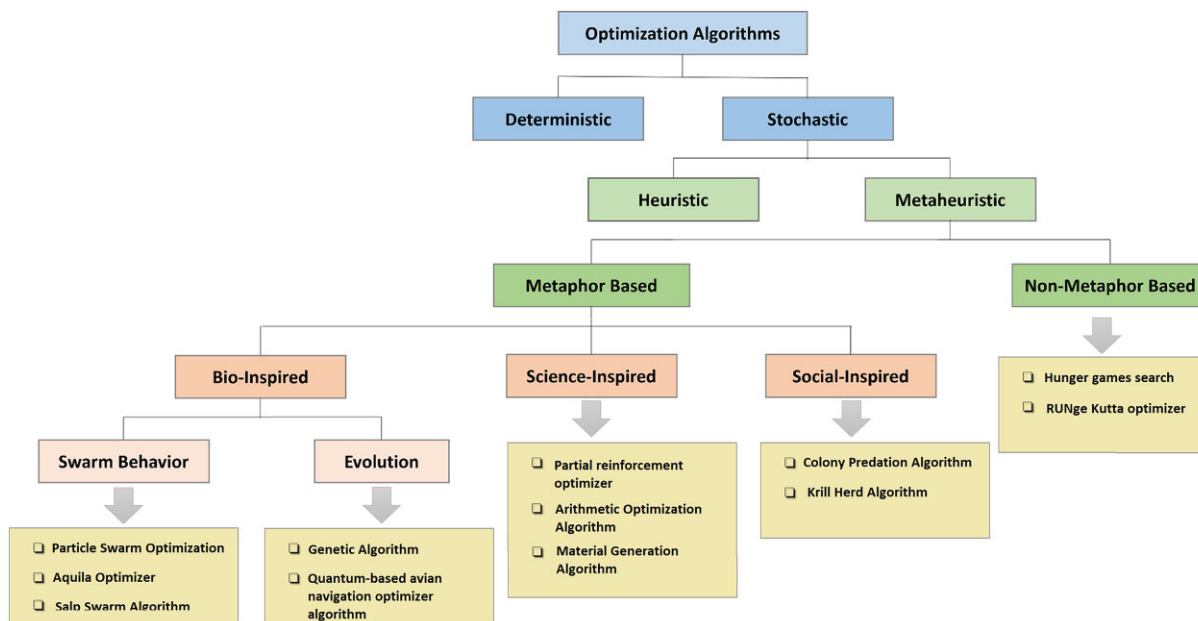
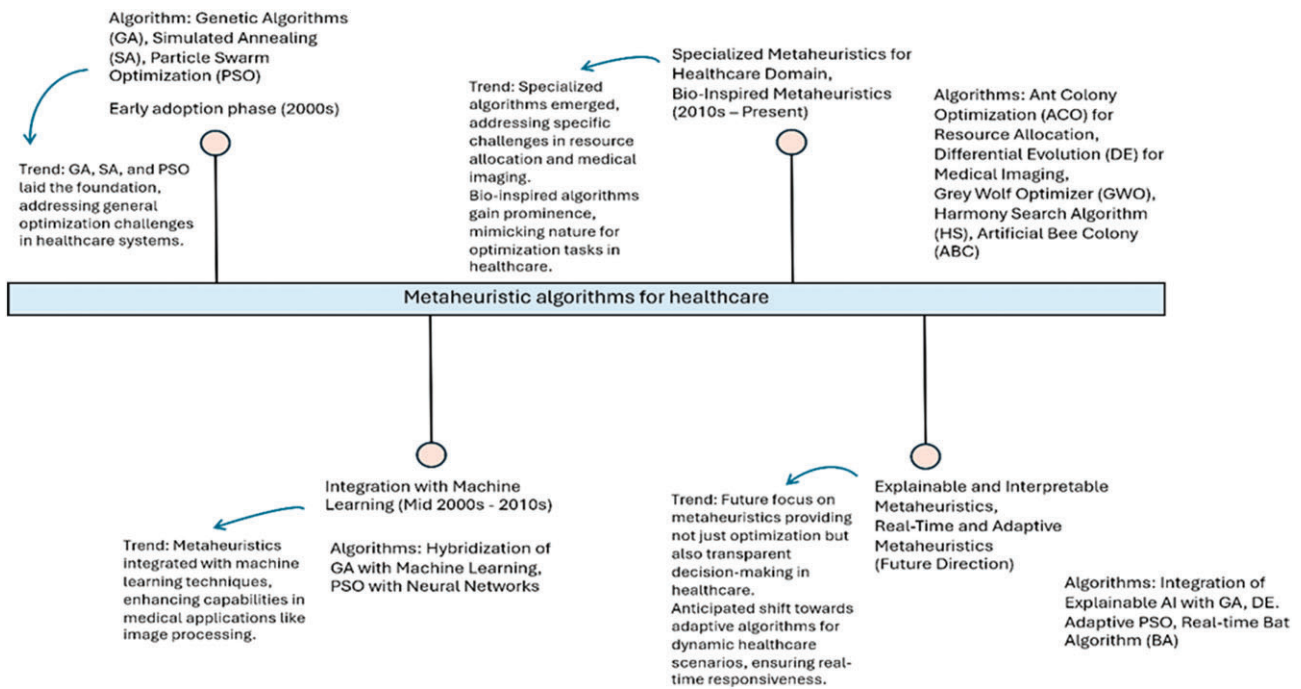


Figure 2: Types of metaheuristic algorithms (Kashani et al., 2022).



**Figure 3:** Development trend for metaheuristic algorithms for healthcare.

which involves combining multiple metaheuristic algorithms or integrating them with other optimization approaches, has gained popularity in leveraging the distinct advantages offered by different algorithms. Furthermore, better performance and faster convergence of these algorithms have been achieved through the experimentation of parameter tuning, adaptive strategies, and parallel computing. Accordingly, by offering innovative solutions to a broad spectrum of challenges within the medicine and healthcare domain, metaheuristic optimization algorithms are used in different areas, such as disease diagnosis, drug discovery, patient scheduling, healthcare logistics, and beyond (Abdalkareem *et al.*, 2021; Houssein *et al.*, 2021).

Metaheuristics contribute to healthcare systems by effectively navigating complex problem spaces, leading to improved disease diagnosis, optimized resource allocation, and enhanced patient outcomes. The advantages of these algorithms are rooted in their competency to address complex, multi-dimensional, and non-linear problems, offering prompt and satisfactory solutions. However, metaheuristics may encounter difficulties when applied to specific problem categories, and determining the most appropriate parameters for achieving optimal performance can be notably challenging. The absence of guaranteed theoretical convergence represents another challenge, necessitating the implementation of meticulous experimentation and customization designed for this specific problem.

## 4. Advancements in the use of metaheuristic algorithms in medicine and healthcare

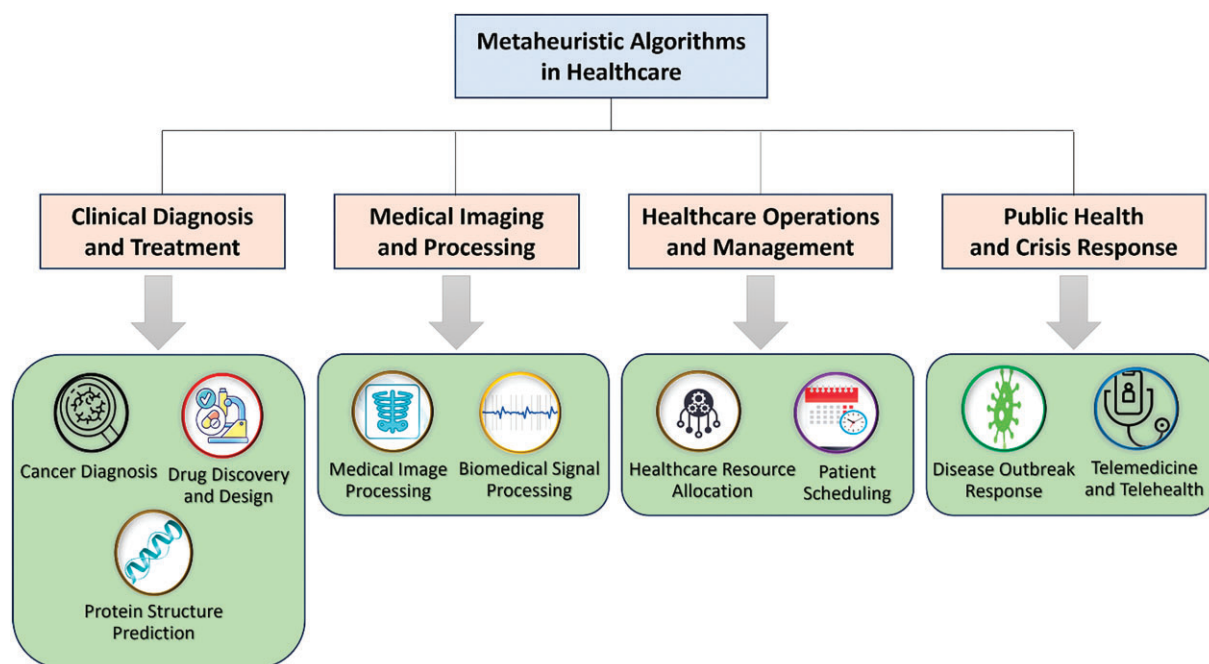
The immense potential of metaheuristic algorithms offers innovative solutions to various complex problems in the healthcare domain (Shivaprasad More *et al.*, 2023). The capacity to optimize dynamic and complex systems motivates using metaheuristic algorithms in clinical diagnosis and treatment, medical imaging and processing, healthcare operations and man-

agement, public health, and crisis response. Metaheuristics are chosen for their capacity to effectively address the inherent complexities of high-dimensional and non-linear problems in these domains. The applications of metaheuristics algorithms can be divided into four groups based on their primary objectives and functionalities, with each group having two or more subgroups, as shown in Fig. 4. For instance, these algorithms assist in disease detection by extracting important features from patient data and perform an important role in drug development by elevating molecular docking simulations (Almufiti *et al.*, 2023). Metaheuristics improve diagnostic accuracy in medical imaging and processing by contributing to picture enhancement, segmentation, and feature extraction. By optimizing logistics in the healthcare supply chain, these algorithms ensure the timely delivery of medical supplies and reduce costs (Salehi-Amiri *et al.*, 2022). In addition, effective strategies for disease surveillance, response planning, and resource allocation during emergencies can be developed with the help of metaheuristics in public health and crisis response. By optimizing diagnostic processes and treatment strategies, the metaheuristic algorithms assist in personalizing patient care plans in clinical diagnosis and treatment. These algorithms assist in maximizing logistics, scheduling, and resource allocation in healthcare operations and management.

