International Journal of Computers and Informatics

Journal Homepage: https://www.ijci.zu.edu.eg

Int. j. Comp. Info. Vol. 4 (2024) 85–99

Paper Type: Review Article

Advances in the Integration of Neutrosophic Sets with Metaheuristic Algorithms

Doaa El-Shahat [1,*] **and Nourhan Talal** [1]

[1] Faculty of computers and informatics, Zagazig University, Zagazig, Sharqiyah, 44519, Egypt.
Emails: doaazidan@zu.edu.eg; N.Talal22@fci.zu.edu.eg

Received: 07 Jul 2024 **Revised**: 10 Sep 2024 **Accepted**: 24 Sep 2024 **Published**: 26 Sep 2024

Abstract

With the ongoing evolution and complexities of our contemporary world, the Neutrosophic Set (NS) was introduced to effectively cope with ambiguous and uncertain situations. It is a form of neutrosophy theory that explores the nature and scope of neutrality, as well as its interactions with other ideational spectra. Hence, it provides a powerful and broad foundation for numerous fields. Also, metaheuristic algorithms have emerged and proven their effectiveness in solving many optimization problems. Thus, incorporating NS with metaheuristic algorithms is a long-lasting method for resolving complicated optimization problems when there is ambiguous and insufficient data. The purpose of this survey is tripartite. Firstly, it starts with a review of the neutrosophic concepts. The survey's second section deals with metaheuristic algorithms. Finally, the most important part of the survey considers the integration between neutrosophic and metaheuristic algorithms. They are used in several fields, such as image segmentation, job shop scheduling, image clustering, and image classification. This research focuses on various ways of image processing that entail optimizing and processing images using neutrosophic sets and metaheuristics.

Keywords: Neutrosophic Set; Classical Set; Fuzzy Set; Intuitionistic Fuzzy Set; Metaheuristic Algorithms; Classification; Segmentation.

1 | Introduction

Fuzzy sets have emerged to deal with ambiguous situations that may arise in various applications [1-3], that classical sets could not deal with. Unfortunately, they failed to handle the indeterminate and inconsistent information that is typically encountered in reality [4, 5]. To overcome this limitation, neutrosophy was first presented by Smarandache [6, 7] as a part of philosophy to investigate the nature and scope of neutrality. NS is considered a generalization of the fuzzy set and the fuzzy intuitionistic fuzzy set by additionally expressing the indeterminacy of information. Hence, the neutrosophic logic can express each proposition with a truth membership (T), indeterminacy membership (I), and falsity membership (F).

Fuzzy logic can interpret inaccurate input with various numerical degrees of membership (ranging from 0 to 1), unlike classical binary logic. Fuzzy logic can handle hazy and partial data, but it cannot grasp ambiguous and contradictory information commonly found in belief systems. Fuzzy logic generates membership functions that specify a class's degree of membership value. Fuzzy logic, on the other hand, does not capture indeterminacy due to the non-availability of information or falsity due to equipment degradation [8].

Corresponding Author: doaazidan@zu.edu.eg

Neutrosophy provides Neutrosophic logic, which addresses ambiguity, imprecision, inconsistency, and redundancy in data.

Neutrosophic concepts have come to handle the ambiguous, uncertain, or inconsistent information that frequently appears in various applications, such as supplier selection problems [9, 10], medical diagnosis [11], image segmentation [12, 13], signal transmission [14], forecasting [15], and sentiment analysis [16]. Figure 1 displays some of the most common applications that employ NS. In recent years, a neutrosophic set has become a general, well-known, and all-encompassing method. Numerous scholars have employed neutrosophic science to address a wide range of issues in their numerous research publications.

