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A bibliometric analysis of neutrosophic set: two decades review from 1998 to 2017

Xindong Peng[1] · Jingguo Dai[1]

Abstract
Neutrosophic set, initiated by Smarandache, is a novel tool to deal with vagueness considering the truth-membership T, indeterminacy-membership I and falsity-membership F satisfying the condition $0 \leq T + I + F \leq 3$. It can be used to characterize the uncertain information more sufficiently and accurately than intuitionistic fuzzy set. Neutrosophic set has attracted great attention of many scholars that have been extended to new types and these extensions have been used in many areas such as aggregation operators, decision making, image processing, information measures, graph and algebraic structures. Because of such a growth, we present an overview on neutrosophic set with the aim of offering a clear perspective on the different concepts, tools and trends related to their extensions. A total of 137 neutrosophic set publication records from Web of Science are analyzed. Many interesting results with regard to the annual trends, the top players in terms of country level as well as institutional level, the publishing journals, the highly cited papers, and the research landscape are yielded and explained in-depth. The results indicate that some developing economics (such as China, India, Turkey) are quite active in neutrosophic set research. Moreover, the co-authorship analysis of the country and institution, the co-citation analysis of the journal, reference and author, and the co-occurrence analysis of the keywords are presented by VOSviewer software.

Keyword Neutrosophic set · Aggregation operators · Decision making · Information measures · Image processing · Bibliometric analysis

1 Introduction

To dispose uncertain or vague information in decision making, Zadeh (1965) presented the fuzzy set (FS) that characterized by a membership function which assigns to each target a membership value ranging between 0 and 1. Alcantud and Díaz (2017) defined the notion of sequential application of fuzzy choice functions, and investigated its normative implications under related concepts of rationalizability. Alcantud and Calle (2017) discussed the problem of collective identity in a fuzzy environment. Intuitionistic fuzzy set (IFS), initially

✉ Xindong Peng
952518336@qq.com

1 School of Information Science and Engineering, Shaoguan University, Shaoguan 512005, China

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proposed by Atanssov (1986), is associated with each element of a universe not only take membership function but also non-membership (whose sum is less than or equal one). Hence it can describe more precisely and definitively than fuzzy set. However, it can only deal with incomplete and uncertainty information but not the indeterminate and inconsistent information which exists commonly in real-life. Therefore, Smarandache (1998) originally proposed the concept of a neutrosophic set (NS) from philosophical point of view. According to the definition of a NS presented by Smarandache, a NS A in a universal set X is characterized independently by a truth-membership function $T_A(x)$, an indeterminacy-membership $I_A(x)$ and a falsity-membership $F_A(x)$. The functions $T_A(x)$, $I_A(x)$, and $F_A(x)$ in X are real standard or nonstandard subsets of $]^-0, 1^+[$, i.e., $T_A(x) : X \to]^-0, 1^+[$, $I_A(x) : X \to]^-0, 1^+[$, and $F_A(x) : X \to]^-0, 1^+[$. Smarandache (1999) and Wang et al. (2010) further proposed a single valued neutrosophic set (SVNS), by modifying the conditions $T_A(x)$, $I_A(x)$ and $F_A(x) \in [0, 1]$ and $0 \leq T_A(x) + I_A(x) + F_A(x) \leq 3$, which are more suitable for solving scientific and engineering problems.

Neutrosophic set has attracted the attention of numerous scholars in a short period of time because of its wide scope of description cases are very common in diverse real-life issue, and this new set boosts the management of vagueness caused by neutrosophic scope. A deep revision of the specialized literature shows the rapid growth and serviceability of NS, which has been expanded to diverse point of visual angle, quantitatively and qualitatively.

Given the neutrosophic-related research has been lasted for 20 years and is increasingly attracting researcher's interests, it is necessary for us to make a comprehensive overview toward this domain to seek for some potential patterns or scientific development path over the NS research. Bibliometric analysis is a widely used method to depict the development of a certain field (Merigó et al. 2016). Although there is a survey related to NS (Nguyen et al. 2017; El-Hefenawy et al. 2016; Rivieccio 2008), it only focused on reviewing the neutrosophic set in biomedical diagnoses. Meanwhile, it did not provide any bibliometric analysis for NS-related research. Therefore, in this paper, we conduct a bibliometric analysis on NS-related research to fill in this gap.