### 4.1. Clinical diagnosis and treatment

#### 4.1.1. Cancer diagnosis

Metaheuristic algorithms, for instance, artificial bee colony (ABC), Harris hawk optimization (HHO) (Heidari *et al.*, 2019), and CSOA provide insightful assistance in disease diagnosis, enhancing the accuracy and efficiency of diagnostic processes. For instance, CSOA has been proven effective in improving cancer diagnosis by aiding in tasks such as lung tumor detection, breast cancer diagnosis from mammograms, and optimizing diagnostic parameters (Kaur *et al.*, 2023). These algorithms are also used to



**Figure 4:** Applications of metaheuristic algorithms in healthcare.

improve radiation therapy treatment plans for cancer patients, aiming to mitigate possible side effects associated with such treatments (Almufti *et al.*, 2023). In addition, integrating metaheuristic algorithms into multi-class ML classifiers, including random forest, support vector machine (SVM), and deep learning models, like convolutional neural networks (CNNs), can provide additional benefits in cancer diagnosis (O. O. Akinola *et al.*, 2022). Thus, metaheuristics contribute to more accurate and efficient cancer diagnosis by optimizing feature selection, image segmentation, and classification processes, ultimately assisting in the early detection and management of cancerous conditions (Kaur *et al.*, 2023).

A skin lesion classification method was introduced by Golnoori *et al.* (2023), which relies on deep features extracted from a CNN optimized using swarm-based and evolutionary methods. A deep CNN was initially optimized using GA to categorize the skin lesion images. Subsequently, the study conducted a comparative analysis of particle swarm optimization (PSO), differential evolution (DE), and GA methods for fine-tuning hyperparameters across five pre-trained models, with GA and DE generally outperforming PSO. After training with optimal hyperparameters, the last layers' features were combined for classification using the K-nearest neighbors (KNN). The results indicated that the combined features from the Inception-v3 and DenseNet-201 models performed exceptionally well on the ISIC2018 dataset, while the DenseNet-201 and ResNet-50 models excelled on the ISIC2017 dataset. Moreover, the recommended method achieved 81.6% accuracy on the ISIC2017 dataset and an accuracy of 90.1% on the ISIC2018 dataset. However, the study focused on optimizing network architecture using serial blocks without delving into more sophisticated convolutional building block designs, such as ResNet or DenseNet.

To categorize the severity of breast cancer, Sannasi Chakravarthy *et al.* (2023) proposed an innovative approach that combines metaheuristic algorithms with deep learning. The research employed MIAS, INbreast, and WDBC datasets and applied transfer learning for feature extraction. The novelty of this research was using the transformation techniques, i.e., DFOA, CSOA, and PSO, to elevate the performance of the weighted-KNN

(wKNN) algorithm. These techniques converted non-linear features into feature vectors that have more linear separability. Two additional classifiers, Gaussian Naïve Bayes (GNB) and SVM with a linear kernel (LSVM), were used for performance evaluation. The research achieved noteworthy detection rates using the CSOA-wKNN algorithm, with results of 82.86% for ResNet18 deep MIAS features, 81.37% for ResNet18 deep INbreast features, and 97.33% for WDBC features. However, performance gains with feature vector values were limited, highlighting the need for future research to improve overall performance through preprocessing, hyperparameter tuning, and automatic tuning for metaheuristic algorithms, as well as extending the approach to multi-class problems.

Skin cancer poses a significant threat to millions of people, with its survival rate declining significantly as it advances, and yet early detection remains costly and challenging. To improve early detection, automatic skin cancer detection, segmentation, and classification, Balaha and Hassan (2023) introduced a method utilizing the sparrow search algorithm (SpaSA) as a metaheuristic optimizer. The segmentation process involved five U-Net models: U-Net, UNet++, attention U-Net, V-Net, and swin U-Net, each with unique settings, while the metaheuristic SpaSA optimized the hyperparameters using pre-trained CNNs. Results showed that the U-Net model with DenseNet-201 as its base was the best-performing model for the "skin cancer segmentation and classification" dataset, achieving 94.16% accuracy and 91.39% F1 score. However, a significant drawback of this study was the high training time complexity, mainly caused by the delayed convergence of the boosting algorithms. Challenges also persisted due to limited datasets, prompting future exploration of alternative techniques, improved segmentation performance, and additional dataset evaluation.

#### 4.1.2. Drug discovery and design

Metaheuristic algorithms are used in optimizing the molecular composition of new drugs, enabling the prediction of their efficacy and ensuring safety (Almufti *et al.*, 2023). Single-solution methods,

including simulated annealing (SA) and tabu search (TS), as well as population-based techniques like GA, DE, and PSO, obtain approximate optimal solutions by improving single or multiple solutions, contributing to various stages of the process (Oliveira *et al.*, 2023). Evolutionary algorithms, like GA, are widely applied in different tasks such as molecular compound design, ligand-based computer-aided drug discovery, and the prediction of properties of molecular compounds in cheminformatics applications. For instance, combining the HHO metaheuristic algorithm with ML techniques can enhance chemical descriptor selection and compound activity prediction, achieving high accuracy compared with other well-established metaheuristic algorithms (Houssein *et al.*, 2020). Moreover, a hybrid HHO algorithm integrated with cuckoo search and chaotic maps improves the overall performance for feature selection and classification and offers enhanced solutions for handling the complexities of cheminformatics (Houssein *et al.*, 2020).

The importance of linear-B cell epitopes (LBCEs) in vaccine development and their identification from protein sequences were emphasized (Angaitkar *et al.*, 2023). In a two-step metaheuristic variant-feature selection procedure, the paper provided a method for LBCE classification that combined an LSVM with a modified GA. The selection focused on various mono-peptide, dipeptide, and tripeptide properties that were then put into a parallel ensemble classifier. This ensemble classifier's astounding accuracy of 99.3% was attained by combining many classifiers, including logistic regression, KNN, SVM, and random forest. This extraordinary accuracy outperformed cutting-edge models and set a new benchmark for LBCE classification.

A novel time-varying chaotic binary whale optimization algorithm (CBWOATV) was presented by Mohd Yusof *et al.* (2022) for optimizing feature selection procedures to categorize amphetamine-type stimulants (ATS) and non-ATS drugs. Two augmentation strategies were presented to strike an equilibrium between exploring and exploiting the search space within the conventional WOA framework. Initially, the binarization process used a time-varying modified sigmoid transfer function. Then, a hybrid Logistic-Tent chaotic map replaced pseudo-random numbers in the probability operator of the conventional WOA. ATS and non-ATS drug-specific, high-dimensional molecular descriptors were applied to assess the effectiveness of the proposed technique. Empirical observations proved that the CBWOATV method effectively addressed the issue of stagnation and getting stuck in local minima in WOA, leading to the selection of optimal descriptors for improved classification performance. However, exploring different strategies for implementing the Logistic-Tent chaotic map can be performed as future research directions.

The issue of feature selection in handling high-dimensional data was addressed by Abd Elaziz and Yousri (2021), which can negatively impact ML accuracy. While metaheuristic feature selection techniques have been introduced to mitigate traditional feature selection limitations, they still have drawbacks. This study introduced a modified Henry gas solubility optimization (HGSO) using enhanced HHO with heavy-tailed distributions (HTDs) to overcome the drawbacks. A dynamic interaction among five HTDs was employed to improve the HHO, consequently modifying the exploitation phase in HGSO. Thus, the study presented a dynamically updated HGSO based on improved HHO (DHGHHD). The performance of the proposed approach was evaluated using 18 UCI datasets and applied to enhance predictions in drug design and discovery. The approach outperformed the existing methods by 2–3% in sensitivity and specificity. This approach could be adapted into a multi-objective optimization strategy for real-world prob-

lems in different areas, such as color image segmentation, remote sensing applications, cloud computing task allocation, etc.

#### 4.1.3. Protein structure prediction

In bioinformatics, metaheuristics are used to predict the three-dimensional structures of proteins, which is essential for understanding their functions and designing drugs that interact with them. Through experiments on various protein sequences, metaheuristic algorithms, such as the ingenious crow search algorithm (ICSA), metaheuristic ant colony optimization with path relinking (MACO-PR), and hybrid whale optimization and sine-cosine algorithm demonstrate their effectiveness in improving protein structure prediction and offer promising solutions for enhancing disease diagnosis, overcoming the limitations of traditional methods (Alshamrani *et al.*, 2023; Saxena *et al.*, 2022; Sekhar *et al.*, 2023). Moreover, metaheuristic algorithms, particularly enhanced chaotic grasshopper optimization algorithms, solve the challenging protein folding optimization problem within the AB-OFF lattice model, leveraging chaotic maps to elevate the efficiency of the grasshopper optimization algorithm and aiming to predict native protein structures (Saxena & Kumar, 2020). Besides, a range of hybrid and specialized algorithms, including an elitist version of animal migration optimization, have shown significant promise in accurately predicting protein structures (Boiani & Parpinelli, 2020; Boumedine & Bouroubi, 2021; Ülker, 2023).

Structure knowledge, a path relinking (PR)-based technique, and Metaheuristic ant colony optimization (MACO) were all combined in the study of Sekhar *et al.* (2023) for predicting protein structure. The study included PR in MACO after realizing that MACO may result in local minima of torsion angles. The proposed model was evaluated on six distinct protein sequences before implementing the fundamental ant colony optimization (ACO) algorithm for calculation. Then, the predicted tertiary structures were validated using average energy consumption and root mean square deviation (RMSD). The findings indicated that the proposed MACO-PR model outperformed basic ACO among the six protein sequences. For instance, the MACO-PR approach revealed that the 2MTW protein ID had the lowest energy at  $-17.45$  kcal/mol as opposed to  $-16.83$  kcal/mol when utilizing the ACO method. Furthermore, when employing the recommended MACO-PR method, the 2MTW PDB ID yielded the lowest RMSD value at 4.16, while SVM and ACO resulted in values of 5.61 and 6.5, respectively. The proposed model could integrate deep learning techniques to enhance prediction accuracy and timeliness.

The ICSA with novel features, including an exponential operator and opposition theory in initialization, was developed by Alshamrani *et al.* (2023). The algorithm was initially tested on well-defined mathematical functions with known parameters. The newly developed ICSA was then applied to predict protein structures. The effectiveness of the method was evaluated using datasets of both artificial and modestly large actual proteins. The study conducted a comparative analysis of optimization performance, comparing ICSA to several well-known crow search algorithm (CSA) variations. The statistical comparison of the findings demonstrated that ICSA consistently outperformed CSA for almost all protein sequences. This exponential-driven approach enabled the algorithm to find minima and promote convergence. Developing a local search algorithm to enhance prediction accuracy for both artificial and real protein sequences and conducting in-depth analysis of longer sequences were recommended for future experimentation.

