A State-of-the-Art Review of Neutrosophic Sets and Theory

İrem Otay and Cengiz Kahraman

Abstract A neutrosophic set is a part of neutrosophy that studies the origin, nature, and scope of neutralities, as well as their interactions with different ideational spectra. Neutrosophic sets are relatively new extensions of intuitionistic fuzzy sets. The neutrosophic logic has been approved by many researchers in a short time. Especially, a significant acceleration in the number of publications on neutrosophic sets is observed after 2015. This chapter aims at classifying all these publications and to exhibiting the place of neutrosophic sets and logic in the literature. This is the most comprehensive and updated review on neutrosophic sets. Tabular and graphical illustrations are used to summarize the review results.

Keywords Neutrosophic sets · Literature review · Neutrosophic hypergraphs
Neutrosophic segmentation · Neutrosophic clustering
Neutrosophic multicriteria decision making

1 Introduction

Atanassov [16] introduced the intuitionistic fuzzy sets which is a generalization of ordinary fuzzy sets. Intuitionistic fuzzy sets consider both truth-membership T and falsity-membership F where T and F $\in$ [0, 1] and $0 \leq T + F \leq 1$. Neutrosophic sets have been introduced to the literature by Smarandache [78] since intuitionistic fuzzy sets could only handle incomplete information, but not the indeterminate information and inconsistent information, which exists commonly in fuzzy systems. The

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term neutro-sophy means knowledge of neutral thought and this neutral represents the main distinction between fuzzy and intuitionistic fuzzy logic and sets. In neutrosophic sets, indeterminacy is quantified explicitly through a new parameter I. Truth-membership (T), indeterminacy membership (I) and falsity-membership (F) are independent and their sum can be between $0 \leq T + I + F \leq 3$. In intuitionistic fuzzy sets, the uncertainty is dependent on the degree of membership and degree of nonmembership. In neutrosophic sets, the indeterminacy factor (I) is independent of truth and falsity values. There are no constraints between the degree of truth, degree of indeterminacy and degree of falsity.

In the literature, single valued neutrosophic sets (SVNS) have been often used rather than the other types of NS. SVNS is defined as an instance of neutrosophic sets and they are the generalization of classic sets, fuzzy sets, interval valued fuzzy sets, and intuitionistic fuzzy sets. In some cases, the degree of truth, falsity, and indeterminacy of a certain proposition can not be exactly defined by single values but interval values. Hence, the interval-valued neutrosophic set (IVNS) have been introduced to the literature.

A neutrosophic set $\dddot{\tilde{A}}$ in X is characterized by a truth-membership function $T_{\dddot{\tilde{A}}}$, an indeterminacy membership function $I_{\dddot{\tilde{A}}}$ and a falsity-membership function $F_{\dddot{\tilde{A}}}$. In this notation, three dots represent degrees of truth, falsity, and indeterminacy while the tilde represents fuzziness. $T_{\dddot{\tilde{A}}}(x)$, $I_{\dddot{\tilde{A}}}(x)$ and $F_{\dddot{\tilde{A}}}(x)$ are real standard or non-standard subsets of $]0^-, 1^+[$. There is no restriction on the sum of $T_{\dddot{\tilde{A}}}(x)$, $I_{\dddot{\tilde{A}}}(x)$ and $F_{\dddot{\tilde{A}}}(x)$ so that $0^- \leq \sup T_{\dddot{\tilde{A}}}(x) + \sup I_{\dddot{\tilde{A}}}(x) + \sup F_{\dddot{\tilde{A}}}(x) \leq 3^+$.

When X is a continuous variable, a NS $\dddot{\tilde{A}}$ can be expressed as in Eq. (1):

$$\dddot{\tilde{A}} = \int_X \langle T(x), I(x), F(x)\rangle / x, x \in X \tag{1}$$

When X is a discrete variable, a NS $\dddot{\tilde{A}}$ can be expressed as in Eq. (2):

$$\dddot{\tilde{A}} = \sum_{i=1}^{n} \langle T(x_i), I(x_i), F(x_i)\rangle / x_i, x_i \in X \tag{2}$$

For instance, a discrete interval-valued NS can be given as follows:

$$\begin{aligned}\dddot{\tilde{A}} = {} & \langle[0.4, 0.6], [0.3, 0.4], [0.4, 0.5]\rangle/x_1 + \langle[0.8, 0.9], [0.1, 0.2], [0.3, 0.4]\rangle/x_2 \\ & + \langle[0.6, 0.8], [0.2, 0.3], [0.1, 0.4]\rangle/x_3\end{aligned}$$

As another example, lets consider the shapes in Fig. 1:

These shapes can be represented by the following NS, respectively: $\langle 0.6, 0.4, 0.4\rangle$, $\langle 0.8, 0.2, 0.3\rangle$, and $\langle 1, 0, 0\rangle$.

Aggregation operators have been developed to aggregate the assessments of more than one expert to a single assessment score. As in the other extensions of fuzzy sets, aggregation operators have been also developed for neutrosophic sets [109]. Interval neutrosophic number weighted averaging operator (INNWA), interval neutro-

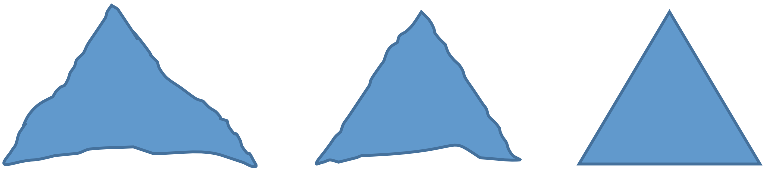

Fig. 1 Shapes similar to a triangle

sophic number weighted geometric operator (INNWG), single neutrosophic number weighted averaging operator (SNNWA) are some of these operators.