The paper is organized as follows. Section 2 reviews seven main research points for NS. Section 3 depicts the patterns and dynamics of neutrosophic research along with six aspects: (1) annual trends; (2) country level; (3) institutional level; (4) publishing journals; (5) highly cited papers; and (6) research landscape. Moreover, (1) the co-authorship analysis of the country and institution; (2) the co-citation analysis of the journal, reference and author; (3) the co-occurrence analysis of the keywords are presented by VOSviewer software. Conclusions with some findings are drawn in the last section.

2 Literature review

Just as denoted by the distinguished British philosopher and Nobel Laureate, Russell (1923), " All traditional logic habitually assumes that precise symbols are being employed. It is therefore not applicable to this terrestrial life but only to an imagined celestial existence," the relationship between precision and uncertain has puzzled scholars and philosopher for centuries. Lukasiewicz, born in Polish, introduced the multi-valued logic that extended the range of truth values to all real numbers in [0, 1] and thus led to an inexact reasoning technique called possibility theory (Lukasiewicz 1930). Later, Black (1937) defined the first simple fuzzy set and outlined the basic ideas of fuzzy set operations. Zadeh (1965) rediscovered fuzziness and extended the work on possibility theory into a formal system of mathematical logic. Nearly 30 years later, Smarandache stated that "Neutrosophy is a new branch of philosophy which studies the origin, nature, and scope of neutralities, as well as their interactions with different ideational spectra" (Smarandache 1998). Neutrosophy is a multiple value logic that specifies classical logic, fuzzy logic, and imprecise probability. Neutrosophy is closer to human rational as it describes the imprecision of knowledge or linguistic inaccuracy established by several observers. Every event in the neutrosophy theory has certain degree of truth, falsity degree, and an indeterminacy degree, which should be considered independently from each other. The realism of the neutrosophic paradigm is justified by well-established social phenomena that include different sports (win–tie–defeat) and voting situations (yes-abstention-no). Alcantud and Laruelle (2014) gave real examples and an axiomatic basis for the voting interpretation of the truth-indeterminacy-falsity setting. As he gave a systematic paradigm to use and operate over NS, Professor Smarandache is deemed as the "master of neutrosophic logic."

In the following, we main focus on seven parts to review the whole development of NS.

2.1 The extensions of neutrosophic set

The core idea of modeling such a neutrosophic situation has been expanded together with the previous methods and tools to the following new cases:

- to handle the neutrosophic in qualitative environments in which information is linguistic form
- to manage the truth-membership, indeterminacy-membership and falsity-membership that are not exactly defined but expressed by interval-values, intuitionistic fuzzy sets, triangular fuzzy sets, cubic sets, bipolar fuzzy set, trapezoidal fuzzy sets, or hesitant fuzzy set
- to deal with the inadequacy of the parameterized by combining soft set
- to cope with the lower and upper approximations by fusing with rough set

These extensions are further detailed in Table 1.

In the future, although some extensions may be proposed, they will not be published in a famous journal. Because of combining NS with other mathematics tools will not obtain special or novel results. Hence, the research directions will focus on the existing fundamental extensions of NS such as SVNS, INS, SNS.

2.2 Aggregation operators

Multitudinous aggregation operators used for decision making are based on the geometric mean, arithmetic mean, and integrals. A number of popularized operators have been developed to aggregate diverse kinds of evaluation information. We will follow with interest in the aggregation operators under neutrosophic set and its extension environment.