Due to the significant computational complexity involved, detecting protein complexes within extensive protein-protein

interaction (PPI) networks remains a formidable challenge. Identifying genuine protein complexes amidst these networks necessitates the use of advanced algorithms. To predict protein complexes within large PPI networks, Shahidul Islam *et al.* (2022) introduced an algorithm by employing a metaheuristic method. The algorithm emulated a density-based graph clustering technique, incorporating biological heuristics to pinpoint these complexes. Moreover, the algorithm was developed with a local search technique, three repair operators, and a new cluster density computation function. The approach was evaluated using data on yeast and human protein interactions, and the results were contrasted with those of cutting-edge algorithms. The experimental findings showed that protein complex prediction (PCP)-chemical reaction optimization (CRO) outperformed the existing methods, and in particular, it obtained 81.7% accuracy and an F-measure of 62.1% on the CYC2008 dataset. Their future research plans involved a further investigation into optimizing PCP-CRO operators to reduce reliance on repair operators and refining them for better prediction of larger protein complexes.

## 4.2. Medical imaging and processing

### 4.2.1. Medical image processing

Bat algorithm optimization, cat swarm optimization, ACO, and CS are hybrid optimization techniques used in medical image processing. The Monarch Butterfly Optimization algorithm has recently been explored to identify optimal threshold values, demonstrating its superiority in accuracy and speed compared with other methods (Dorgham *et al.*, 2021). In medical image registration, metaheuristic methods, such as the firefly algorithm, GWO, GA, and PSO, have been proven to be efficacious by optimizing the alignment of two medical images based on similarity criteria (Dida *et al.*, 2020). The emerging Biogeography-Based Optimization algorithm mitigates the challenge of optimizing similarity metrics between images from different modalities, leveraging the advantages of metaheuristic approaches to achieve robust global optima, thereby enhancing the accuracy of the registration process (Chen *et al.*, 2020). Furthermore, novel metaheuristic algorithms, such as fireworks boosted coral reefs optimization and united equilibrium optimizer, contribute to the field of multi-modal image registration, addressing exploration-exploitation balance, adaptive parameter tuning, and enhanced convergence (Chen *et al.*, 2021; Gui *et al.*, 2021).

A metaheuristic optimization method known as RSA-SSA was introduced by Abualigah *et al.* (2023), which combines the reptile search algorithm (RSA) with the salp swarm algorithm (SSA) to perform grayscale multi-level thresholding for image segmentation. The proposed technique facilitated the search space by finding ideal solutions throughout each iteration. In addition to obtaining the optimal multi-level thresholds, the method was designed to handle the problem of recurrent searching in the same region. The optimal threshold values for each level were determined using Otsu's variance class function. The proposed strategy was evaluated using several criteria, including fitness function, structural similarity index, peak signal-to-noise ratio (PSNR), and the Friedman ranking test. Testing on COVID-19 benchmark images demonstrated that RSA-SSA could outperform other metaheuristic optimization algorithms in the literature. The ability to avoid getting stuck at local optima enabled this technique to be proficient in finding optimal image solutions. This technique was recommended for various image processing applications in future work, which often encounter challenges related to image quality, such as low resolution, excessive noise, or poor contrast.

A modified reptile search algorithm (mRSA) approach was introduced by Emam *et al.* (2023), which combines the RSA with the Runge-Kutta optimizer (RUN). This approach significantly enhanced the performance of the original RSA through the incorporation of "enhanced solution quality" (ESQ) and "scale factor" (SF) mechanisms in several ways, including faster convergence, reduced risk of getting stuck in local optima, and improved balance between exploration and exploitation techniques. The effectiveness of mRSA was rigorously assessed through two sets of experiments. Firstly, mRSA was applied to different types and dimensions of CEC2020 benchmark functions, showcasing its superior resilience compared with the original RSA. In the second experiment, mRSA demonstrated its formidable optimization capabilities in the magnetic resonance imaging (MRI) brain image segmentation. In particular, the performance of this approach was exceptionally good in multi-level thresholding segmentation, where, out of 40 test instances, mRSA excelled in 25 cases (comprising 63% of all instances), attaining the highest PSNR score. However, it is important to acknowledge that the inclusion of ESQ and SF parameters led to a notable increase in computational cost.

Breast cancer is a significant threat to women worldwide, emphasizing the crucial need for early detection to improve treatment options and survival rates. However, distinguishing abnormal breast tissues from normal ones is challenging due to their complex structures and unclear boundaries. Ahila *et al.* (2022) addressed this challenge by proposing a computer-aided diagnosis system that integrated a wavelet neural network (WNN) with the GWO method to detect abnormalities in breast ultrasound images. Anisotropic diffusion and interference-based despeckling were used after preprocessing breast ultrasound images using a sigmoid filter. Following the automated segmentation of the region of interest, morphological and texture characteristics were calculated. The GWO-based WNN was used for classification. The performance of this approach was validated using 346 ultrasound images and assessed through confusion matrices and receiver operating characteristic (ROC) curves. The proposed method achieved a remarkable accuracy of 98%, highlighting its potential as an efficient breast cancer prediction model.

### 4.2.2. Biomedical signal processing

Metaheuristic algorithms aid in processing biomedical signals such as electrocardiogram (ECG) and electromyographic (EMG), facilitating denoising, feature extraction, and anomaly detection tasks (Nayak *et al.*, 2020). Butterfly optimization algorithm (BOA), manta ray foraging optimization (MRFO), marine predators algorithm, artificial butterfly optimization algorithm, and emperor penguin optimizer (EPO) play a crucial role in biomedical signal processing within mobile healthcare systems. They enhance both the compression of ECG signals and the efficiency of arrhythmia identification, ultimately contributing to the development of advanced healthcare systems reliant on wireless biomedical wearables (Mian Qaisar *et al.*, 2023; Qaisar *et al.*, 2022). Moreover, these algorithms are used for efficiently compressing ECG signals, crucial for storage and transfer in telemedicine-based healthcare systems, and enhancing security through advanced encryption techniques, ensuring the protection of sensitive health data (Ahmed *et al.*, 2022; Pal *et al.*, 2022). Furthermore, PSO and GWO elevate the performance of a multi-layer perceptron in categorizing EMG signals by fine-tuning hyperparameters, demonstrating potential in optimizing deep learning for biomedical signal processing (Aviles *et al.*, 2023).

An approach for arrhythmia identification from ECG signals was studied by Mian Qaisar *et al.* (2023), which achieved efficient compression, processing, transmission, and power usage while maintaining precision. The proposed technique combined multi-rate signal processing, QRS selection, variational mode decomposition, statistical feature extraction, metaheuristic-driven feature selection, and ML techniques. Experimentation was conducted using the MIT-BIH dataset, comparing three metaheuristic optimization algorithms, i.e., BOA, MRFO, and EPO, for feature selection. This research employed a multi-subject and multi-class dataset using 10-fold cross-validation for classification. The results showed significant compression gains (up to 46.29-fold) and high classification accuracies (up to 99.14%), demonstrating the efficacy of the proposed approach in enhancing signal processing and data transmission for arrhythmia detection. Further evaluation of this approach on different datasets and exploration of the integration of deep learning algorithms are potential future directions for this research.

To classify EMG signals, Aviles *et al.* (2023) introduced a metaheuristic-driven method to optimize hyperparameters in a multi-layer perceptron. The main objective was to enhance model performance by fine-tuning four critical hyperparameters: the number of neurons, epochs, learning rate, and batch size. In the experiment, employing PSO and GWO significantly increased the effectiveness of a multi-layer perceptron in categorizing EMG motion signals. The model achieved an impressive accuracy of 93% during validation. However, different strategies, such as increasing the training data, using data augmentation techniques, employing advanced signal preprocessing methods, and exploring different neural network architectures, could be explored for future work. In addition to normalizing the data and carefully selecting cost functions for metaheuristic algorithms, future research should also address the initialization of network weights and continuously explore novel techniques for further performance improvement.

The need for efficient compression methods for ECG signals was addressed by Pal *et al.* (2022), which is crucial for storing and transferring data in telemedicine-based healthcare systems. The proposed approach employed tunable-Q wavelet transform (TQWT) and metaheuristic optimization algorithms, such as variants of PSO, ABC, and hybrid combinations with PSO, GWO, and sparse PSO to automatically determine optimal TQWT parameters based on input signal characteristics. Following this, thresholding and quantization were adopted to the coefficients, and a lossless encoding technique further enhanced compression. The experiments conducted on the MIT-BIH arrhythmia dataset demonstrated significant compression improvements compared with existing techniques. The results also indicated that sparse PSO and hybrid methods offer minor deviations in fitness function minimization and notable improvements in time complexity. Therefore, the research proved that these techniques effectively compress various ECG signals while maintaining reconstruction quality, indicating their potential applicability in mobile health and telemedicine for improved resource utilization.

### 4.3. Healthcare operations and management

#### 4.3.1. Healthcare resource allocation

Metaheuristic optimization algorithms are widely used for healthcare resource allocation, enabling the exploration of different scenarios, optimizing the allocation of medical resources, and thus ensuring proper patient care (Hernández-Pérez & Ponce-Ortega, 2021). In recent decades, metaheuristic methods have been in-

creasingly employed in healthcare scheduling research to ensure the optimal allocation and management of hospital resources, aiming to enhance cost-efficiency and patient flow and utilize available resources (Abdalkareem *et al.*, 2021). For instance, the hybrid Glocal-GASA algorithm, combining the global and local search capabilities of GA and SA, optimizes healthcare resource allocation for sustainability and equity while balancing exploration and exploitation aspects (Sohrabi *et al.*, 2023). Additionally, metaheuristic algorithms can optimize operating room scheduling, aiming to efficiently allocate medical staff and equipment in healthcare organizations (Maghzi *et al.*, 2022).

There are now substantial overcrowding difficulties in the emergency department because of the increased demand for emergency resources in recent years. Addressing this issue, Kuo *et al.* (2023) introduced a multi-objective mathematical model for optimal healthcare resource allocation. The optimization of resource allocation was achieved using several metaheuristic algorithms, including the fast and elitism non-dominated sorting genetic algorithm (NSGA), non-dominated sorting differential evolution (NSDE), and non-dominated sorting particle swarm algorithm (NSPSO). Subsequently, a simulation model was developed, incorporating the generated solutions by the resource allocation model into the simulation procedure. The results indicated that NSGA outperformed NSPSO and NSDE, with an average staff utilization and service level of 0.751 and 0.844, respectively. The simulation model also identified the optimal combination of staff-bed ratio, ranging from one to ten staff and one to six beds, enhancing resource utilization and service levels. Integrating additional techniques, such as neural networks, into the resource allocation process was recommended in future research to strengthen simulation performance.