Neutrosophic sets have been used in various areas in the literature. Some of these areas are clustering, segmentation, and hypergraphs. Neutrosophic sets have been also employed in multicriteria decision making methods. Neutrosophic AHP [22, 70, 71], Neutrosophic TOPSIS [87, 98, 99], Neutrosophic ELECTRE [65] are some of these studies.

The rest of this chapter is organized as follows. Section 2 presents some graphical analyses summarizing the results of a literature review on neutrosophic sets. Section 3 includes a topical classification on neutrosophic sets such as neutrosophic logic & neutrosophic sets, neutrosophic hypergraphs, neutrosophic segmentation, and neutrosophic clustering. Section 4 concludes the chapter.

2 Neutrosophic Sets: Graphical Analyses

By typing "***Neutrosophic Set***", "***Neutrosophic***", "***Neutrosophic Logic***", *and* "***Neutrosophy***" all types of papers are sorted whether they include these words in their article title, abstract and/or keywords. The summarized data obtained from Scopus are listed in Table 1.

Figure 2 illustrates the numbers of published papers on "Neutrosophic set" between the years 2005 and 2018 based on their titles, abstracts and keywords. Most of these papers were published in conference proceedings and international jour-

Table 1 Summarized data from Scopus

Keyword	Article + Abstract + Keywords	Title	Abstract	Keywords
Neutrosophic set	307	121	259	267
Neutrosophic	469	417	460	409
Neutrosophic logic	45	13	41	35
Neutrosophy	33	4	25	14

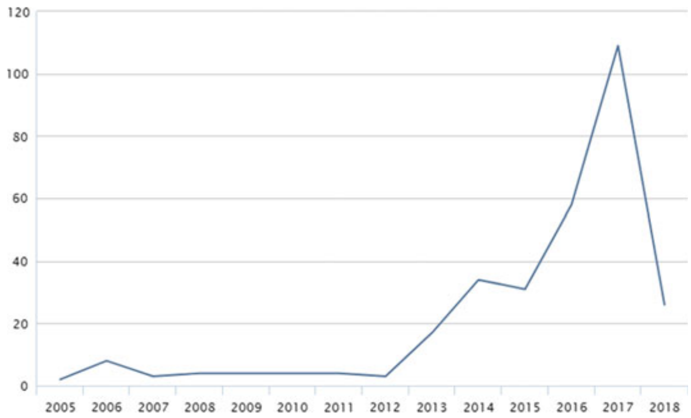

Fig. 2 Published papers regarding to their publication years

nals such as "Journal of Intelligent and Fuzzy Systems" (34 papers), "Symmetry" (12 papers), and "Applied Soft Computing" (8 papers). Figure 3 shows the journals publishing neutrosophic papers.

The researchers publishing neutrosophic papers are ranked based on their total number of neutrosophic publications. Some researchers publishing neutrosophic papers are as follows: J. Ye (Shaoxing University, 36 papers), F. Smarandache (University of New Mexico, 25 papers), J. Q. Wang (Central South University China, 23 papers), Y. Guo (University of Illinois at Springfield, 22 papers), and H. Y. Zhang (Central South University China, 18 papers). Figure 4 demonstrates the researchers based on the number of their neutrosophic papers.

It is also observed that Shaoxing University, Central South University China and University of New Mexico are leading universities that have published many papers on neutrosophic sets and applications as illustrated in Fig. 5.

On the other hand, countries are ranked according to the number of neutrosophic publications they produced as seen in Fig. 6.

A total of 307 publications have been found when "neutrosophic sets" is entered to Scopus database. Within these publications, 204 papers are classified as articles; 70 papers are listed as conference papers; 21 papers are defined as Article in Press and 9 papers are listed as Conference Review. Figure 7 illustrates the document types of these 307 publications.

When the papers are sorted depending on the subject areas, the distribution is obtained as follows: "Computer Science (77.5%)", "Mathematics (46.6%)", and "Engineering (34.5%)" as shown in Fig. 8.