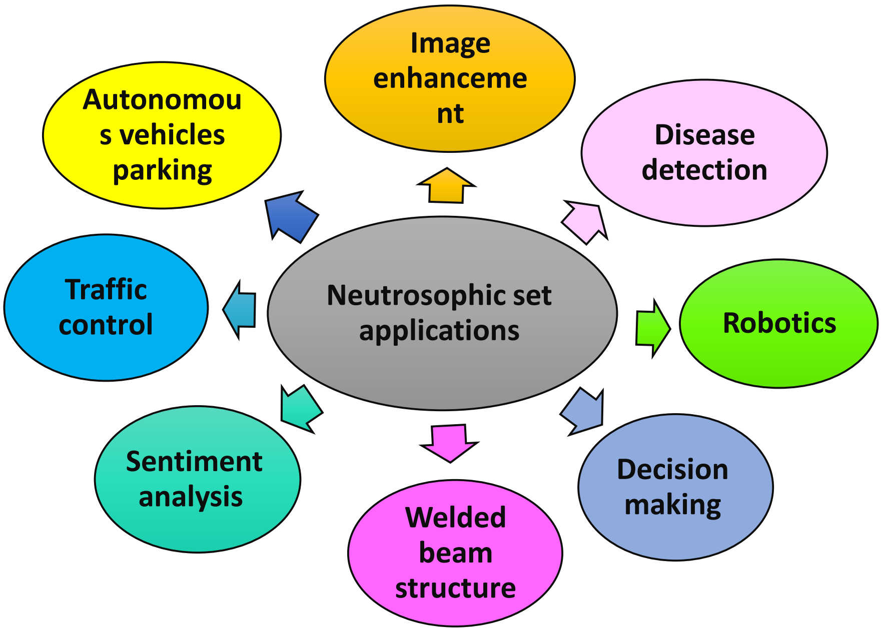

Figure 1. Applications of neutrosophic sets.

Metaheuristics [17] are versatile stochastic techniques used to address challenging optimization issues. These algorithms direct the search process throughout the solution space. They don't require any special knowledge about the problem structure. There exist many metaheuristics, such as Young's double-slit experiment optimizer [18], grey wolf optimizer [19], whale optimization algorithm [20], genetic algorithm [21], and particle swarm optimization [22]. Because of their remarkable expansion and wide range of applications [23-25], metaheuristic techniques have solidified their reputation (see Figure 2). Figure 3 classifies metaheuristic algorithms into four categories, including evolutionary-based algorithms, human-based algorithms, swarm intelligence algorithms, and physics-based algorithms.

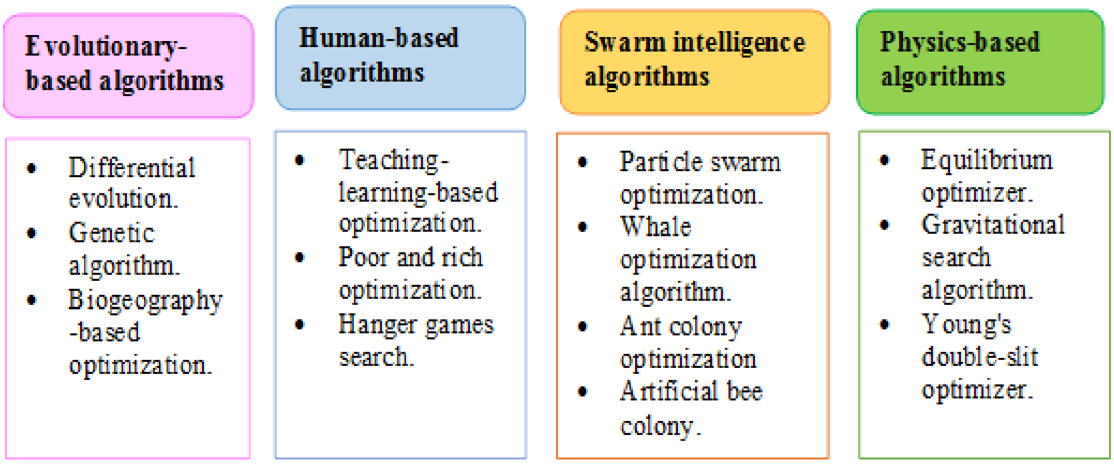

Figure 2. Classification of metaheuristic algorithms.

These methods stand in stark contrast to traditional optimization strategies, which can backfire in a variety of straightforward situations. However, early metaheuristic systems still had several design flaws, such asearly convergence and the incapacity to preserve population variety [26]. These challenges have been resolved by recent metaheuristic techniques, which have generally produced superior outcomes [27]. Recently, a lot of these innovative meta-heuristic methods have also been presented.

Generally speaking, they provide fresh models and creative evolutionary operators to generate a suitable exploration and exploitation of big search spaces taking into account a lot of factors. The prominence of neutrosophic concepts and metaheuristics, motivates us to introduce a comprehensive survey that covers the connection between the neutrosophic set theory and metaheuristics to generate the most optimally suggested remedies for a variety of research issues.

Our survey of metaheuristics and neutrosophic theory is organized as follows. Moreover, some preliminaries on the basic concepts of neutrosophic set and neutrosophic image are illustrated in Section 2. Section 3 provides an overview of the prior research conducted by many scholars on neutrosophic sets and neutrosophic images. Section 4 discusses the related work of metaheuristics for image data. Furthermore, the integration between the neutrosophic set and the metaheuristic algorithms is presented in section 5. Conclusively, section 6 presents conclusions, future work, and challenges.