The challenges faced by healthcare systems in achieving sustainable inventory management of blood products were addressed by Sohrabi *et al.* (2023). To solve these issues, this study presented a realistic demand-driven multi-objective inventory model that incorporated hybrid strategies to manage the uncertainties of the healthcare environment. Elective and non-elective requests were separated into two categories based on medical urgency, allowance for substitution, and the freshness of the products. The model employed a hybrid resilient fuzzy stochastic programming approach to address real-world uncertainties. Focusing on blood platelet management, the solution was obtained by combining GA and SA for local and global searches. Sensitivity analysis and performance validation demonstrated that the proposed model outperformed the nominal model, effectively minimizing system costs, reducing environmental impact, and mitigating shortages and wastage while promoting equitable healthcare access and emergency preparedness. However, the study only focused on a single healthcare system and did not consider disaster scenarios. Extending the model to the entire network and exploring different metaheuristic algorithms could be performed for future research.

Addressing resource planning and routing challenges, Goodarzian *et al.* (2021) explored the significance of home health care (HHC) services as a cost-effective alternative to hospitalization. The proposed bi-objective model integrates the generalization of the vehicle routing problem with time windows and employee planning to efficiently allocate tasks to therapists, considering patient time windows and employee preferences. To handle the nondeterministic polynomial (NP)-hard nature of the problem, a fuzzy approach was introduced to manage uncertainties in transportation and travel cost parameters. Formulating an integer linear programming model, they employed

multi-objective imperialist competitive algorithm (MOICA), NSGA-II, and multi-objective social engineering optimization (MOSEO) algorithms. The experimental results demonstrate the superiority of the MOSEO algorithm over NSGA-II and MOICA. As part of future research directions, the study aims to conduct comprehensive experiments, develop new metaheuristic algorithms, and explore additional factors such as patient inconvenience, environmental impact, and multi-period, multi-product considerations.

To solve resource management issues associated with hospitalizing critically sick patients, particularly in emergency settings like pandemics, Hernández-Pérez and Ponce-Ortega (2021) proposed a unique multi-objective stochastic optimization framework that blends deterministic optimization with metaheuristic techniques. The methodology of this research involved applying various algorithms, including the deterministic optimization algorithm (DOA), stochastic optimization algorithm (SOA), and multi-objective algorithm (MOA), to handle decision-making and resource allocation during the healthcare crisis pandemic. The study used a specific scenario to assess the model's efficiency, specifically in optimizing the allocation of resources during healthcare emergencies. The optimization objectives encompassed both social and economic aspects. Considering changing demand uncertainties, the experimental results provided optimal configurations for acquiring medical resources (hospital beds and intensive care units (ICUs)) and distributing patients to hospitals. In the future, this versatile approach can offer promising solutions to many problems involving parameter uncertainties and multiple objectives.

In post-disaster scenarios, Jain and Bharti (2023) emphasized the critical importance of optimizing emergency response systems, highlighting the efficient allocation of resources and services. Formulating the emergency response as an optimization problem, they employed four metaheuristic algorithms: PSO, CS, GWO, and a variant of DE known as iLSHADE-RSP. Additionally, this research introduced a benchmark dataset of 16 situations to evaluate the performance of the proposed model. The optimization algorithms demonstrated their applicability through empirical analysis in locating near-optimal solutions for diverse emergencies. The algorithms are compared through convergence analysis and statistical tests, revealing iLSHADE-RSP as the most effective on average, with PSO requiring the least CPU time. This research also outlines future research directions, including a more in-depth exploration of pertinent factors, experimentation with real-world data, and enhancements to optimization algorithms to achieve better outcomes in combinatorial optimization problems.

#### 4.3.2. Patient scheduling

Metaheuristic algorithms are increasingly used in healthcare scheduling tasks, specifically in scheduling patient admissions, nurse assignments, and operating room schedules, aiming to optimize resource allocation and increase the proficiency of healthcare facilities (Abdalkareem et al., 2021). Addressing objectives, such as minimizing nurse numbers, completion times, operating costs, and maximizing resource utilization, SA, TS, GA, and ACO are versatile in operating room and surgery scheduling, while Non-dominated Ranking Genetic Algorithm and NSGA-II have been particularly effective in optimizing operating room scheduling considering complex factors like time constraints, equipment capacity, and fuzzy uncertainty (Maghzi et al., 2022; Rahimi & Gandomi, 2021). In response to real-life emergencies like the COVID-19 outbreak, metaheuristic algorithms optimize patient scheduling for HHC services, prioritizing care based on triage levels and min-

imizing patient service times (Akbari et al., 2023; Manavizadeh et al., 2020).

Addressing the optimization of HHC through staff routing and scheduling, Belhor et al. (2023) focused on determining the shortest paths for caregivers when visiting patients at home within a specified time horizon. They proposed a mixed-integer linear programming (MIP) model to minimize overall service time while ensuring adherence to workload balancing constraints. However, practical-sized instances become computationally challenging with large time horizons, prompting the introduction of a learning genetic algorithm (LGA) for multiple travelling salesman problem (mTSP) (LGA-mTSP). It combines a new GA with a learning approach, reflecting increased caregiver productivity with experience. The proposed MIP model is tested on instances generated from a single-depot mTSP benchmark. Results demonstrate the efficiency of LGA-mTSP, showcasing its runtime effectiveness and the reliability of learning curves in minimizing service times and reducing costs. Considering uncertainty in task time duration is recommended for their future work.

A study by Akbari et al. (2023) focused on scheduling and routing issues for various teams of healthcare service providers tasked with home visits to patients. Patients were grouped into teams to reduce the weighted waiting time depending on triage levels, and routes were designed. They suggested an integer programming model for small- to medium-sized cases. However, they proposed a metaheuristic approach for larger and more complex scenarios incorporating a specialized saving technique and the generalized variable neighborhood search (GVNS) algorithm. The research findings demonstrated that the metaheuristic method consistently yielded optimal solutions for all cases within seconds. In contrast, the integer programming model required an extensive 3-hour computational time to achieve optimal results, particularly for more minor instances.

Using a mixed integer programming model that considered nurse-patient assignments, nurse scheduling, and routing, Alkabaneh and Diabat (2023) addressed the problem of home care planning. While maximizing the compatibility between patients and nurses, the main objective was to reduce expenses associated with healthcare services and routing. An algorithm based on branch-and-price and a two-stage metaheuristic were both created. An arc-flow formulation for the HHC delivery issue was the foundation for the mathematical programming model initially used with certain binary decision variables susceptible to linear relaxation. The solution space was analyzed in the second step using a TS method to ensure feasibility despite perhaps going above the maximum workload for a nurse. The computational results showed that this multi-objective approach saved healthcare costs while improving nurse-patient compatibility. Future improvements may focus on reducing uncertainty linked to travel and visit times to strengthen the model's dependability.

The patient admission scheduling problem (PAS) was addressed by Bolaji et al. (2022), which involved assigning patients to limited resources like rooms, timeslots, and beds while adhering to specific constraints. This research explored the limitations of existing population-based algorithms in solving PAS and introduced the ABC algorithm as a potential solution. The ABC algorithm, motivated by the foraging behavior of bees, was adapted to the discrete nature of PAS. The proposed algorithm started with an initial feasible solution utilizing a room-oriented approach and then optimized these solutions using ABC with the help of embedded neighborhood structures. The ABC algorithm was chosen because it maintains an equilibrium between exploring and exploiting the search space, leading to near-optimal solutions. While

**Table 2:** Surveyed studies of metaheuristics-based approaches in clinical diagnosis.

Applications	Algorithm/method	Main task	Outcome	Remarks	References
Cancer diagnosis	PSO, DE, GA, CNN, and KNN	Skin lesion classification	Achieved an accuracy of 81.6% on the ISIC2017 dataset and an accuracy of 90.1% on the ISIC2018 dataset.	The study focused on optimizing network architecture using serial blocks without delving into more sophisticated convolutional building block designs, such as ResNet or DenseNet.	(Golnoori et al., 2023)
	CSOA, DFOA, PSO, wKNN, GNB, and LSVM	Classifying breast cancer severity	Obtained an 82.86% detection rate in the MIAS dataset, 81.37% in the Inbreast dataset, and 97.33% in the WDBC dataset.	Performance gains with feature vector values were limited, highlighting the need for future research to improve overall performance through preprocessing, hyperparameter tuning, and automatic tuning for metaheuristic algorithms.	(Sannasi Chakravarthy et al., 2023)
	SpaSA, CNN, and U-Net	Skin cancer detection, segmentation, and classification	U-Net model with DenseNet-201 as a backbone was the best-performing model for achieving 94.16% accuracy and 91.39% F1 score.	A significant drawback of this study was the high training time complexity, mainly caused by the delayed convergence of the boosting algorithms.	(Balaha & Hassan, 2023)
Drug discovery and design	GA, LSVM, RF, and Logistic Regression CBWOATV	Identifying LBCEs from protein sequence ATS drug classification	99.3% accuracy CBWOATV addressed the issue of stagnation and getting stuck in local minima in the WOA.	Set a new benchmark for LBCE classification. Exploring different strategies for implementing the Logistic-Tent chaotic map can be performed as future research directions.	(Angaitkar et al., 2023) (Mohd Yusof et al., 2022)
	HGSO and HHO	Tackling the issue of feature selection in high-dimensional data	The approach outperformed the existing methods by 2–3% in sensitivity and specificity.	This approach could be adapted into a multi-objective optimization strategy for real-world problems in different areas, such as color image segmentation, remote sensing applications, cloud computing task allocation, etc.	(Abd Elaziz & Yousofi, 2021)
Protein structure prediction	ACO and SVM ICSA	Protein tertiary structure prediction by PR-based technique Predicting protein structure	The proposed MACO-PR model outperformed Basic ACO. ICSA outperformed the CSA for all protein sequences in the experiment.	The proposed model could integrate deep learning techniques to enhance prediction accuracy and timeliness. In-depth analysis of longer sequences is a recommended step for future experimentation.	(Sekhar et al., 2023) (Alshamrani et al., 2023)
	Chemical Reaction Optimization	Predicting protein complexes within considerable PPI networks	Obtained 81.7% accuracy and an F-measure of 62.1% on the CYC2008 dataset.	Future research could involve further investigation into optimizing the model's operators to reduce reliance on repair operators.	(Shahidul Islam et al., 2022)