2.2.1 Algebraic aggregation operators

In real world decision situation, the aggregation problems in the MCDM are solved using the scoring techniques such as the weighted aggregation operator based on multi attribute theory. The classical weighted aggregation is usually known by the weighted average (WA) or

Table 1 The extensions of neutrosophic set

Sets	Abbreviation	Proposed
Single valued neutrosophic set	**SVNS**	Wang et al. (2010)
Interval neutrosophic set	**INS**	Wang et al. (2005a)
Simplified neutrosophic set	**SNS**	Ye (2014h)
Neutrosophic soft set	**NSS**	Maji (2013)
Single valued neutrosophic linguistic set	**SVNLS**	Ye (2015a)
Multi-valued neutrosophic set	**MVNS**	Wang and Li (2015)
Rough neutrosophic set	**RNS**	Broumi et al. (2014a)
Simplified neutrosophic linguistic set	**SNLS**	Tian et al. (2016b)
Bipolar neutrosophic set	BNS	Deli et al. (2015)
Trapezoidal neutrosophic set	TNS	Biswas et al. (2014b)
Neutrosophic hesitant fuzzy set	NHFS	Ye (2015d)
Neutrosophic cubic set	NCS	Ali and Deli (2016) and Jun et al. (2017)
Possibility neutrosophic soft set	PNSS	Karaaslan (2017b)
Neutrosophic vague soft expert set	NVSES	Al-Quran and Hassan (2016)
Time neutrosophic soft set	TNSS	Alkhazaleh (2016)
Triangular neutrosophic set	TrNS	Deli and Şubaş (2017b)
Interval-valued neutrosophic soft set	IVNSS	Deli (2017)
Complex neutrosophic set	CNS	Ali and Smarandache (2017)
Normal neutrosophic set	NNS	Liu and Teng (2017a)
Simplified neutrosophic uncertain linguistic set	SNULS	Tian et al. (2018)
Interval neutrosophic linguistic set	INLS	Ye (2014f)
Single-valued neutrosophic refined soft set	SVNRSS	Karaaslan (2017a)
ivnpiv-Neutrosophic soft set	ivnpiv-NSS	Deli et al. (2018)
Probability multi-valued neutrosophic set	PMVNS	Peng et al. (2016b)
Probability multi-valued linguistic neutrosophic set	PMVLNS	Wang and Zhang (2017)
Interval neutrosophic hesitant fuzzy set	INHFS	Ye (2016a)
Intuitionistic neutrosophic set	InNS	Bhowmik and Pal (2009)
Generalized neutrosophic soft set	GNSS	Broumi (2013)
Intuitionistic neutrosophic soft set	INSS	Broumi and Smarandache (2013b)
Neutrosophic refined set	NRS	Smarandache (2013)
Possibility simplified neutrosophic set	PSNS	Şahin and Liu (2017c)
Linguistic neutrosophic set	LNS	Li et al. (2017)
Single valued neutrosophic trapezoid linguistic set	SVNTLS	Broumi and Smarandache (2014c)
Single-valued neutrosophic uncertain linguistic set	SVNULS	Liu and Shi (2017)
Multi-valued interval neutrosophic set	MVINS	Wang et al. (2005b)

Table 1 continued

Sets	Abbreviation	Proposed
Single valued neutrosophic rough set	SVNRS	Yang et al. (2017a)
Neutrosophic valued linguistic soft set	NVLSS	Zhao and Guan (2015)
Single valued neutrosophic multiset	SVNM	Ye and Ye (2014)
Single valued multigranulation neutrosophic rough set	SVMNRS	Zhang et al. (2016b)
n-Valued refined neutrosophic soft set	n-VRNSS	Alkhazaleh (2017)
Double-valued neutrosophic set	DVNS	Kandasamy (2018)

The bold eight NS extensions are widely used in real life

weighted geometric (WG) or simple additive weighting method. A very common aggregation operator is the ordered weighted averaging (OWA) operator or ordered weighted geometric (OWG) which provides a parameterized family aggregation operator between the minimum, the maximum, the arithmetic average, and the median criteria whose originally introduced by Yager (1988).

The related neutrosophic Algebraic aggregation operators are shown in Table 2.