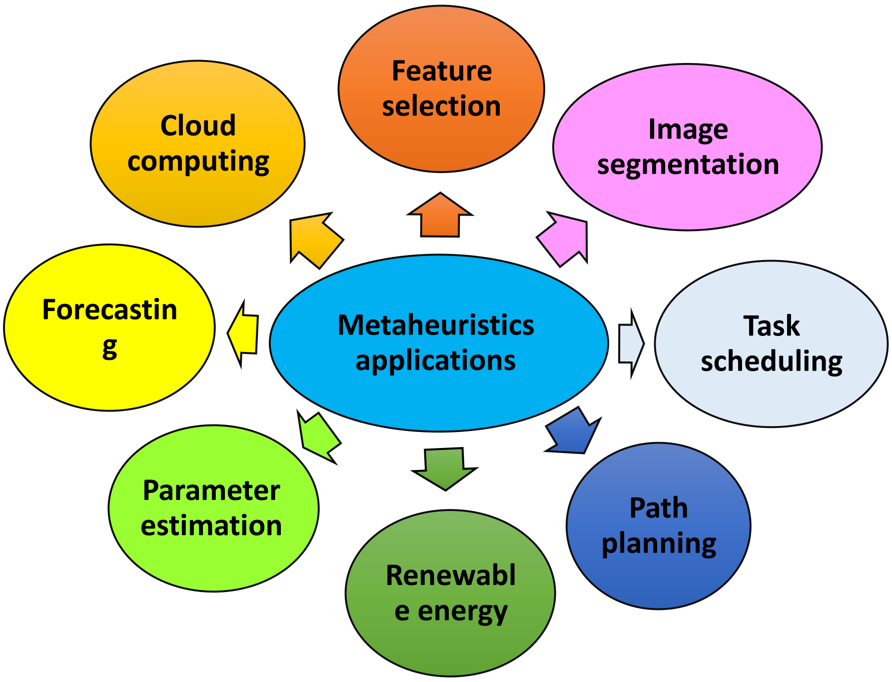

Figure 3. Applications of metaheuristics.

2 | Basic Concepts

2.1 | Preliminary Concepts of Neutrosophic Set

In this section, we will cover the most common and fundamental concepts and preliminaries covered in this paper, including the classical set, fuzzy set, intuitionistic fuzzy set, and neutrosophic set.

2.1.1 | Classical Set

Given a classical set (A) defined on a universe of discourse (X) each element in X is denoted as x. Generally, the set A contains a collection of elements. Being part of set A gives an element x a membership degree of 1, while not being part of set A gives the element x a membership degree of 0.

2.1.2 | Fuzzy set

Fuzzy set (FS) was first introduced in [28] to handle any vagueness encountered in many realistic systems, that the classical sets can't express. Given a fuzzy set (A) defined on a universe of discourse (X), each element *x* has a membership degree in [0, 1], as the degree to which the element belongs to the set A is not recognized. It is mathematically defined as $\mu_A(x) \in [0,1]$.

2.1.3 | Intuitionistic fuzzy set

Intuitionistic fuzzy set (IFS) [29] comes as an extension to FS. Let A be an intuitionistic fuzzy set defined on a universe of discourse X. In contrast to FS, Each element *x* in the set A has a degree of non-membership ($v_A(x)$) besides the degree of membership ($\mu_A(x)$), such that $\forall x \in X\ \mu_A(x) + \mu_A(x) \leq 1$. After that, the Interval-Valued Intuitionistic Fuzzy Set (IVIFS) is defined, since it is more reasonable to assign an interval of values to an expert's opinion rather than an exact value. There are some attempts to convert the FS into IFS [30, 31].

2.1.4 | Neutrosophic Set

NS is primarily coming as a generalization of IFS. Assume that X is a universe of discourse and A is an NS. Then, each element *x* from *U* concerning the set *A* can be denoted by three independent neutrosophic components: truth membership (T), indeterminacy membership (I), and falsity membership (F), such that 0 ≤ T+I+F ≤ 3. If two of the neutrosophic components are dependent, while the third one is independent, then, the sum of neutrosophic components is 2 (0 ≤ T+I+F ≤ 2). Furthermore, if three neutrosophic components are dependent, the sum of neutrosophic components is 1 (0 ≤ T+I+F ≤ 1). When each neutrosophic component has a single value, then, set A is called a Single-Valued Neutrosophic Set (SVNS). When each neutrosophic component has an interval of lower and upper bounds, then, set A is called an Interval-Valued Neutrosophic Set (IVNS). Figure 4 depicts the relationship among classical, fuzzy, fuzzy intuitionistic, and neutrosophic sets and the evolution from the classical set to the neutrosophic one.