**Table 3:** Surveyed studies of metaheuristics-based approaches in medical imaging and processing.

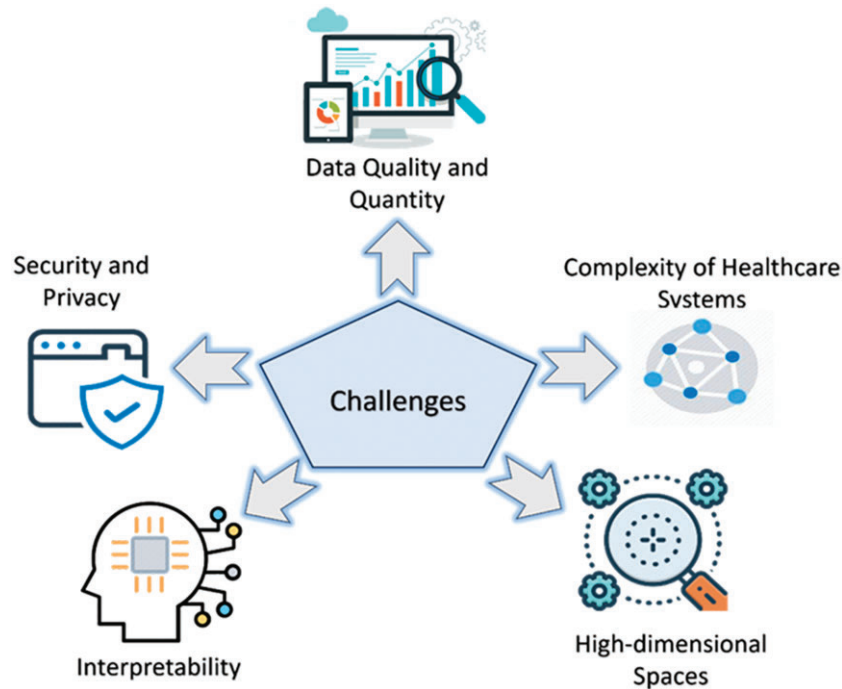
Applications	Algorithm/method	Main task	Outcome	Remarks	References
Medical image processing	RSA and SSA	Image segmentation	The ability to avoid getting stuck at local optima enabled the proposed technique to be proficient in finding optimal image solutions.	The technique could be evaluated for low resolution, excessive noise, or poor contrast images.	(Abualigah et al., 2023)
	RSA with RUN	Image segmentation (brain MRI images)	The performance of this method was exceptionally good in multi-level thresholding segmentation, where, out of 40 test instances, the technique excelled in 25 cases (comprising 63% of all instances).	Including “ESQ” and “SF” parameters led to a notable increase in computational cost.	(Emam et al., 2023)
	GWO with WNN	Detecting abnormalities in breast ultrasound images	Achieved a remarkable accuracy of 98%.	The method achieved significant robustness with a smaller number of training data.	(Ahila et al., 2022)
Biomedical signal processing	BOA, MRFO, and EPO	Enhancing signal processing and data transmission for arrhythmia detection from ECG signals	Demonstrated the effectiveness of this approach through significant compression gains (up to 46.29-fold) and high classification accuracies (up to 99.14%).	Further evaluating this approach on different datasets and exploring the integration of deep learning algorithms were potential future directions of this research.	(Mian Qaisar et al., 2023)
	ABC, PSO, GWO, and TQWT	Effectively compressing various ECG signals while maintaining reconstruction quality	The experiments conducted on the MIT-BIH arrhythmia dataset demonstrated significant compression improvements compared with existing techniques.	The results indicated that sparse PSO and hybrid methods offer minor deviations in fitness function minimization and notable improvements in time complexity, proving the effectiveness of these techniques in compressing ECG signals.	(Pal et al., 2022)
	PSO and GWO	Enhancing model performance by fine-tuning four critical hyperparameters: the number of neurons, epochs, learning rate, and batch size	Obtained 93% accuracy.	Increasing the training data, using data augmentation techniques, employing advanced signal preprocessing methods, selecting cost functions for metaheuristic algorithms, and exploring different neural network architectures could be explored for future work.	(Aviles et al., 2023)

**Table 4:** Surveyed studies of metaheuristics-based approaches in healthcare operations and management.

Applications	Algorithm/method	Main task	Outcome	Remarks	References
Healthcare resource allocation	Fast and elitism NSGA, NSPSO, and NSDE	Optimal resource allocation for the emergency department	NSGA outperformed NSPSO and NSDE, with an average staff utilization and service level of 0.751 and 0.844, respectively.	Integrating additional techniques, such as neural networks, into the resource allocation process is recommended for future research.	(Kuo et al., 2023)
	GA	Achieving sustainable inventory management of blood products	The proposed model outperformed the nominal model, effectively minimizing system costs, reducing environmental impact, and mitigating shortages and wastage.	Exploring different metaheuristic algorithms could be performed for future research.	(Sohrabi et al., 2023)
	DOA, SOA, and MOA	Solving resource management issues associated with hospitalizing critically sick patients, particularly in emergency settings like pandemics	The method demonstrated competitive results in an acceptable computation time.	This approach can offer promising solutions to many problems involving parameter uncertainties and multiple objectives in the future.	(Hernández-Pérez & Ponce-Ortega, 2021)
Patient scheduling	GVNS algorithm and integer programming model	Optimizing homecare service planning	Whereas the metaheuristic obtained optimum answers for all cases in seconds, the integer programming model took 3 hour to find optimal solutions for more minor instances.	The model was evaluated on COVID-19 patient cases in a district of Istanbul.	(Akbari et al., 2023)
	Branch-and-price algorithm, a two-stage metaheuristic method where stage-1 contains a mathematical model based on arc-flow formulation and stage-2 contains TS for solution space analysis. ABC	Reducing expenses associated with healthcare services and routing	The computational results showed that this multi-objective approach saved healthcare costs while improving nurse-patient compatibility.	Future improvements may focus on reducing uncertainty linked to travel and visit times to strengthen the model's dependability.	(Alkaabneh & Diabat, 2023)
	Addressing PAS		Demonstrated its superiority over other existing algorithms, including population-based, heuristic, hyperheuristic, and integer programming methods.	Enhancing the exploitation capabilities of this algorithm and integrating it with local search-based metaheuristics to further improve solution quality are suggested as potential research directions.	(Bolaji et al., 2022)

**Table 5:** Surveyed studies of metaheuristics-based approaches in public health and crisis response.

Applications	Algorithm/method	Main task	Outcome	Remarks	References
Disease outbreak response	WOA with agent-based models	Optimizing reopening strategies addressing the limitations of conventional macro models in understanding COVID-19 transmission	Proved the efficacy of the approach in exploring solution spaces and provided significant insights for developing reopening plans in complex scenarios related to disease outbreaks.	Incorporating social interactions among agents and adopting multi-objective approaches for more complex scenarios during disease outbreak response and management were recommended for further research.	(Cuevas et al., 2023)
	A heuristic method using relax-and-fix and fix-and-optimize techniques, and a metaheuristic method employing PESA-II with PSO-GA operators	Addressing vaccine distribution expenses, enhancing vaccination coverage with equity considerations, and minimizing vaccine shortage risk	Evaluated on randomly generated instances and an Iranian case study, demonstrating that the heuristic method excelled in Pareto front approximation, while the metaheuristic was faster for more significant problems.	Additional metaheuristic optimization algorithms should be explored in different pandemic scenarios, addressing uncertainties in pandemic parameters, strengthening the transportation system, and incorporating vehicle routing concepts into the model.	(Nikoubin et al., 2023)
	DTO, PSO, and VGG19 deep network	Analyzing lung regions in X-ray images for rapid and reliable automated diagnosis of coronavirus	Evaluated using a COVID-19 dataset to ensure its reliability and stability, demonstrating significant improvements in COVID-19 diagnosis and achieving over 99.88% accuracy	Assessing the approach on more complex datasets and developing a parallel version of the DTPSO model were recommended for future work.	(Samee et al., 2022)
Telemedicine and telehealth	Salp swarm intelligence	Generating robust session keys for securing the transmission of clinical signals within the TMIS	The proposed technique demonstrated its effectiveness in handling multiple session keys concurrently, thereby enhancing security against potential intruders.	The research focused on cardiac-related patient data and suggested improvements, such as real-time implementation, hardware security enhancements, and data compression techniques.	(Dey et al., 2023)
	DWT, WOA cost function, SVD, and ISVD methods	Protecting individuals' privacy by watermarking medical images	Despite facing various attack methods, the scheme achieved a 22% improvement in PSNR and a 17% improvement in normalized correlation.	Exploring a hybrid secure architecture for diverse DMI watermarking procedures and biomedical signals was recommended for further research.	(Rezaee et al., 2022)
	A modified version of AES with harmony search algorithm	Providing wireless online medical services to patients in remote locations while minimizing the risk of hospital-acquired infections	The approach guaranteed problem diversification and convergence, supported by consistent test results.	The length of the biometrically generated key affected the time required to decode the pattern, enabling the proposed approach to be highly resilient and robust against intrusion.	(Sarkar et al., 2021)



**Figure 5:** Challenges of metaheuristic algorithms in healthcare.

the proposed method was assessed, it demonstrated its superiority over other algorithms, including population-based, heuristic, hyperheuristic, and integer programming. Enhancing the exploitation capabilities of this algorithm and integrating it with local search-based metaheuristics to further improve solution quality were suggested as potential research directions.

#### 4.4. Public health and crisis response

##### 4.4.1. Disease outbreak response

Metaheuristic algorithms optimize parameter estimation under constraints, uncertainties, and without gradient information, contributing to effective disease outbreak response strategies. Recently, the Corona Virus Optimization method has been introduced to simulate the pandemic behavior of the coronavirus and efficiently solve optimization problems, potentially aiding in optimizing resource placement and scheduling during disease outbreaks (Salehan & Deldari, 2022). Search-based metaheuristic algorithms, namely, constrained multi-dimensional success history-based adaptive differential evolution enriched with whale optimization, learn the parameters of large-scale epidemiological models, aiding in building multi-dimensional predictive models for pandemics (Tutsoy, 2023). Moreover, the hyperparameters of pre-trained CNN models can be optimized using HHO to categorize patients into disease categories, such as usual, monkeypox, chickenpox, and measles, aiding early outbreak diagnosis and response (Almutairi, 2022). Additionally, metaheuristics optimize the allocation of vaccines, facilitating the generation of near-optimal solutions for vaccine distribution and ensuring timely and efficient vaccine delivery to vulnerable populations (Hirbod et al., 2023).