2.2.2 Bonferroni mean aggregation operators

The Bonferroni mean (BM) was originally introduced by Bonferroni (1950). The classical Bonferroni mean is an extension of the arithmetic mean and its generalized by some researchers based on the idea of the geometric mean (Sun and Sun 2012). The BM differs from the other classic means such as the arithmetic, the geometric and the harmonic because this mean reflect the interdependent of the individual criterion meanwhile on the classic means the individual criterion is independent, which makes BM very useful in various application fields.

The related neutrosophic Bonferroni mean aggregation operators are shown in Table 3.

2.2.3 Einstein aggregation operators

The related neutrosophic Einstein aggregation operators are shown in Table 4.

2.2.4 Power aggregation operators

Power average (PA), originally proposed by Yager (2001), uses a non-linear weighted average aggregation tool and a power ordered weighted average (POWA) operator to provide aggregation tools which allow exact arguments to support each other in the aggregation process. The weighting vectors of the PA operator and the POWA operator depend on the input arguments and allow arguments being aggregated to support and reinforce each other. In contrast with most aggregation operators, the PA and POWA operators incorporate information regarding the relationship between the values being combined. Recently, these operators have received much attention in the literature.

The related neutrosophic Power aggregation operators are shown in Table 5.

Table 2 Distribution based on neutrosophic Algebraic aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Ye (2015a)	NHFS	SVNHFWA and SVNHFWG	Decision making
Deli et al. (2015)	BNS	BNWA and BNWG	Decision making
Ye (2014f)	INLS	INLWAA and INLWAG	Decision making
Peng et al. (2016b)	PMVNS	PMVNNWA	Decision making
Şahin and Liu (2017c)	PSNS	PISNWAA and PISNWGA	Decision making
Broumi and Smarandache (2014c)	SVNTLS	SVNTrLWAA and SVNTrLWAG	Decision making
Zhao and Guan (2015)	NVLSS	NVLSSGWA	Decision making
Zhang et al. (2014)	INS	INNWA and INNWG	Decision making
Peng et al. (2016a)	SNS	SNNWA, SNNWG, SNNOWA, SNNOWG, SNNHOWA, SNNHOWG, GSNNWA, GSNNWG	Decision making
Liu and Shi (2015)	INHFS	INHFGWA, INHFWQA, INHFWG, INHFWA, INHFGOWA, INHFOWA, INHFGOWG, INHFGOWQA, INHFGHWA, INHFHWA, INHFHWG, INHFHQWA	Decision making
Ye (2015c)	INS	INNOWA and INNOWG	Decision making
Ye (2017d)	INULS	INULWAA and INULWGA	Decision making
Zhao et al. (2015)	INS	IVNSGWA	Decision making
Ye (2016e)	INS	CIINWAA and CIINWGA	Decision making
Liu (2016)	SVNS	ASVNNWA and ASVNNWG	Decision making
Ye (2015e)	TNS	TNNWAA and TNNWGA	Decision making
Tan et al. (2017a)	SVNLS	GSVNLWA, GSVNLOWA, GSVNLHA	Decision making
Zhan et al. (2017)	NCS	NCWA and NCWG	Decision making
Peng and Wang (2015)	MVNS	MVNNWA, MVNNWG, MVNNOWA, MVNNOWG, MVNNHOWA, MVNNHOWG	Decision making
Zheng et al. (2017)	NS	NNWAA, NNOWAA, NNHWAA, NNWGA, NNHWGA, NNGWA, NNGOWA, NNGHWA	Decision making

2.2.5 Hamacher aggregation operators

The related neutrosophic Hamacher aggregation operators are shown in Table 6.