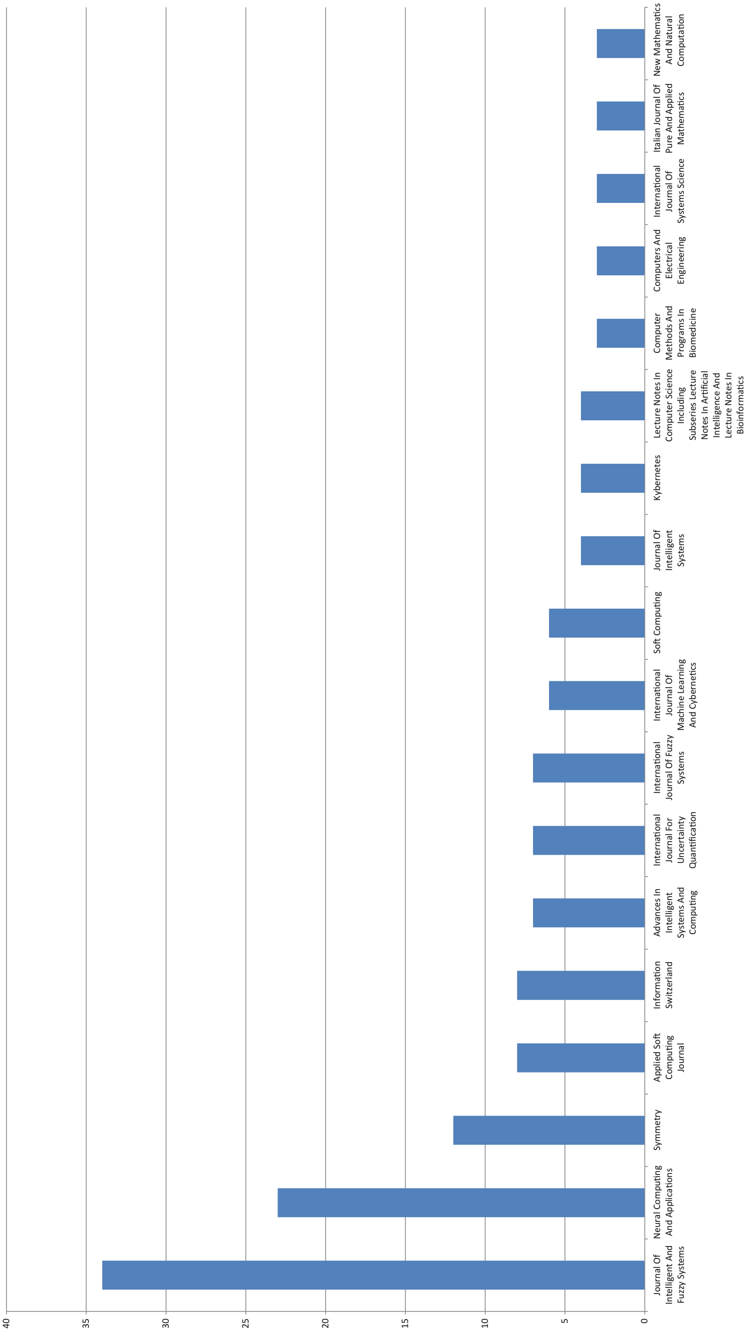

Fig. 3 Journals publishing neutrosophic papers

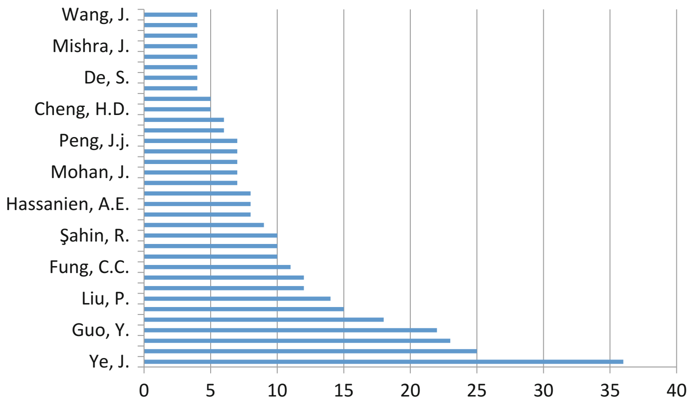

Fig. 4 Researchers publishing neutrosophic papers

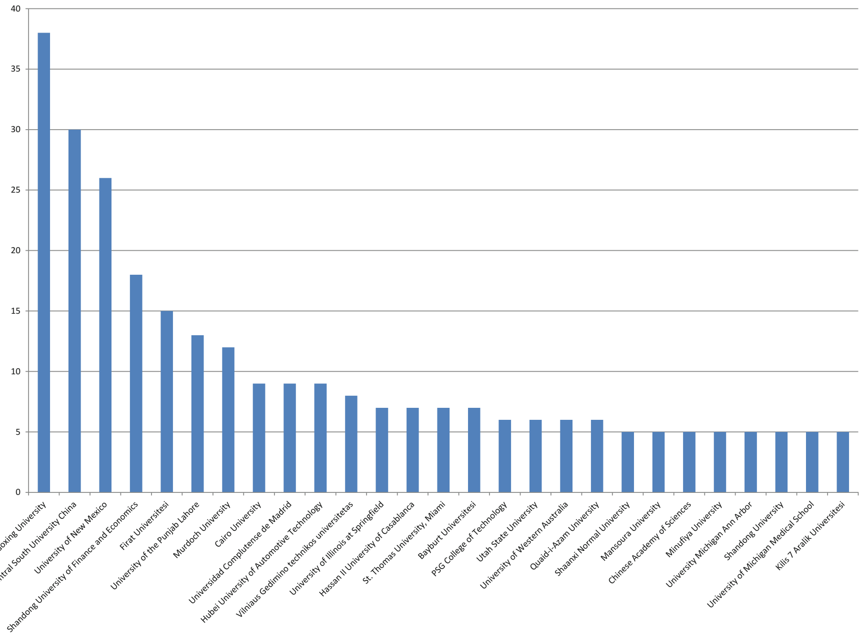

Fig. 5 Universities publishing neutrosophic papers

3 A Topical Classification on Neutrosophic Sets

Based on the review of Scopus database, Sciencedirect and Google Scholar, the analyzed papers are divided into seven groups which are "Theoretical Basics of Neutrosophic Logic & Neutrosophic Sets", "Neutrosophic Classification", "Neutrosophic Hypergraphs", "Neutrosophic Segmentation", "Neutrosophic Clustering",