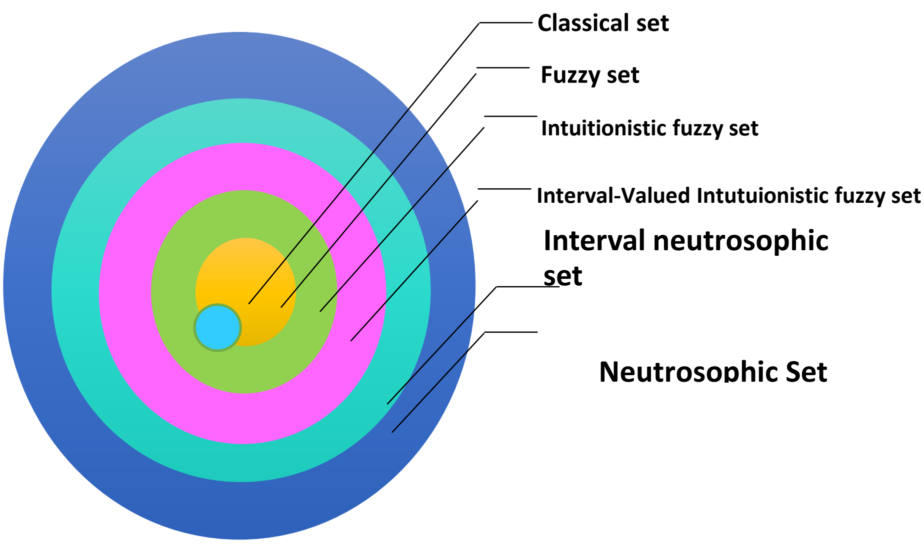

Figure 4. The evolution from classical sets to neutrosophic sets.

2.2 | Neutrosophic Image

The neutrosophic domain represents images with three neutrosophic components: T, I, and F. A pixel z (*a, b*) in the image under the neutrosophic domain is represented as z (*t, i, f*), with *t* representing truth, *i* representing indeterminacy, and *f* representing falsity. If the segmentation operation is applied to the input image, each pixel z (*t, i, f*) in the neutrosophic domain represents that pixel. The value *t* indicates that pixel z (*a, b*) belongs to the foreground area of the segmented item in the image, whereas *i* indicates that the pixel uncertainly belongs to the boundary zone, whereas *f* denotes the percentage of pixels in the background area. The equations below are used to convert the input image into a neutrosophic domain [32]:

$$T(a,b)=\frac{\bar{g}(\mathrm{a,b})-\bar{g}_{\min}}{g_{\max}-\bar{g}_{\min}} \tag{1}$$

$$\bar{g}(a,b)=\left(\frac{1}{win\times win}\right)\sum_{x=a-\frac{win}{2}}^{a+\frac{win}{2}}\sum_{y=a-\frac{win}{2}}^{a+\frac{win}{2}} g(x,y) \tag{2}$$

$$I(a,\mathrm{b})=\frac{\delta(\mathrm{a,b})-\delta_{\min}}{\delta_{\max}-\delta_{\min}} \tag{3}$$

$$\delta(\mathrm{a,b})=|\,\mathrm{g(a,b)}-\bar{g}(\mathrm{a,b})\,| \tag{4}$$

$$F(\mathrm{a,b})=1-\mathrm{T(a,b)} \tag{5}$$

Where $\bar{g}(\mathrm{a,b})$ is the mean intensity value of pixels in the window of size $(win\times win)$ and $\delta(\mathrm{a,b})$ determines the absolute difference between the intensity value of a pixel $\mathrm{g(a,b)}$ and its local mean value $\bar{g}(\mathrm{a,b})$. The image often includes noise, which is essentially a form of intermediate information. An important area of study in computer science is image noise reduction. The neutrosophic theory aims to handle uncertainty in images and improve efficiency during the image preprocessing phase.