2.2.6 Cloud aggregation operators

The normal cloud (NC) model, which is based on probability theory and fuzzy set theory (Yang et al. 2014), was originally proposed by Li et al. (1995, 2004) as a novel cognition model

Table 3 Distribution based on basic neutrosophic aggregation operators by Bonferroni mean

Authors	Sets	Aggregation operators	Application scenes
Tian et al. (2016b)	SNLS	SNLNWBM	Decision making
Liu and Wang (2014)	SVNS	SVNNWBM	Decision making
Liu and Li (2017)	NNS	NNBM, NNWBM, NNGBM, NNWGBM	Decision making
Tian et al. (2017b)	SNLS	SNLNGWBM	Decision making
Liang et al. (2016)	TNS	SVTNNWBM	Decision making
Ji et al. (2016)	SVNS	SVNFNPBM	Decision making

Table 4 Distribution based on neutrosophic Einstein aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Zhang et al. (2014)	INS	INNEWA and INNEWG	Decision making
Peng et al. (2016a)	SNS	SNNEWA, SNNEWG, SNNOEWA, SNNOEWG, SNNHOEWA, SNNHOWG, GSNNEWA, GSNNEWG	Decision making
Liu (2016)	SVNS	ESVNNWA and ESVNNWG	Decision making

Table 5 Distribution based on neutrosophic Power aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Peng et al. (2015a)	MVNS	MVNPWA and MVNPWG	Decision making
Yang and Li (2016)	SVNS	SVNPA and SVNPWA	Decision making
Liu and Tang (2016)	INS	INPGA, INPGWA, INPGOWA	Decision making
Liu and Liu (2018)	SVNS	NNWPA, NNWGPA, GNNWPA	Decision making
Liu and Luo (2017)	SNS	SNNPWA, SNNPWG, SNNPOWA, SNNPOWG	Decision making

Table 6 Distribution based on neutrosophic Hamacher aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Liu (2016)	SVNS	HSVNNWA and HSVNNWG	Decision making
Liu et al. (2014a)	SVNS	GNNHWA and GNNHHA	Decision making

of uncertainties in response to the randomness of membership functions. Wang et al. (2014) defined several aggregation operators, including the cloud weighted arithmetic averaging (CWAA) operator, cloud weighted geometric averaging (CWGA) operator, cloud-ordered weighted arithmetic averaging (COWA) operator, and cloud hybrid aggregation operator in order to develop a linguistic decision-making approach.

The related neutrosophic Cloud aggregation operators are shown in Table 7.

2.2.7 Exponential aggregation operators

Some optimization models cannot deal with the NSs directly, and also cannot make full use of the original neutrosophic information. To overcome this issue and avoid the loss of decision information in the aggregation and modelling process, some exponential operational law

Table 7 Distribution based on neutrosophic Cloud aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Zhang et al. (2016d)	SVNS	NNCWAA and NNCWGA	Decision making

Table 8 Distribution based on neutrosophic Exponential aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Şahin and Liu (2017a)	SNS	SNWEA and DSNWEA	Decision making
Ye (2016b)	INS	INWEA and DINWEA	Decision making
Lu and Ye (2017)	SVNS	SVNWEA	Decision making

Table 9 Distribution based on neutrosophic Prioritized aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Tian et al. (2018)	SNULS	GSNULPWA and GSNULPWG	Decision making
Li et al. (2017)	LNS	LNPGHM	Decision making
Ji et al. (2016)	SVNS	SVNFNPBM	Decision making
Ma et al. (2017)	INLS	GINLPWHM and GINLPHHM	Decision making
Liu and Wang (2016)	INS	INPOWA	Decision making
Şahin (2017b)	NNS	NNPWA, NNPWG, NNGPWA, NNGPWG	Decision making
Wu et al. (2016)	SNS	SNNPWA and SNNPWG	Decision making

for SVNS, INS and SNS are developed. The related neutrosophic Exponential aggregation operators are shown in Table 8.

2.2.8 Prioritized aggregation operators

In practical situations, decision-makers usually consider different criteria priorities. To deal with this issue, Yager (2008) proposed prioritized average (PA) operators by modeling the criteria priority on the weights associated with the criteria, which depend on the satisfaction of higher priority criteria. The PA operator has many advantages over other operators. For example, the PA operator does not need to provide weight vectors and, when using this operator, it is only necessary to know the priority among the criteria.

The related neutrosophic Prioritized aggregation operators are shown in Table 9.