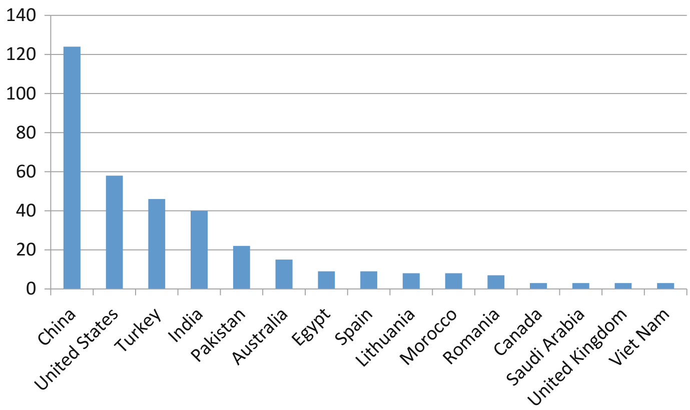

Fig. 6 Neutrosophic publications with respect to the countries

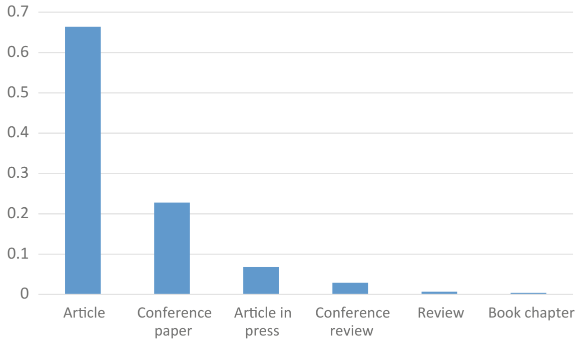

Fig. 7 Distribution of publications with respect to document types

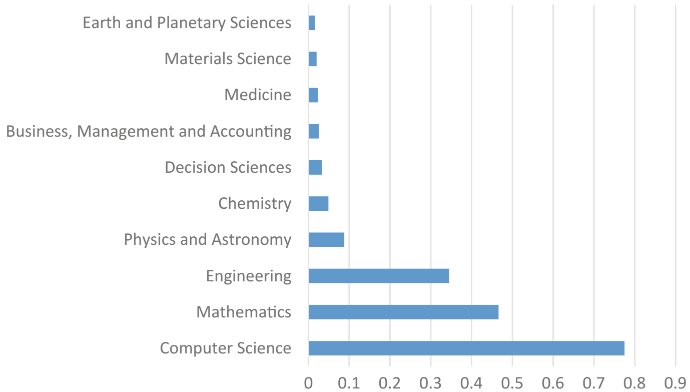

Fig. 8 Publications with respect to the subject areas

"Neutrosophic Multicriteria Decision Making", and "Other Neutrosophic Application areas".

- Theoretical Basics of Neutrosophic Logic & Neutrosophic Sets

Rivieccio [74] presented a critical introduction to neutrosophic logics, stated its prospects and problems related with it, analyzed the relationship between neutrosophic logics and intuitionistic and interval-valued) fuzzy systems and Belnap's logic which have been using for reasoning with uncertainty and vagueness. Lupiáñez [62] investigated interval neutrosophic sets and their topology. Wang et al. [90] proposed single valued neutrosophic sets (SVNSs) to deal with real-life problems. Solis and Panoutsos [81] studied on granular computing which is a computational paradigm and proposed Granular Computing Neural-Fuzzy model based on Neutrosophic Logic. The researchers applied the proposed approach to a real life industrial case study. Broumi et al. [23, 24] were the first presenters of the rough neutrosophic sets and their properties. Alkhazaleh [10] stated the concept and properties of time-neutrosophic soft set and present some arithmetic operations such as complement, union and intersection. Ali and Smarandache [8] presented a paper that first introduced complex neutrosophic sets which was an extension of the neutrosophic set having complex-valued truth membership function, complex-valued indeterminacy membership function, and complex-valued falsehood membership functions defined by real-valued truth, indeterminate and indeterminate amplitude terms with phase terms. Jun et al. [49] extended Cubic Sets by integrating them with neutrosophic sets. In the study, the authors analyzed truth-internal neutrosophic cubic sets and truth-external neutrosophic cubic sets. Akram and Shahzadi [6] introduced single-valued neutrosophic graphs by level graphs, and some fundamental operations on single-valued neutrosophic graphs and presented an application of the graphs in the field of social network. Liu et al. [61] improved the interval neutrosophic cross entropy and "the Induced Generalized Interval Neutrosophic Shapley Hybrid Arithmetic Averaging operator and the Induced Generalized Interval Neutrosophic Shapley Hybrid Geometric Mean operator" where the input elements are interdependent.

- Neutrosophic Classification

Kraipeerapun and Fung [53] proposed the application of neural network and interval neutrosophic sets for binary classification problems. A bagging technique was implemented for identifying the degree of truth membership, indeterminacy membership, and false membership using interval neutrosophic sets. The researchers applied the proposed techniques for the solution of benchmark problems considering ionosphere, pima-Indians diabetes, and liver-disorders. Kavitha et al. [52] concentrated on intrusion detection systems offering a new Neutrosophic Logic Classifier being an extension/combination of the fuzzy logic, intuitionistic logic, paraconsistent logic, and the three-valued logics, enable to handle uncertainty because of imprecise and incomplete knowledge in classifying the normal and/or abnormal behaviour patterns. Ansari et al. [13] introduced a neutrosophic classifier which is an extension to fuzzy classifier. The proposed neutrosophic classifier differs from its fuzzy version in terms of nature of membership functions, number of rules and indeterminacy. The proposed approach highlighted that it has optimized the parameters in comparison to the fuzzy version. Akbulut et al. [1] proposed k-nearest neighbors (k-NN) being a non-parametric classifier. In the study, the researcher extended the approach using NS theory based on a supervised neutrosophic c-means (NCM) algorithm. Real life data was used to test the applicability of the model. The results of the suggested method were compared with k-NN, fuzzy k-NN, and two weighted k-NN methods. Sayed and Hassanien [75] suggested a new approach consisting of two stages which were candidate's extraction and candidate's classification. They applied the approach for detecting images of mitosis cells using neutrosophic sets and the meta-heuristic moth-flame optimization algorithm. The experimental results revealed that the suggested approach was fast, robust, and efficient.

- Neutrosophic Hypergraphs

Smarandache and Hassan [80] defined the regular and totally regular single Valued neutrosophic hypergraphs and discussed their properties. Akram and Sarwar [7] studied on bipolar neutrosophic graphs including the dominating and independent sets and represented an MCDM approach depending on bipolar neutrosophic sets and bipolar neutrosophic graphs. Akram and Luqman [4] discussed several concepts such as intuitionistic single-valued neutrosophic hypergraphs and dual intuitionistic single-valued neutrosophic hypergraphs. In the study, the authors emphasized that it is more convenient to use single-valued neutrosophic sets compared to neutrosophic sets. In the application section, the authors presented the solution of a clustering problem by means of intuitionistic single-valued neutrosophic hypergraphs. Akram and Luqman [5] combined bipolar neutrosophic sets with directed hypergraphs. The authors represented concepts and properties related to bipolar neutrosophic directed hypergraphs, and regular bipolar neutrosophic directed hypergraphs. Akram and Siddique [3] integrated the single-valued neutrosophic sets with competition graphs and stated their properties.