Highlighting the limitations of conventional macro models in understanding COVID-19 transmission and emphasizing the advantages of agent-based modeling, Cuevas et al. (2023) introduced a technique to optimize reopening strategies. Considering factors such as asymptomatic or vaccinated individuals and exter-

nal contagion, the proposed approach integrated the WOA with agent-based models to automate simulations and efficiently identify optimal conditions for reopening strategies. The WOA facilitates a systematic search for the best solutions, enabling safe reopening policies with minimal transmission risk. Two general reopening policies were addressed in this research: determining the maximum safe occupancy of a facility and identifying the minimum number of vaccinated individuals needed to reduce outbreak risks. Experimental results demonstrated the efficacy of the WOA algorithm in exploring solution spaces and provided significant insights for developing reopening plans in complex scenarios related to disease outbreaks. Lastly, the authors suggested promising research directions, including incorporating social interactions among agents and adopting multi-objective approaches for more complicated scenarios during disease outbreak response and management.

During pandemics, a bi-objective mixed-integer linear model was proposed by Nikoubin et al. (2023) for vaccine distribution, aiming to balance economic and social objectives. The research addressed vaccine distribution expenses, enhanced vaccination coverage with equity considerations, and minimized vaccine shortage risk through a mix-and-match vaccination approach. The proposed model also accommodated multi-dose vaccine administration, common for COVID-19 vaccines. A heuristic and a metaheuristic algorithm were developed to tackle this complex problem efficiently. Both methods decomposed the primary concern, with the heuristic method using relax-and-fix and fix-and-optimize techniques, whereas the metaheuristic employed pareto envelope-based selection algorithm II (PESA-II) along with PSO-GA operators. Performance evaluation on randomly generated instances and an Iranian case study demonstrated that the heuristic method excelled in Pareto front approximation, while the metaheuristic was faster for more significant problems. Additional metaheuristic optimization algorithms should be explored in different pandemic scenarios, addressing uncertainties in pandemic parameters, strengthening the

**Table 6:** Identified challenges and openings for metaheuristic algorithms in medicine and healthcare.

Topic	Challenges	Openings	References
Data quality and quantity	Data quality is adversely affected by missing values, which can compromise the reliability of conclusions drawn from these algorithms.	Metaheuristic algorithms can address this challenge by optimizing imputation processes.	(Rahul & Banyal, 2022)
	Healthcare applications, especially for clinical decision support systems, telemedicine, personalized medicine, and preventive services, rely heavily on high-quality and abundant data to provide accurate and precise outcomes. Therefore, inconsistent and limited data pose difficulties to effective decision-making. Challenges also persist in handling data quality issues such as missing data, data redundancy, data heterogeneity, semantic data integration, as well as managing noisy data and outliers.	By effectively handling large datasets and eliminating noise and inconsistencies, metaheuristic algorithms offer innovative solutions to healthcare data quality and quantity challenges.	(Bashabsheh <i>et al.</i> , 2022; Santhalakshmi & Kavitha, 2022; Singh & Kumar, 2023)
Complexity of healthcare systems	Amidst the complexity resulting from the increasing patient population and rising demand for hospital services, the intricate and heterogeneous nature of medical data further complicates the task of finding optimal scheduling solutions. The growing need for HHC services also poses complexity, especially for the elderly, where patients can order multiple interdependent services with various time windows.	Metaheuristic algorithms can be applied to optimize data cleansing processes, handle missing data, eliminate duplicate entries, and manage noisy data and outliers effectively.	(Rahul & Banyal, 2022)
	Emerging algorithms, such as the adaptive extension of SEO, reveal more complexity for patients' allocation and caregivers' routing and scheduling studies. However, it considers patients' satisfaction under uncertainty very well.	Metaheuristic algorithms efficiently navigate the search space by measuring data complexity and strategically optimizing the feature space, leading to faster and more effective solutions in different tasks.	(Arun Kumar <i>et al.</i> , 2022; Houssein <i>et al.</i> , 2023; Khan <i>et al.</i> , 2021)
High-dimensional spaces	Generally, class imbalance is a common issue in high-dimensional medical datasets, where there is a significant difference in the number of samples between two classes, leading most metaheuristic optimization algorithms to prioritize the majority class and disregard the minority class.	Considering workload balance, arriving on time, and patient preferences, metaheuristic algorithms offer effective solutions by simultaneously addressing multiple aspects of the HHC services, such as staff travel optimization, nurse-patient assignments, workday scheduling, and routing.	(Alkaabneh & Diabat, 2023; Belhor <i>et al.</i> , 2023; Manavizadeh <i>et al.</i> , 2020)
	Also, the curse of dimensionality leads to several issues, such as insufficient training and redundant data.	Besides mitigating data complexity by optimizing feature selection and significantly reducing computational time, the parallel implementations of evolutionary algorithms can minimize data complexity and improve response time.	(Fathollahi-Fard <i>et al.</i> , 2020; Sharma & Kumar, 2022)
Interpretability	The high dimensionality of healthcare data, mainly gathered from various sources, can substantially slow down computational processes, resulting in increased memory consumption, model overfitting, and longer computing times.	Metaheuristic optimization algorithms can handle class imbalance in high-dimensional medical datasets by implementing oversampling, undersampling, or hybrid approaches to ensure balanced class representation and improve classification accuracy.	(Arun Kumar <i>et al.</i> , 2022)
	While these algorithms excel at optimizing feature selection and model performance, their outcomes can often be intricate and difficult for healthcare professionals to interpret.	Recent research has shown that integrating hybrid feature selection techniques and metaheuristic optimization methods identifies the optimal feature sets and contributes to dealing with the complexity of high-dimensionality spaces in healthcare.	(Arun Kumar <i>et al.</i> , 2022)
Interpretability	The lack of interpretability raises issues about the trustworthiness of algorithmic recommendations, regulatory compliance, and the potential for unintended biases in clinical decision-making.	Metaheuristic algorithms possess the potential to effectively identify and select the most relevant features, reducing dimensionality and improving the performance of computational processes in healthcare applications.	(O. A. Akinola <i>et al.</i> , 2022; Anand, 2021; Gupta <i>et al.</i> , 2022; Selvam <i>et al.</i> , 2022)
		Emerging research has shown that these approaches, when integrated with techniques like data augmentation and transfer learning, can substantially enhance the accuracy and comprehensibility of models used in healthcare.	(Bajaj <i>et al.</i> , 2023)
		By carefully selecting and optimizing relevant features, metaheuristic algorithms offer immense promise for enhancing the transparency and interpretability of the models that facilitate trustworthiness, regulatory compliance, and reduced bias in clinical decision-making.	(Houssein <i>et al.</i> , 2023)

Table 6: Continued

Topic	Challenges	Openings	References
Security and privacy	Integrating metaheuristics with deep learning methods, such as LSTM, DMLP, and CNN results in interpretability challenges due to the complex, black-box nature of these algorithms.	Exploring the hybrid approaches that merge the optimization power of metaheuristics with the transparency of interpretable ML models can enrich the efficiency and reliability of healthcare systems.	(Bajaj et al., 2023; Nssibi et al., 2023)
	As the IoT-based healthcare system expands, it becomes increasingly critical to safeguard sensitive healthcare data during transmission. Data transfer introduces several security vulnerabilities, including data tampering, wiretapping, and replay attacks, which can pose severe threats to security.	Metaheuristic algorithms offer promising solutions to address these challenges by optimizing data encryption, access control mechanisms, and data integrity checks. Through incorporation into cryptographic engineering, these algorithms can contribute to dynamic key generation, robust encryption, and improved non-distortion ability, making it harder for intruders to compromise sensitive medical data and ensuring resilience against unauthorized access or manipulation.	(Dey et al., 2023; Saif et al., 2022; Sharma & Tripathi, 2022)
	Another critical area of concern is data aggregation, which prioritizes factors such as authenticity, data integrity, and confidentiality during data acquisition and transfer to minimize network energy consumption and achieve optimal outcomes.	Metaheuristic algorithms can assist in handling data aggregation by optimizing the aggregation process while ensuring patient trust, mitigating data breaches, and upholding the integrity of medical data, leading to enhanced patient care and outcomes in the digital healthcare era.	(Bharti et al., 2023; Singh & Kumar, 2023)

Table 7: Future of metaheuristic algorithm and the opportunities in the medicine and healthcare sector.

Topic	Future opportunities	Future direction
Personalized treatment plans	<ul style="list-style-type: none"> <li>– Developing personalized medicine</li> <li>– Optimizing better treatment plans based on patient profile</li> <li>– Enabling early intervention</li> </ul>	Future efforts to combat various diseases will benefit from patient-specific care plans and individualized treatment strategies by developing more accurate metaheuristic algorithms.
Drug discovery	<ul style="list-style-type: none"> <li>– Identifying potential drug candidates</li> <li>– Unveiling new therapeutic applications for available drugs</li> <li>– Discovering treatments for rare diseases</li> <li>– Finding out the bioactive compounds from plants and microorganisms to develop medicine</li> </ul>	Further research will help in molecular docking in the advanced drug-designing process.
Remote monitoring	<ul style="list-style-type: none"> <li>– Optimizing patient schedule</li> <li>– Ensuring timely access to telemedicine</li> <li>– Real-time ubiquitous communication between the patient and the healthcare personnel</li> </ul>	Increased usage of health monitoring devices by legal authorities will aid in the reduction of health complications, and the ability to use real-time data will ensure accuracy.
Clinical trial design	<ul style="list-style-type: none"> <li>– Designing effective clinical trials</li> <li>– Optimizing the allocation of resources</li> </ul>	Designing adequate clinical trials will help achieve successful outcomes.
Genomic data analysis	<ul style="list-style-type: none"> <li>– Identifying genetic markers associated with diseases</li> <li>– Analyzing genomic data to track disease outbreaks</li> </ul>	Developing medicine based on personalized genetic profiles will be beneficial in helping patients recovering from genetic diseases.
Healthcare logistics	<ul style="list-style-type: none"> <li>– Identifying disease transmission patterns</li> <li>– Optimizing the distribution of pharmaceuticals</li> <li>– Minimizing waste generated in the healthcare sector</li> </ul>	More advanced metaheuristic algorithms would be able to determine when medical equipment needs maintenance, which can minimize downtime and guarantee the availability of vital resources.

transportation system, and incorporating vehicle routing concepts into the model.

For the rapid and reliable automated diagnosis of coronavirus by utilizing chest X-ray images an approach was introduced by Samee et al. (2022). Their proposed approach used a hybrid dipper-throated optimizer (DTO) and PSO algorithm (i.e., DTPSO)

to analyze lung regions in X-ray images. These images were augmented using various transformations and then processed through a visual geometry group 19 (VGG19) deep network for feature extraction. The chosen features were employed in a neural network to identify COVID cases, with optimization carried out through the suggested hybrid optimizer to enhance performance.