3 | Related Work for Neutrosophic Sets

This section includes an extensive survey of neutrosophic sets. Furthermore, the benefits, drawbacks, restrictions, and potential future applications have been examined for these corresponding surveys. Said, Broumi, et al. [33] conducted a review on using neutrosophic logic for handling traffic control problems to optimize the traffic flow. Although the different neutrosophic techniques were proved to be more effective than FS, they may suffer from some limitations, such as the disability to deal with uncertainty for interval values and other parameters like pedestrian movements and emission of pollutants are not considered in some models. Sarkar, M., & Roy, T. K. [34] introduced a comparative study that investigates the performance of the neutrosophic optimization approach compared to other metaheuristics hoping to minimize the cost of the welded steel beam. The results demonstrated the efficiency of the neutrosophic optimization approach in a precise and imprecise environment.

Treating Nosiy's medical images is a crucial task for the medical image analysis process. Fs may be used but they may condone the pixel's spatial context. Hence, in [35], the authors proposed an enhanced approach using neutrosophic theory to deal with the uncertainty with a degree of indeterminacy for X-ray image enhancement. The statistical analyses show that the effectiveness of the NS Bilateral filter approach for X-ray image enhancement outperforms other denoising filters. Garg, Harish [36] incorporated the exponential and logarithmic operations with SVNS to address the decision-making issues.

Also, the researchers in [37] classified and recognized the different types of lung infections with a neutrosophic approach. The main drawback is the lack of images to effectively train the model, and utilizing complete lung images without localizing opacity regions can further lessen the time. Furthermore, an efficient parking algorithm [38] for autonomous vehicles is suggested based on neutrosophic fuzzy and various operational laws and the probabilistic neutrosophic hesitant fuzzy to tackle the hesitant information. The study did not take into consideration the risk factor, and nonlinear information among various attribute features was not regarded. Another study of a neutrosophic approach and deep learning model is proposed for fine-grained sentiment analysis [39]. Also, a combined compromise solution method is developed under the double-valued NS for assessing blended teaching quality [40]. Table 1 presents a summary of the published papers that make use of NS.

Table 1. A summary of some published papers that make use of NS.

Ref.	Problem	Summary	Limitations
[41]	Risk assessment of university Sustainability.	• A set of performance indicators are constructed for universities as a reference to ensure sustainable development. • NS is used to handle the uncertainty of specialist opinions.	• The Sustainable Development Obstacles (SDOs) were determined by specialists in university systems and other academic systems that must adjust SDOs. • The mutual influence between the university SDOs was not explored.
[42]	Smartphone supply chain.	• A modified novel four-valued refined multi-objective neutrosophic algorithm is suggested. • The object is to minimize greenhouse gases and costs while maximizing the resilience of a closed-supply chain network.	• The study is applied only to the smartphone supply chain. • The model is assumed to be deterministic.
[43]	Sustainability performance assessment of freight transportation.	• A mathematical model is proposed to select the most suitable route and transportation type. • The model applied the Delphi technique extended with NS for considering 42 sustainable criteria.	• The adopted model cannot be applied to all decision problems. • A specific neutrosophic set cannot model all uncertainties.
[44]	Blockchain application barriers.	• A model based on the bipolar neutrosophic to select the consensus algorithm to solve the obstacles that may face blockchain technologies.	• Adopting different blockchain technologies are explored. • The need to explore blockchain technologies for small and large businesses.
[45]	Emergency decision-making.	• A dynamic case-based emergence decision model in a time-varying VSNS environment to better assist in emergency response support. • VSNS was introduced to depict uncertainty and continuous change of information.	--
[46]	Waste medicine management.	• A Multi-Criteria Decision-Making (MCDM) methodology is presented to analyze the customers' opinions on waste medicine management based on 15 criteria. • SVNS is used to build relationships among criteria.	• More criteria can be adopted.
[47]	Cybersecurity of connected and autonomous vehicles.	• A hybrid MCDM is introduced to mitigate the cyber risks caused by different threat agents. • Single-valued neutrosophic fuzzy sets are implemented to support the subjectivity of the linguistic opinions given by the experts.	• It is more reasonable to employ an interval-valued neutrosophic fuzzy set to assign an interval of values to each expert opinion rather than a single value.

[48]	Transportation problem.	• A neutrosophic hyperbolic programming approach is suggested to handle the uncertain parameters in multi-objective transportation problems.	• The satisfaction percentage (87%), needs to be improved.
[49]	Power generator sustainable supplier park.	• The model aims to extract the necessary criteria and sub-criteria for evaluating and prioritizing the suppliers of a power generator manufacturer to build the supply network. • The model employs IVNS to prioritize alternative suppliers according to the criteria of industry experts.	• The a need to increase experts' numbers to achieve a more general conclusion for the power generator industry.
[50]	The integration of the metaverse and chat generative pre-trained transformer in software development.	• The SVNS-Dombi Bonferroni-based AROMAN technique is proposed to identify the most suitable software development strategy. • A perspective for incorporating artificial intelligence (ChatGPT) and virtual reality (Metaverse) is studied.	• Excluding other perspectives, such as end-users and project stakeholders might limit the comprehensive understanding of the impact of artificial intelligence and virtual reality in software development.
[51]	Fresh food supplier selection.	• A decision-making model is introduced to address high vagueness to solve the selection of fresh food suppliers.	• No database is available for the fresh food industries. • The lack of specialists in fresh food supply chains.