- Neutrosophic Segmentation

Yu et al. [104] proposed an unsupervised algorithm adopting mean shift clustering for the purpose of segmenting images. The proposed algorithm compared with four algorithms for six images with two types of resolutions. The comparison analysis results demonstrated that the proposed algorithm was robust for dealing with images with different qualities and resolutions. Hanbay and Talu [41] improved a synthetic aperture radar (SAR) image segmentation algorithm with neutrosophic sets. The authors used improved artificial bee colony (I-ABC) algorithm for finding the optimal threshold value. The input SAR image was converted to neutrosophic sets domain for obtaining fitness function for I-ABC algorithm. An optimal threshold value was obtained by maximizing the separability in gray level image. Guo and Sengur [39] developed a three dimensional algorithm for defining the skeleton for the objects with or without noise considering neutrosophic cost function. The authors applied a shortest path algorithm for the aim of finding an optimum path in the 3D volume. In the analysis, costs of the paths were identified with neutrosophic cost function. The optimum path was assumed to be the skeleton of the 3D volume. Alsmadi [12] aimed to develop a new fully automatic and effective method for segmenting and detecting the jaw lesion region. The researcher suggested a hybrid Fuzzy C-Means and Neutrosophic approach and conducted sensitivity and compared the proposed approach with the Hybrid Firefly Algorithm with the Fuzzy C-Means, and the Artificial Bee Colony with the Fuzzy C-Means algorithm. Guo et al. [40] focused on Breast ultrasound image segmentation. The researchers studied on a new breast ultrasound image segmentation algorithm using neutrosophic similarity score and level set algorithm. The researchers transformed the input image into the NS domain. Then, the similarity score was used to measure the degree to the true tumor region. Later, the level set method was used for classifying the tumor from the background tissue. Heshmati et al. [42] focused on image segmentation meaning of partitioning an image into some meaningful regions having homogeneous characteristics. The researchers analyzed unsupervised colour-texture image segmentation based on nonsubsampled contourlet transform and neutrosophic sets for indeterminacy assessment of the images. In the proposed approach, the K-means clustering algorithm was also applied to segmenting images. Zhao et al. [110] focused on image segmentation methods and introduced side scan sonar image thresholding segmentation method using neutrosophic set and quantum-behaved particle swarm optimization algorithm. Dhar and Kundu [29] mentioned about uncertainties arising from gray level and spatial ambiguities in an image, and they proposed a new text region segmentation method depending on digital shearlet transform (DST) and employed the neutrosophic sets to handle the uncertainties in the segmentation process. Guo et al. [36] improved an efficient image segmentation algorithm based on neutrosophic graph cut. In the study, images were divided input images into various homogenous regions using neutrosophic sets. The results were obtained by employing a maximum-flow algorithm, and the results were compared with a neutrosophic similarity clustering segmentation algorithm and a graph-cut-based algorithm. Hu et al. [44] developed a robust MeanShift object tracking system based on single-valued neutrosophic sets to deal with some factors such as occlusion, blur, and fast motion. The authors introduced the single valued neutrosophic cross-entropy measure considering both color and depth domains. Siri and Latte [77] studied on computer-aided diagnosis of liver which speeds up the diagnosis, helps to make accurate investigations and to plan surgeries. The researchers make analysis on Liver segmentation algorithms and stated the drawbacks of current liver segmentation algorithms such as ambiguous boundaries, variability of liver geometry from patient to patient and noise. The proposed approach composed of 3 phases which were (1) Pre-processing (2) Computed Tomography (CT) scan image transformation to Neutrosophic Set (NS) and (3) Post-processing. The authors transformed a CT scan image into neutrosophic domains expressing three membership subset as True subset (T), False subset (F) and Indeterminacy subset (I). In the study, it was stated that the suggested method was found as effective and robust for segmentation CT scan images of liver.