The hybrid optimizer employed DTO to explore search spaces effectively over extended iterations, maintaining a balance between exploration and exploitation, as well as enhancing population diversity and production efficiency. The proposed approach was rigorously evaluated using a COVID-19 dataset to ensure its reliability and stability, demonstrating significant improvements in COVID-19 diagnosis and achieving over 99.88% accuracy. Assessing the approach on more complex datasets and developing a parallel version of the DTPSO model were recommended for future work.

#### 4.4.2. Telemedicine and telehealth

Metaheuristic algorithms are used in telemedicine and telehealth to enhance the security and efficiency of various processes, such as data encryption, disease diagnosis, and secure communication. Such as the Multi-Objective Water Wave Optimization algorithm improves cluster-based healthcare monitoring with wearables in telemedicine by optimizing the clustering process and fine-tuning SVM parameters for enhanced disease diagnosis (Dhanasekaran *et al.*, 2021). On the other hand, the harmony search algorithm strengthens the advanced encryption standards (AES) to ensure patient data privacy in wireless medical communication systems (Sarkar *et al.*, 2021). Simultaneously, WOA increases privacy by optimizing watermark embedding coefficients for medical images in telehealth and Internet of Things (IoT) applications (Rezaee *et al.*, 2022). Moreover, the SSA plays a crucial role in encrypting ECG within telecare medical information system (TMIS), addressing security concerns in digitally connected healthcare environments, particularly during the post COVID-19 era (Dey *et al.*, 2023).

In response to the challenges posed by the COVID-19 pandemic, Dey *et al.* (2023) proposed a method that utilizes metaheuristics to generate robust session keys for securing the transmission of clinical signals within the TMIS. The goal of this research was to ensure the security and privacy of the clinical data of patients, allowing them to communicate with healthcare providers for diagnosis and follow-ups. The proposed scheme utilized metaheuristic salp swarm intelligence to secure the privacy of ECG through encryption techniques within the TMIS. The session key was derived from the weight vector of the fastest moving salp, leveraging a blend of exploration and exploitation strategies to control their movements. In addition, the proposed framework demonstrated its efficacy in handling multiple session keys parallelly, thereby enhancing security against potential intruders. However, the research was primarily focused on cardiac-related patient data and suggested further improvements, including real-time implementation, hardware security advancements, and data compression techniques to optimize network traffic.

Integrating IoT principles and optimization approaches, Rezaee *et al.* (2022) presented a hybrid image watermarking scheme for telemedicine. The primary objective of this study was to protect individuals' privacy by watermarking medical images. This study employed the discrete wavelet transform (DWT) to estimate coefficients and integrate singular values. Optimal embedding coefficients were obtained using the cost function of the WOA. The watermarking was achieved through singular value decomposition (SVD) and inverse SVD (ISVD) methods. Despite facing various attack methods, the proposed scheme achieved a 22% improvement in PSNR and a 17% improvement in normalized correlation, ensuring high-quality results and privacy preservation while demanding less computational processing time. Therefore, the proposed watermarking scheme proved efficient and robust for medical images in healthcare applications and digital medical imaging (DMI) services, even under severe attacks. Exploring a hybrid secure ar-

chitecture for diverse DMI watermarking procedures and biomedical signals was recommended for further research.

Telecare medical communication systems (TMCS) are crucial in modern healthcare, providing wireless online medical services to patients in remote locations while minimizing the risk of hospital-acquired infections. However, maintaining data security and patient privacy during wireless communication is challenging. To address this challenge, Sarkar *et al.* (2021) proposed an enhanced security approach for TMCS by involving a modified version of AES based on biometrically generated keys from patients' fingerprints. The AES S-boxes were strengthened using a musical harmony search algorithm, and clinical ECG signals were incorporated to improve the security of TMCS. The approach guaranteed problem diversification and convergence, supported by consistent test results. Additionally, the biometrically generated key length affected the time required to decode the pattern, enabling the recommended approach to be highly resilient and robust against intrusion. Ultimately, this secure transmission method was well-suited for telemedicine systems.

Tables 2–5 present a comprehensive compilation of surveyed studies that have explored utilizing metaheuristic algorithms across different areas of the healthcare industry.

## 5. Challenges and openings

While metaheuristic algorithms have proved their promising capabilities in optimizing complex healthcare processes and aiding in clinical decision-making, they also pose consequential challenges related to data quality and quantity, high-dimensional spaces, interpretability, and ethical considerations. Figure 5 visually represents the challenges that metaheuristic algorithms face in medicine and healthcare. Despite these challenges, metaheuristic algorithms promise to optimize treatment planning, drug discovery, and patient care, leading to better healthcare delivery, personalized medicine, and breakthroughs in medical research.

### 5.1. Case studies

In response to the challenges posed by the COVID-19 pandemic, establishing an efficient and effective vaccine supply chain (VSC) has become a crucial aspect of healthcare networks. This endeavor is particularly challenging in developing countries like Bangladesh due to the unique complexities associated with vaccine distribution, including a high volume of orders, intricate networks, and the need for a multi-echelon supply chain. These challenges hinder the timely and effective vaccination of the population, necessitating innovative solutions. To address this, Chowdhury *et al.* (2022) explored the utilization of metaheuristic algorithms, specifically MOSEO and Multi-Objective Feasibility Enhanced Particle Swarm Optimization, to optimize the multi-objective VSC planning problem. These algorithms are chosen for their demonstrated effectiveness in handling complex optimization tasks and large numbers of variables. The application of metaheuristic approaches provides a promising avenue to enhance the efficiency, economic sustainability, and environmental and social considerations in the COVID-19 vaccine distribution process in Bangladesh.

In HHC, managing human resources efficiently poses a significant challenge due to varied nurse-to-patient skill levels, uncertain service times, and numerous candidate locations for health facilities. This challenge is generally tackled using metaheuristics or optimization algorithms. A case study conducted in Sanandaj,

Iran, by Shiri *et al.* (2021) emphasizes the importance of effective nurse scheduling and facility selection. Their study introduced a novel approach, namely the Three-Phase Multi-objective Robust Home Healthcare Routing and Scheduling Problem, incorporating the Fuzzy Analytic Hierarchy Process-Gray Relational Analysis method. This method provides an innovative way to rank potential healthcare facility locations. The multi-objective robust model minimizes network costs, reduces overqualified skill levels, and maximizes qualitative factors. They also introduced the Nimbus method for interactive multi-objective functions, showcasing the robustness of solutions in uncertain environments.

## 5.2. Data quality and quantity

### 5.2.1. Challenges

In medicine and healthcare, data quality and quantity present significant challenges for the effective implementation of metaheuristic algorithms. Data quality is adversely affected by missing values, which can compromise the reliability of conclusions drawn from these algorithms. Moreover, data cleaning and data analysis are essential preprocessing steps in healthcare applications, especially for clinical decision support systems, personalized medicine, preventive healthcare services, and telemedicine, where these applications rely heavily on high-quality and abundant data to provide accurate and precise outcomes (Rahul & Banyal, 2022). Therefore, inconsistent and limited data pose difficulties to effective decision-making (Bashabsheh *et al.*, 2022). However, challenges also persist in handling data quality issues such as missing data, data redundancy, data heterogeneity, semantic data integration, as well as managing noisy data and outliers. As healthcare datasets, including those related to diabetes, cancer, and heart disease, frequently contain missing and noisy data, addressing these challenges is a prerequisite to harnessing the full potential of metaheuristic algorithms for improved healthcare decision-making and patient care (Rahul & Banyal, 2022).

### 5.2.2. Openings

Metaheuristic algorithms, including GA, PSO, and SA, can address data quality issues effectively. These algorithms have high potential in healthcare data cleaning processes, where they can effectively handle large datasets and eliminate noise and inconsistencies. By incorporating metaheuristic algorithms at various stages, including operational sources, data transformation, and data warehousing, healthcare organizations can optimize data quality, ultimately supporting the development of advanced healthcare applications like clinical decision support systems, personalized medicine, preventive healthcare services, and telemedicine (Rahul & Banyal, 2022). Moreover, metaheuristic algorithms, such as Archimedes optimization algorithm and butterfly optimization with adaptive threshold-sensitive energy-efficient routing protocol, offer innovative solutions to tackle data quality and quantity challenges in healthcare, particularly in IoT-based medical data transmission (Santhalakshmi & Kavitha, 2022; Singh & Kumar, 2023). Metaheuristic algorithms are essential for optimizing the allocation of resources, scheduling, and adapting models to the changing healthcare data. They ensure that challenges in healthcare become opportunities for ongoing improvement and innovation in delivering healthcare and improving patient outcomes.

## 5.3 Complexity of healthcare systems

### 5.3.1. Challenges

The key challenge in healthcare cost-efficiency lies in providing services, including clinical trials and medicine updates, while managing the growing patient population and increasing demand for emergency services in hospitals. This surge in demand can lead to delays and complexities in scheduling and optimizing service delivery. In addition, the intricate and heterogeneous nature of medical data further complicates finding optimal scheduling solutions (Houssein *et al.*, 2023; Khan *et al.*, 2021). The growing need for HHC services also poses complexity, especially for the elderly, where patients can order multiple interdependent services with various time windows. Furthermore, emerging algorithms, such as the adaptive extension of social engineering optimizer (SEO), reveal more complexity for allocating patients, routing, and scheduling caregivers. However, the algorithm considers patient satisfaction under uncertainty very well (Fathollahi-Fard *et al.*, 2020). Effectively addressing these complex routing and scheduling problems necessitates using sophisticated metaheuristic algorithms to provide reasonable solutions (Manavizadeh *et al.*, 2020).

### 5.3.2. Openings

Metaheuristic algorithms, including evolutionary algorithms, can address data complexity challenges by optimizing the feature selection process. By measuring data complexity and strategically reducing the feature space, these algorithms efficiently navigate the search space, leading to faster and more effective solutions in different tasks, such as classification (Arun Kumar *et al.*, 2022). For instance, GA optimizers effectively mitigate data complexity by optimizing feature selection, which significantly reduces the computational burden and response times, leading to faster and more efficient predictions. The parallel implementations of GA can further enhance data complexity reduction and response time improvements (Sharma & Kumar, 2022). Considering workload balance, arriving on time, and patient preferences, metaheuristic algorithms offer effective solutions by simultaneously addressing multiple aspects of the HHC services, such as staff travel optimization, nurse-patient assignments, workday scheduling, and routing. These algorithms optimize healthcare-related services and routing costs while enhancing compatibility between patients and nurses, ultimately maximizing patient satisfaction in the face of uncertainties related to care processes (Alkaabneh & Diabat, 2023; Belhor *et al.*, 2023). Metaheuristic algorithms facilitate the adaptation of healthcare models to accommodate the ever-changing and dynamic nature of patient needs and system requirements. Utilizing metaheuristic algorithms offers a means to effectively navigate and take advantage of the complexities of healthcare systems, promoting innovation and ongoing improvement in healthcare delivery.