The neutrosophic theory has proved its success in representing many images under the neutrosophic domain. The authors [52] introduced the neutrosophic similarity measure as an alternative assessment metric for evaluating watermarked images instead of the d peak signal-to-noise ratio metric. Chaira et al. [53] proposed a novel clustering strategy that makes use of the NS to identify and isolate the lesion or area of interest in mammography images. There is less uncertainty in the photos because NS can handle indeterminate data. A novel method based on Shannon entropy and standard deviation is used to compute indeterminate degrees. Table 2 presents a summary of published papers that focus on neutrosophic theory for images.

Table 2. A summary of published papers on neutrosophic logic for images**.**

Ref.	Task	Dataset	Method	Evaluation metrics
[53]	Clustering	Fifty images from Google.(mammography pictures)	• Clustering approach using NS, based on Shannon entropy and standard deviation.	- -
[54]	Segmentation	90 images from the ISIC2016 skin lesion.	• NS using unsharp 5×5with an average of 3×3 followed by K-means.	• Accuracy=96%
[55]	Segmentation	Three types of images: artificial, medicinal, and natural.	• Neutrosophic Fuzzy Clustering method with Non-Local information (NLNFC).	• Segmentation accuracy (SA%) in the medical image is 94.97%, 96.36%, and 97.82%. For CSF, GRY, and WHT, Respectively.
[56]	Segmentation	Fingerprint images	• Neutrosophic image segmentation based on the value of global neutrosophic image data.	• Accuracy of average RNS Binary = 63.4384%

			• Three different RNS techniques were offered: minimum, average, and maximal.	
[57]	Segmentation	Two datasets (Kaggle dataset, Dhar and Kundu).	• Neutrosophic-based image segmentation algorithm.	• 18% for ASVS (Average Squared Visual Salience) • 0.9919 and 38.96 for MSSIM and PSNR respectively.

4 | Related Work of Metaheuristic Algorithms for Images

Over the years, metaheuristics have proven to be suitable for solving many problems, and also in images. Daniel et al. [58] suggested an Optimum Spectrum Mask Fusion (OSMF) employing the traditional Grey Wolf Optimizer (GWO). The GWO dynamically and quickly selects scales in the multimodal medical images. The suggested OSMF was examined using brain imaging data. Image segmentation has a critical and significant role in distinguishing between the various types of tumors in Computed Tomography (CT) images. In this context, Ramakrishnan et al. [59] employed GWO for image segmentation and support vector machine for classification. Furthermore, Another study [60] improved the African vultures optimization algorithm with three binary thresholds (Kapur's entropy, Tsallis entropy, and Ostu's entropy) to perform multi-threshold image segmentation.

Jiang et al. [61] integrated particle swarm optimization and ant colony optimization techniques to obtain the optimal homomorphic wavelet image fusion. Another study [62] presented the traditional particle swarm optimization and its variations for multi-level thresholding. Mahajan et al. [63] suggested a unique image thresholding method based on type II fuzzy entropy (TII-FE) and the adaptive flower pollination algorithm. The thresholding process is evaluated in terms of segmented image quality, accuracy, and convergence versus competing methods. Table 3 describes the aforementioned papers in terms of the used metaheuristic algorithm, application, dataset, integrated method, and evaluation metrics.

Table 3. A summary of some metaheuristics for image processing.

Ref.	Metaheuristic Algorithm	Application	Dataset	Integrated method	Evaluation metrics
[58]	Grey wolf optimizer	Image fusion	Brain's images MR: T1-T2 , MRSPECT, MR-PET, and MR-CT.	Optimum Spectrum Mask Fusion	The standard deviation for MR-CT = 85.4942
[59]	Grey wolf optimizer	Classification , Segmentation	CT images.	SVM-SMO for classification and MRG-GWO for segmentation	Accuracy=99.05 %
[60]	African vultures optimizati on algorithm	Image segmentation	Eight images with large dimensions from https://lan	Quantum Rotation Gatemechanism and Association Strategy	Accuracy