- Neutrosophic Clustering

Ye [97] focused on clustering the data which were defined by single-value neutrosophic sets. The researcher suggested minimum spanning tree clustering algorithm using single-valued neutrosophic sets. The algorithm was based on the generalized distance measure of the single-value neutrosophic sets. Guo and Sengur [38] also concentrated on data clustering and image processing. The authors introduced a new clustering algorithm, neutrosophic c-means (NCM) combining fuzzy c-means and the neutrosophic sets. The proposed model was formulated as a constrained minimization problem dealing with the ambiguity and the distance rejection for the patterns close to bounders and far away from the clusters, respectively. They used both synthetic and real data sets for application of the proposed algorithm and compared the results with other methods. D'Urso [30] studied on uncertain clustering methods based on different theoretical approaches for modeling the uncertainty and presented literature review of the clustering methods such as "Fuzzy clustering, Possibilistic clustering, Shadowed clustering, Rough sets-based clustering, Intuitionistic fuzzy clustering, Evidential clustering, Credibilistic clustering, Type-2 fuzzy clustering, Neutrosophic clustering, Hesitant fuzzy clustering, Interval-based fuzzy clustering, and Picture fuzzy clustering". Guo et al. [37] transformed images into neutrosophic sets. The author suggested indeterminacy filtering method and used Neutrosophic c-means clustering method to cluster the pixels into different groups. Karaaslan [50, 51] define theoretical operations for two single-valued neutrosophic refined soft sets and analyze correlation coefficient between two single-valued neutrosophic refined soft sets. In the study, a clustering analysis was conducted. Rashno et al. [72] improved a fully-automated algorithm for segmenting fluid-associated and cyst regions in optical coherence tomography of retina images and proposed a new neutrosophic transformation and applied a graph-based shortest path method. The authors also introduced a new cost function for cluster-based fluid/cyst segmentation aiming to forecast the number of clusters automatically. Thanh et al. [88] focused on medical diagnosis by analyzing the relationship between symptoms and diseases considering uncertainties. The researchers introduced a novel clustering algorithm and defined new algebraic structures i.e. lattices, De Morgan algebra, Kleen algebra, MV algebra, BCK algebra, Stone algebra, and Brouwerian algebra. Based on these structures, they suggested a new neutrosophic similarity matrix and a neutrosophic recommender equivalence matrix. The results highlighted that the proposed method provided better results compared to others in terms of clustering quality and computational time. Ye [102, 103] analyzed clustering problems under a simplified neutrosophic environment. The researcher first presented new coefficients between simplified NSs, single-valued NSs and interval NSs; then suggested a netting method to cluster simplified neutrosophic data depending on the coefficient matrix of simplified NSs. Ali et al. [9] focused on the advance of new technologies in medical imaging systems such as X-Ray machines, computed tomography scans, magnetic resonance imaging, which are very useful for diagnosing clinical cases. The authors suggested a new fuzzy clustering algorithm depending on the neutrosophic orthogonal matrices for segmenting dental medical images. The real dental datasets of Hanoi Medical University Hospital in Vietnam was employed to show the applicability of the proposed approach.

- Neutrosophic Multicriteria Decision Making

Broumi et al. [23, 24] developed neutrosophic parameterized soft set and presented their properties including aggregation operator. Then, the authors solved a multi criteria decision making (MCDM) problem using the developed sets. Bausys and Zavadskas [18] presented the extension of VIKOR method by employing interval valued neutrosophic sets. Extended approach was conducted for the solution of a logistic terminal location selection problem by taking into account both conflicting and non-common measurable criteria. Bausys et al. [19] extended COPRAS abbreviated from the complex proportional assessment method by single value neutrosophic sets. The suggested method was applied to natural gas terminal location selection problem. Ye [98, 99] examined trapezoidal neutrosophic number weighted arithmetic and geometric averaging operators and their properties including the score and accuracy functions. In the study, the researcher implemented the approach for software selection problem. Biswas et al. [21] developed TOPSIS method for group decision-making under single-valued neutrosophic environment. In the study, they used single-valued neutrosophic set-based weighted averaging operator for aggregating the decision makers' opinions. Ji et al. [46] suggested a new method based on the single-valued neutrosophic Frank normalized prioritized Bonferroni mean operator evaluating interrelationships between criteria and priority levels, for third-party logistics providers selection problem. Liu [58] proposed Archimedean t-conorm and t-norm using the single-valued neutrosophic sets by suggesting a various operators such as a single-valued neutrosophic number-weighted averaging operator and a single-valued neutrosophic number-weighted geometric operator. Liu and Tang [59] proposed an MCDM method based on "interval neutrosophic power generalized aggregation operator, interval neutrosophic power generalized weighted aggregation operator and interval neutrosophic power generalized ordered weighted aggregation operator". Peng et al. [64] suggested probability multi-valued neutrosophic sets. In the study, the authors introduced a novel qualitative flexible multiple criteria method (QUALIFLEX) and weighted average operator based on the probability multi-valued neutrosophic sets. Şahin and Liu [85] introduced the concept of possibility Simplified neutrosophic set including the neutrosophic performance and its possibility degree. For this aim, the authors developed a possibility-induced simplified neutrosophic weighted arithmetic averaging operator and possibility-induced simplified neutrosophic weighted geometric averaging operator. They applied the proposed approach for MCDM problem by calculating the weights of criteria and subcriteria using entropy measure. Wang and Liu [93] suggested the application of PROMETHEE method with interval neutrosophic sets for dynamic-group decision-making problems. They implemented the suggested approach for an energy storage alternative selection problem. Wang et al. [91] analyzed generalized Maclaurin symmetric mean aggregation operators when there is interrelationships between multiple inputs. In their study, the athors also proposed MCDM based on single-valued neutrosophic linguistic sets by employing Maclaurin symmetric mean operators. Ye [100] centered on "interval neutrosophic weighted exponential aggregation operator" as well as "a dual interval neutrosophic weighted exponential aggregation operator".