## 5.4. High-dimensional spaces

### 5.4.1. Challenges

High-dimensional spaces in healthcare data present significant challenges for metaheuristic algorithms, such as increased computational complexity, risk of overfitting, etc. In such cases, effective exploration of complex, high-dimensional medical data becomes necessary for insightful data analysis and informed decision-making. In general, a class imbalance is a common issue in high-dimensional medical datasets, where there is a significant difference in the number of samples between two classes, leading most of the metaheuristic optimization algorithms to prioritize the majority class and disregard the minority

class. In addition, the curse of dimensionality leads to several issues, such as insufficient training samples and redundant data (Arun Kumar et al., 2022). Moreover, the high dimensionality of healthcare data, mainly gathered from various sources, can substantially slow down computational processes (Gupta et al., 2022). Consequently, this situation results in increased memory consumption, model overfitting, and longer computing times, necessitating optimizing features for improved algorithm performance in healthcare applications (Anand, 2021).

#### 5.4.2. Openings

In healthcare, dealing with high-dimensionality spaces can be effectively addressed through feature selection techniques, which reduce feature set size, enhance accuracy, and decrease computation time and memory requirements. Recent research has shown the integration of hybrid feature selection techniques and metaheuristic optimization methods, which not only identifies optimal feature sets to improve disease prediction accuracy but also contribute to the ongoing improvement of early disease detection and prevention strategies, overall effectively handling the complexities of high-dimensionality spaces in healthcare (Arun Kumar et al., 2022). In addition, metaheuristic algorithms, such as Chaotic Spider Monkey Optimization, Binary Dwarf Mongoose Optimization, GA, and PSO, effectively identify and select the most relevant features, reducing dimensionality and increasing the ML model's performance in biomedical and medical applications (O. A. Akinola et al., 2022; Selvam et al., 2022). By harnessing the potential of metaheuristic optimization algorithms, healthcare professionals can make more informed decisions and extract valuable insights from complex, high-dimensional data, ultimately enhancing patient care and medical research. For instance, metaheuristic algorithms strengthen the efficiency of healthcare analytics and facilitate innovation in personalized medicine by enabling optimized models to identify crucial factors that impact patient outcomes. Utilizing metaheuristic algorithms in high-dimensional spaces is a driving force for the progress of precision healthcare. This allows customized interventions and treatments to be developed by better comprehending crucial variables within intricate datasets.

### 5.5. Interpretability

#### 5.5.1. Challenges

Interpretability challenges of metaheuristic algorithms in medicine and healthcare arise from their inherent complexity. While these algorithms excel at optimizing feature selection and improving model performance, their outcomes can often be intricate and complex for healthcare professionals to interpret. The lack of interpretability raises concerns about the reliability of algorithmic recommendations, compliance with regulations, and the possibilities for unintended biases in healthcare decision-making (Houssein et al., 2023). Moreover, interpreting metaheuristics becomes more challenging when incorporated into deep learning algorithms, such as long short term memory (LSTM), deep multi-layer perceptron (DMLP), and CNNs due to their complex, black-box nature (Bajaj et al., 2023). In such cases, interpretable ML methods, such as decision trees and SVM, should be explored more extensively (Nssibi et al., 2023). Therefore, addressing these challenges is essential to ensure that metaheuristic algorithms can be effectively integrated into healthcare systems, supporting improved patient care while maintaining transparency and accountability.

#### 5.5.2. Openings

In medicine and healthcare, ensuring interpretability is critical due to the complexities of high-dimensional data and the need for comprehensible models. Integrating different feature selection techniques with metaheuristic algorithms can mitigate such difficulties. Emerging research has shown that these approaches, when integrated with techniques like data augmentation and transfer learning, can substantially enhance the accuracy and comprehensibility of models used in healthcare. By carefully selecting and optimizing relevant features, metaheuristic algorithms offer immense promise for enhancing the transparency and performance of healthcare models, a fundamental aspect considering the often complex nature of healthcare data. Moreover, metaheuristic algorithms can also assist in improving the interpretability and readability of machine-learning models by optimizing feature subsets (Nssibi et al., 2023). For instance, to optimize the structure and parameters of ML models, such as GA or SA, the models become precise and interpretable. Exploring the hybrid approaches that integrate the predictive capabilities of interpretable machine learning models with the optimization capabilities of metaheuristics may enhance the dependability and transparency of healthcare systems, which is crucial for trustworthy decision-making in healthcare applications (Bajaj et al., 2023).

The algorithms facilitate the identification of the most pertinent features and relationships within healthcare datasets by guiding the model-building process. This feature improves the clarity of predictive models and creates opportunities for novel approaches in clinical decision support systems. Enhanced interpretability facilitates the confidence and comprehension of healthcare practitioners in the results produced by these models, thereby encouraging an effective relationship between artificial intelligence and human proficiency. Consequently, implementing metaheuristic algorithms in the healthcare sector not only resolves the issue of interpretability but also provides a foundation for reliable and noticeable advances in decision-making.

### 5.6. Privacy and security

#### 5.6.1. Challenges

In medicine and healthcare, adopting metaheuristic algorithms introduces innovative solutions while concurrently unveiling several challenges, particularly concerning data privacy and security. As the IoT-driven healthcare ecosystem expands, it becomes increasingly critical to safeguard sensitive healthcare data during transmission. The process of data transfer itself introduces several security vulnerabilities, including data tampering, wiretapping, and replay attacks, which can pose serious security threats (Sharma & Tripathi, 2022). Although several optimization techniques have been developed to address these challenges, it is necessary to prioritize factors like data integrity, authenticity, and confidentiality during data acquisition and transfer to achieve optimal outcomes. Data aggregation is another critical area of concern, a fundamental technique to minimize network energy consumption (Singh & Kumar, 2023). The convergence of metaheuristic algorithms and robust security measures becomes crucial as the healthcare industry increasingly relies on data-driven decisions to protect patient data and enhance trust in healthcare systems (Rostami et al., 2023).

#### 5.6.2. Openings

In the rapidly evolving landscape of healthcare technology driven by Industry 4.0, ensuring the privacy and security of patient data has become a significant concern. Metaheuristic algorithms, such

as GA, PSO, DE, and salp swarm-based intelligence, offer promising solutions to address these challenges by optimizing data encryption, access control mechanisms, and data integrity checks (Saif et al., 2022). Through incorporation into cryptographic engineering, these algorithms can contribute to dynamic key generation, robust encryption, and improved non-distortion ability, making it harder for intruders to compromise sensitive medical data and ensuring resilience against unauthorized access or manipulation (Dey et al., 2023). Additionally, metaheuristic algorithms, such as the Hybrid Teaching and Learning Based Optimization, can be used to select the optimal number of users and secure cloud servers in the Internet of Healthcare Things. By utilizing metaheuristic techniques like ACO or differential privacy, algorithms such as homomorphic encryption or differential privacy can maximize the balance between data utility and privacy protection. Through the innovative enhancement of healthcare data security protocols, these algorithms advance reliable models that protect privacy. Adherence to data protection regulations is not only assured, but it also produces trust among healthcare stakeholders and patients. Consequently, utilizing metaheuristic algorithms enables the development of inventive approaches that balance data-driven advancements in healthcare with the urgency of protecting patient confidentiality and security. Optimization techniques in healthcare systems can enhance patient trust, mitigate data breaches, and uphold the integrity of medical data, leading to improved patient care and outcomes in the digital healthcare era (Bharti et al., 2023).

The challenges identified in the present review and the current opportunities for applying metaheuristic algorithms in medicine and healthcare are outlined in Table 6.

## 6. Future directions

Implementing various optimization algorithms to address current challenges in medicine and healthcare, together with technological advances, has significantly assisted these fields. According to academics in computer science, metaheuristic algorithm consists of two primary components: exploitation and exploration (Mohammed et al., 2019). Exploitation is the algorithm's approach that concentrates on stepping up the search around the most popular options. It incorporates a search technique that emphasizes going far beyond the boundaries of the currently examined area. By investigating the nearness of the current solutions in the search space, it seeks to improve and refine the existing solutions. Exploiting the prospective areas of the search space can help find the best or high-quality solution. Reduced degrees of exploration increases the likelihood that an algorithm will become trapped in local solutions. On the other hand, less exploitation often results in the creation of subpar approximations (Tilahun, 2019). In data analysis, the data's quality is important for generating better results and providing help with metrics like accuracy, precision, recall, sensitivity, and so on (Priestley et al., 2023). Therefore, careful exploitation and considerable exploration must be employed in the healthcare industry to produce the most efficient solutions.

According to scientific predictions, the metaheuristic algorithm will remain the preferred and respected solution in medicine and healthcare. The assumption is based on its proven track record of effective field implementation. These are frequently used to automate administrative processes within healthcare organizations in the modern era of advanced technology to more effectively model and treat infectious diseases (Kaur et al., 2023). Despite the significant amount of existing research and the wide variety of metaheuristic algorithms developed to address specific difficul-

ties within these fields, medicine, and healthcare still have many unrealized prospects for further research and development. Table 7 summarizes the future opportunities and direction of this optimization process in the medicine and healthcare sector.

## 7. Conclusions

Metaheuristic algorithms contribute to improving our health and the efficacy and effectiveness of the medicine and healthcare industry. This is one of the many areas where artificial intelligence is becoming increasingly widely practiced, and metaheuristic algorithms play a crucial role in solving healthcare-related problems as a component of artificial intelligence. This study investigated the use of metaheuristic algorithms in various sectors of medicine and healthcare to provide a deeper understanding of how these algorithms are developed to advance the medical and healthcare industries. In addition, the emphasis was placed on the most recent research utilizing metaheuristic algorithms and enhancements to generate better optimal solutions for healthcare and medicine. The effectiveness of metaheuristic algorithms depends on a precisely defined algorithmic solution, highlighting the need to determine whether a particular answer is suitable for optimization. These algorithms can substantially enhance clinical decision-making, healthcare workflow, and resource allocation. However, the complexity of algorithms, interpretability, and ethical concerns regarding data privacy remain obstacles. The need for improved interpretability, algorithmic hybridization, real-world validation, adaptability, and a broader understanding of ethical implications are all highlighted in this article as areas requiring additional research. Investigating these possibilities and incorporating metaheuristic algorithms with emerging technologies can enhance health outcomes and service quality.

## Data availability

No data were used to support this study.

## Conflict of interest statement

The authors have disclosed no conflict of interest that would be perceived as having influenced the work presented in this paper, either financially or otherwise.

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