			dsat.visibleearth.nasa.gov/index.php?&p=1		
[61]	Hybrid particle swam optimization and ant colony optimization	image fusion	MR-PET, MR-SPECT, MR T1-T2, and MR-CT images	Optimum Homomorpic Wavelet Fusion (OHWF).	Obtained best scale values: 0.2396, 0.4687, 0.5091and 0.4822 for MR-SPECT, MR-PET, MR-CT and MR-T1-T2, respectively.
[62]	Particle swam optimization	image segmentation	Standard color image and hematopathology	Otsu and Tsallis entropy in multi-level thresholding domain	Accuracy
[63]	Adaptive flower pollinatn algoritm	Image segmentation	Natural images with numerous distributions of histograms.	type II fuzzy entropy (TII-FE)	SSIM=8.75E01, PSNR=2.29E+01, MSE=3.52E+02.

5 | Related Work for Neutrosophic Set and the Metaheuristics Integration

It can be seen that the integration of neutrosophic sets with metaheuristic algorithms has many advantages in solving optimization problems, especially when information is partial or unknown. The uncertain or indeterminate in the objective functions or input data can be well handled by considering neutrosophic sets in the formulation of the objective functions and that can be captured effectively by the metaheuristic algorithms, which construct more reliable and robust solutions.

Incorporation between metaheuristics and neutrosophic sets leads to best solutions which led us to introduce this survey to cover metaheuristics with neutrosophic theory from all aspects. Likewise, the combination of neutrosophic sets with metaheuristic algorithms is expected to develop a more competent and durable strategy for solving complex optimization issues in the presence of uncertain and incomplete data. Neutrosophic set and metaheuristic integration are used in several fields such as image segmentation, job shop scheduling, image clustering, image classification, and others.

El-Shorbagy et al. [64] explored the potential of using image analysis for COVID-19 detection in X-ray and CT-scan images of patients. Deep learning has outperformed other image classification methods. However, the effectiveness of deep learning-based approaches heavily relies on the design of the deep neural network. Metaheuristics and neutrosophic sets have gained popularity for fine-tuning deep network structures. Due to their adaptability, simplicity, and task-specific nature, metaheuristics have been applied to solve complex non-linear optimization problems. The authors of this study conducted a review of a neurotrophic model and metaheuristics methods to accurately identify COVID-19 patients from their chest X-rays.

In [65], medical image analysis, cloud services, grouping, fragmentation, and categorization, among other image processing operations, have all employed judgment methods. But the aspects of work between them were not covered well. Also, this essay's [66] objective is to give a thorough understanding of the main metaheuristic algorithms that have been integrated with neutrosophic set theory to introduce some effective solutions or platforms to a range of issues throughout ten years, together with an understandable description of NS and metaheuristic ideas.

Table 4. Summarization of papers that combined metaheuristic algorithms and NS.

Ref.	Problem	Dataset	Method	Summary
[67]	Document-level sentiment analysis	Large-sized text collected from Blitzer, aclIMDb, Polarity and Subjective Dataset	NS and particle swarm optimization	• PSO is applied directly to the Neutrosophic values of the document. • The proposed method classified the large-sized text based on two classifiers: binary and ternary. • Various evaluation metrics are used as precision, recall, accuracy, and F-measure.
[68]	Automatic mitosis detection in breast cancer histology images	50 histopathological images	Ns and Moth-Flame Swarm Optimization (MFO)	• An automatic mitosis detection approach is proposed for histopathology slide imaging based on NS and MFO. • The enhanced image using the Gaussian filter was mapped into the NS domain. • The MFO algorithm selects the best discriminating features of mitosis cells.
[69]	Synthetic aperture radar image segmentation	Synthetic aperture radar (SAR) images: Ku-band of China Lake Airport in California, Piers along Washington Channel, and Ku-band in Rio Grande River near Albuquerque	NS and improved Artificial Bee Colony (I-ABC) algorithm	• The I-ABC algorithm searched for the optimal threshold value. • The input SAR image is transformed into the NS domain.
[70]	Flexible job-shop scheduling problem	Kim's benchmark instances	NS and Teaching Learning-Based Optimization (TLBO)	• The proposed method optimizes flexible job-shop scheduling problems with uncertain processing times. • The solutions are evaluated using the neutrosophic makespan.
[71]	Liver tumor segmentation	CT images	NS, PSO with Fuzzy C-Mean Algorithm (PSOFCM)	• The CT image is transformed into the NS domain to remove noise and enhance the CT image. • The NS mage is passed to the PSOFCM approach to segment the liver from abdominal CT.
[72]	Image enhancement	Egyptian medical dataset collected from Menoufia University Hospital	NS and Salp Swarm Algorithm (SSA)	• An adaptive scheme based on SSA and NS under multi-criteria to enhance the dark regions of the skeletal scintigraphy image. • The SSA is used to find the best improvement for each image separately. • The neutrosophic algorithm is used to find the similarity score of each image.