Ye also suggested an MCDM method using cosine measure functions and the proposed aggregation operators for evaluating and selecting global suppliers. Ye [101] also analyzed an interval neutrosophic hesitant fuzzy set and proposed a multiple attribute decision making method with interval neutrosophic hesitant sets by taking into account the correlation coefficients. Zavadskas et al. [107] concentrated on a lead-zinc flotation scheme selection problem. The authors evaluated circuit design schemes as Sequential Selective Pn-Zn flotation, Collective-Sequential Selective Pn-Zn flotation, Collective Pn-Zn flotation, by applying WASPAS method with single valued neutrosophic sets. Garg and Nancy [33] develop a nonlinear programming (NP) model based on TOPSIS to solve decision-making problems using interval neutrosophic numbers (INNs). The researchers converted the nonlinear fractional programming model into the linear programming model. For the ranking of the alternatives, they employed likelihood-based comparison relations. Zhang et al. [108] first applied ELECTRE IV using interval neutrosophic numbers and stated features of the outranking relations. Akram and Siddique [3] integrated single-valued neutrosophic sets with competition graphs. The researchers implemented the proposed approach for bringing solution to decision-making problems related to ecosystem and job competition. Alkhazaleh and Hazaymeh [11] applied a 'n'-valued refined neutrosophic soft sets to solve decision making problems in medical diagnosis and proposed a similarity measure between two 'n'-valued refined neutrosophic soft sets. Bao and Yang [17] examined single valued neutrosophic refined rough sets from the constructive and axiomatic viewpoints and applied the proposed sets for multi-attribute decision making problem. Baušys et al. [20] studied the location selection problem for a single-family residential house. The criteria were evaluated by AHP. Then the model was solved by WASPAS model with single valued neutrosophic sets. Chen et al. [25] firstly introduced a refined simplified neutrosophic set composed of the refined single and interval-valued neutrosophic sets, and studied on vector and the weighted similarity measures based on the Jaccard, Dice, and cosine measures in vector space. For the application section, the researchers presented an actual example on construction projects. Deli [26] defined the interval valued neutrosophic soft set and the relations between the soft set, fuzzy soft set, interval valued fuzzy soft set, intuitionistic fuzzy soft set, interval valued intuitionistic fuzzy soft set and neutrosophic soft set. Then, the author introduced some definitions and arithmetic operations and proposed a decision making method based on the interval valued neutrosophic soft sets. Deli and Şubaş [27] defined the concepts of cut sets of a single valued neutrosophic numbers, suggested a ranking method by using the concept and applied it to multi-attribute decision making problems. Deli and Şubaş [28] studied on the single valued triangular neutrosophic number and developed "weighted geometric operator, ordered weighted geometric operator and ordered hybrid weighted geometric operator based on single valued triangular neutrosophic number. The authors used the developed operators and single valued triangular neutrosophic sets for MCDM problem. Fan and Ye [31] introduced a Refined-Interval Neutrosophic Set and proposed the decision-making approach based on the Cosine Measure using Refined-Single and Interval-Valued Neutrosophic Sets. Fu and Ye [32] suggested a new exponential similarity measures for single and interval–valued neutrosophic sets in order to prevent the loss of incomplete, uncertain, and inconsistent information in the clinical survey and initial evaluation processes of the symptoms for a patient. Hu et al. [43] presented a projection-based difference measure combined with VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje method with interval neutrosophic sets (INSs) for patients to select a suitable doctor on a mobile healthcare application. Jiang and Shou [47] concentrated on single-valued neutrosophic sets and measured the similarity between single-valued neutrosophic sets by means of Dempster-Shafer evidence theory for multicriteria decision-making problems. Karaaslan [50, 51] studied the possibility neutrosophic soft set and its arithmethic operations and properties including such as “possibility neutrosophic soft subset, possibility neutrosophic soft null set, and possibility neutrosophic soft universal set”. The author also proposed possibility neutrosophic soft decision making method for decision making problems requiring AND-product operation. Li et al. [54] developed linguistic neutrosophic sets and defined “the linguistic neutrosophic geometric Heronian mean operator” and “the linguistic neutrosophic prioritized geometric Heronian mean operator”. The researchers employed the sets for solving low-carbon supplier selection problem. Liang et al. [55] analyzed the interrelationships among criteria, considered different priority levels of criteria and proposed decision making trial and evaluation laboratory (DEMATEL) approach with a single-valued trapezoidal neutrosophic sets (SVTNSs) for evaluating e-commerce websites. Liang et al. [56] to propose single-valued trapezoidal neutrosophic preference relations (SVTNPRs) as a strategy for tackling multi-criteria decision-making problems. The researchers introduced two aggregation operators which were the single-valued trapezoidal neutrosophic weighted arithmetic average operator and the single-valued trapezoidal neutrosophic weighted geometric average operator. The authors applied SVTNPRs for solving green supplier selection problems. Liu and Luo [57] defined the score function, accuracy function and certainty function of the single-valued neutrosophic hesitant fuzzy set being a combination of single-valued neutrosophic set and hesitant fuzzy set and proposed the single-valued neutrosophic hesitant fuzzy ordered weighted averaging operator and the single-valued neutrosophic hesitant fuzzy hybrid weighted averaging operator. Liu and Zhang [60] modified new Heronian mean operators for neutrosophic hesitant fuzzy set. The authors developed “the neutrosophic hesitant fuzzy improved generalized weighted Heronian mean operator” and “the neutrosophic hesitant fuzzy improved generalized geometric weighted Heronian mean operator”, and applied the proposed operators for decision making problem. Nie et al. [63] concentrated on solar-wind power station location selection problem. The researchers solved the problem employing weighted aggregated sum product assessment (WASPAS) technique based on interval neutrosophic sets which were defined as feasible for modeling more uncertainty. The authors also performed a sensitivity analysis and a comparative analysis for checking out the validity and feasibility of the proposed approach. Peng and Dai [68] improved interval neutrosophic similarity measure with interval neutrosophic number. The researchers used Shannon entropy theory for determining the weights of attributes and implemented multiattributive border approximation area comparison (MABAC), evaluation based on distance from average solution (EDAS), and similarity measure for interval neutrosophic decision-making problems. Peng et al. [66] applied the Choquet integral with simplified neutrosophic sets. In the study, the technique for order preference by similarity to ideal solution (TOPSIS) based on simplified neutrosophic sets was developed. Peng et al. [67] extended ELECTRE method abbreviated from an extension Elimination and Choice Translating Reality for bridging solution to neutrosophic multi-criteria decision-making problems based on multi-values. The suggested outranking method was similar to ELECTRE III. Pramanik et al. [69] proposed some vector similarity measures for both single-valued and interval neutrosophic sets by integrating Dice concepts and cosine similarity measures for dealing with MCDM problems. The results were compared with other existing similarity measures. Ren [73] presented the Dice similarity for ranking of single valued neutrosophic numbers and developed weighted geometric operator for single valued neutrosophic sets. The author applied MCDM method based on the developed operator and Dice similarity considering different priority levels. Stanujkic et al. [82] extended MULTIMOORA approach using single valued neutrosophic sets. Singh [76] developed the component wise three-way formal fuzzy concept together with their hierarchical order visualization. The researcher introduced the properties such as neutrosophic graph, neutrosophic lattice, and Gödel residuated lattice for a single-valued neutrosophic set. Şahin [83] proposed the single-valued neutrosophic graph and define theoretical properties including the Cartesian product, composition, and union. The researcher developed a neutrosophic graph-based multicriteria decision-making model. Şahin [84] analyzed some of the aggregation operators such as normal neutrosophic generalized prioritized weighted averaging operator and normal neutrosophic generalized prioritized weighted geometric operator. The author implemented the proposed operators for the decision making problems in which the evaluated attributes may have different priority level defined by neutrosophic sets. Wang and Zhang [92] developed the probability multivalued linguistic neutrosophic sets for multicriteria group decision making problems. The authors extended TODIM using the probability multivalued linguistic neutrosophic sets. The proposed approach was applied for project selection problem. Xu et al. [94] presented the TODIM (a Portuguese Word meaning of interactive and multiple attribute decision making) method with single-valued neutrosophic sets and extended the method using interval neutrosophic sets. Yang et al. [96] introduced single valued neutrosophic rough sets on two-universes by integrating single valued neutrosophic sets and rough sets, and proposed a hybrid model composed of constructive and axiomatic approaches. They presented a decision making algorithm with single valued neutrosophic rough sets on two-universes. Ye [102, 103] focused on a projection-based method based on simplified neutrosophic harmonic averaging that considers both the distance and the angle between the evaluated elements for solving MCDM problems. For obtaining the ranking of the alternatives, the author used the harmonic averaging projection measure. Zavadskas et al. [105, 106] developed a theoretical evaluation model by evaluating parameters related to building materials which were cost, thermal bridging, and load-bearing capacity, and the outer material selection for solving the single-family house construction materials and elements selection. The authors applied Step-wise Weight Assessment Ratio Analysis (SWARA) approach and MULTIMOORA (Multiobjective Optimisation by Ratio Analysis Plus Full Multiplicative Form) method with single-valued neutrosophic sets. Zavadskas et al. [105, 106] developed the Neutrosophic Multi-Attribute Market Value Assessment (MAMVA) method for the real estate asset assessment problem considering its economic, social, physical and locational Factors and applied the proposed approach for the market valuation of Croydon University Hospital. Ji et al. [45] solved personnel selection problem by proposed a projection-based TODIM—abbreviated from Portuguese words meaning of interactive and multi-criteria decision-making method- based on multi-valued neutrosophic sets. Uluçay et al. [89] examined similarity measures such as Dice similarity measure, weighted Dice similarity measure, Hybrid vector similarity measure and weighted Hybrid vector similarity measure for bipolar neutrosophic sets. Then, they constructed a bipolar neutrosophic multi-criteria decision-making method with the similarity measures.