				• The drawback comes from using the variant of the gamma camera, which may greatly affect the quality of the image.
[73]	Side scan sonar image segmentation		NS and Quantum-behaved Particle Swarm Optimization (NS+QPSO)	• A new segmentation algorithm NS+QPSO is proposed. • The entropy of grey level image is used as the evaluation metric. • The input image is transformed into the NS domain.
[74]	Medical image processing	MR images	NS combined with fuzzy *c*-means clustering (FCM) and modified PSO	• FCM is combined with PSO to optimize the image segmentation. • The input MR image is transformed into the NS domain.
[75]	Skin lesion detection in dermoscopy images	50 images from the ISIC 2016 challenge dataset are used in training while 850 images are used for testing	Optimized Neutrosophic K-Means (ONKM) and Genetic Algorithm (GA)	• The ONKM method is developed to segment the dermoscopy images. • GA is employed for optimizing α value in α-mean operation in the NS for further *k*-means clustering of the dermoscopy images.
[76]	Forest fires	forest fires data	Fuzzy *c*-means clustering, PSO, and information theory measures.	• A method based on PSO and information theory measures is suggested for modeling neutrosopic temperature variables.
[77]	Image segmentation	Nondestructive testing images of a metal	NS and Bat Algorithm (BA)	• The nondestructive testing image is converted into the NS domain. • α - mean and β - enhancement operations are employed for proper NS value representation. • BA is utilized to find the proper values of α and β values.
[78]	Cubic Assignment Problem (CAP)	An illustrative example of CAP	Neutrosophic theory and GA (NGA)	• The NGA treats the crossover effect as a neutrosophic fuzzy set. • A neutrosophic fitness function value is created.
[79]	Rock discontinuity clustering problem	Images of rock discontinuity sets	Neutrosophic Genetic Algorithm (NGA)	• The neutrosophic concept is incorporated into GA. • The NGA is used to optimize the K-means method for clustering analysis of rock discontinuity sets.

6 | Conclusions and Future Work

Many problems contain inaccuracy, inconsistency, and unclear or missing data, and from there, NS combined with metaheuristic algorithms appeared to solve these problems. Recently, we have noticed the combination of NS with metaheuristics to solve many image-related tasks. In this survey, we discussed some of the research interests in the two fields, whether NS or metaheuristic, and we discussed some of the research that combines them. The study's core goal is to research the applications of neutrosophic sets and metaheuristic algorithms in images. To attain this purpose, research articles concentrate on neutrosophic logic in image processing and research articles concentrate on metaheuristics methods in image processing.

The combination of NS and other metaheuristic algorithms has piqued the curiosity of several researchers. Neutrosophic sets can represent uncertainty, vagueness, and inconsistency in data. This way was very useful for solving real-world optimization problems in which these aspects coexist. However, handling these aspects properly in combination with the metaheuristic algorithms is still a challenge, to be addressed by future research.

Metaheuristic algorithms come with several parameters that have to be set for optimal performance. The optimization of these parameters is much more compounded with the application of the neutrosophic framework in neutrosophic set models. It is recommended that efficient methods be developed for optimizing parameters in this combination of neutrosophic sets and metaheuristic algorithms.

The study of neutrosophic papers could look deeper into how to use neutrosophic thinking in many areas, such as engineering, computers, money, and health. People can also work on finding new ways to handle neutral data better and faster. Some hard parts that people might meet in the future include making set ways for showing and working with neutrosophic facts and dealing with the hard part of neutrosophic thinking. Also, there is a need for a better way to show and make rules for neutrosophic thinking so that it can work well in real-world problems. Working with many people from different areas can help fix these hard parts and push forward the study of neutrosophics. Finally, more research is needed to determine if metaheuristic algorithms and neutrosophic approaches can address issues, such as agriculture and other industries.

Acknowledgments

The author is grateful to the editorial and reviewers, as well as the correspondent author, who offered assistance in the form of advice, assessment, and checking during the study period.

Author Contribution

All authors contributed equally to this work.

Funding

This research has no funding source.

Data Availability

The datasets generated during and/or analyzed during the current study are not publicly available due to the privacy-preserving nature of the data but are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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