- Other Neutrosophic Application Areas

Ju and Cheng [48] studied on Outer Membrane Proteins and introduced Support Vector Machine inputs based on a novel neutronsophic set considering the weighting function. The authors tested the performance of the proposed approach. The analysis results showed that the proposed approach have reduced the effects of outliers and outperformed the traditional Support Vector Machine.

Arora and Biswas [14] developed neutrosophic relational data model for retrieving answers for queries which have posted in natural language. The proposed intelligent soft-computing method help the users for their imprecise queries based on Neutrosophic Proximity search and α-Neutrosophic-equality Search.

Thamaraiselvi and Santhi [86] developed a mathematical model for solving a transportation problem under neutrosophic environment. In the proposed model, indeterminate and inconsistent information were handled by neutrosophic sets. A real life case study was also presented to check the applicability of the proposed mathematical model.

Radwan et al. [70, 71] centered on a neutrosophic expert system with regard to learning management systems. The researchers prepared surveys and asked five experts to fulfill the surveys and then conducted the analysis by means of Fuzzytech 5.54d software. Akbulut et al. [2] proposed neutrosophic weighted extreme learning machine. In their study, the authors applied neutrosophic c-means clustering algorithm for the approximation of the output weights related to the extreme learning machine.

Guan et al. [34, 35] concentrated on daily fluctuation trends of a stock market and proposed a new forecasting model, a fluctuation time series with neutrosophic sets. The researchers applied the proposed method to forecast Taiwan Stock Exchange Capitalization Weighted Stock Index (TAIEX) and the Shanghai Stock Exchange Composite Index (SHSECI).

4 Conclusion

The advancement of fuzzy sets and fuzzy logic have mostly become in the area of the definition of membership functions. Membership functions of ordinary fuzzy sets are composed of the discrete values or continuous functions indicating only membership. Later, the criticisms made for the crispness of the membership degrees caused the emergence of type-2 fuzzy sets. The idea that the sum of membership and non-membership is exactly equal to 1 has been changed by Atanassov [16] to be at most 1 and these sets have been named as intuitionistic fuzzy sets (IFS). Smarandache [79] extended IFS to neutrosophic sets by incorporating a third parameter "indeterminacy" to IFS definition. Later, this idea has been extended to intuitionistic type 2 fuzzy sets by Atanassov [15] to be square sum of membership and non-membership degrees is at most equal to 1. This provided a larger domain to decision makers in order to define fuzzy sets. Intuitionistic type 2 fuzzy sets have been renamed as Pythagorean fuzzy sets (PFS) by Yager [95].

This chapter summarized the advancement of neutrosophic sets in the history of fuzzy sets through a state-of-the-art literature review. The neutrosophic works in the literature have been classified with respect to research areas and illustrative figures have been given. For further research, we suggest a research on common and uncommon features of IFS, PFS, and NS. This can meet the need for understanding the mathematical relations among these sets and help fuzzy sets to be progressed on more robust theoretical basis.

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