2.2.9 Choquet integral aggregation operators

One of the popular aggregation operator fuzzy integrals is the Choquet integral which is introduced by Choquet (1953). Choquet integral is defined as a subadditive or superadditive to integrate functions with respect to the fuzzy measures (Murofushi and Sugeno 1989).

The related neutrosophic Choquet integral aggregation operators are shown in Table 10.

Table 10 Distribution based on neutrosophic Choquet integral aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Peng et al. (2017a)	SNS	SNCIWA and SNCIWG	Decision making
Sun et al. (2015)	INS	INNCI	Decision making
Yang et al. (2018)	INS	GINFCA	Decision making
Han and Wei (2017)	SVNS	SVNCI	Decision making

Table 11 Distribution based on neutrosophic Heronian aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Li et al. (2017)	LNS	LNGHM and LNPGHM	Decision making
Liu and Shi (2017)	SVNULS	SVNULIGWHM and SVNULIGGWHM	Decision making
Li et al. (2016)	SVNS	IGWHM, IGWGHM, SVNNIGWHM, SVNNIGWGHM	Decision making
Liu and Zhang (2017b)	NHFS	NHFIGWHM and NHFIGGWHM	Decision making
Liu and Teng (2017b)	NNS	NNNIGWHM and NNNIGGWHM	Decision making

Table 12 Distribution based on neutrosophic Correlated aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Liu and Luo (2016b)	SNS	SNCA and SNCG	Decision making

2.2.10 Heronian aggregation operators

Heronian mean (HM) operator is an important aggregation operator which has the characteristic of capturing the correlations of the aggregated arguments. Beliakov et al. (2007) had firstly proved that Heronian mean was an aggregation operator, but he did not do further researches. Further works are extended to the generalized Heronian means, and discussed two special cases of them. Meanwhile, combining Heronian means and neutrosophic set with its extensions, some related neutrosophic Heronian aggregation operators are shown in Table 11.

2.2.11 Correlated aggregation operators

The related neutrosophic Correlated aggregation operators are shown in Table 12.

2.2.12 Frank aggregation operators

The related neutrosophic Frank aggregation operators are shown in Table 13.

2.2.13 Dombi aggregation operators

Dombi (1982) developed the operations of the Dombi T-norm and T-conorm, which have the advantage of good flexibility with the operational parameter. Hence, Liu et al. (2018) extended

Table 13 Distribution based on neutrosophic Frank aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Ji et al. (2016)	SVNS	SVNFNPBM	Decision making
Nancy and Garg (2016b)	SVNS	SVNFWA and SVNFWG	Decision making

Table 14 Distribution based on neutrosophic Dombi aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Chen and Ye (2017)	SVNS	SVNDWAA and SVNDWGA	Decision making

Table 15 Distribution based on neutrosophic Maclaurin symmetric mean aggregation operators

Authors	Sets	Aggregation operators	Application scenes
Wang et al. (2016a)	SVNLS	SVNLMSM	Decision making

the Dombi operations to IFSs and proposed some intuitionistic fuzzy Dombi Bonferroni mean operators and applied them to multiple attribute group decision-making (MAGDM) problems with intuitionistic fuzzy information.

The related neutrosophic Dombi aggregation operators are shown in Table 14.

2.2.14 Maclaurin symmetric mean aggregation operators

The related neutrosophic Maclaurin symmetric mean aggregation operators are shown in Table 15.

From above 14 kinds of aggregation operators, we can know that the final destination is to make decision. Meanwhile, for some real applications, different aggregation operators have different application scenes. In the future, some research points are shown as follows.

(1) Extended the 14 kinds of aggregation operators into diverse extensions of NS;
(2) Combined novel aggregation operators out of above 14 kinds with NS or its extensions;
(3) Applied one kind of aggregation operators to solve a decision making problem in certain filed;
(4) Combined some existing aggregation operators for obtaining new aggregation operators (still in above 14 kinds) such as neutrosophic prioritized power aggregation operators (prioritized + power).

2.3 Information measures

In this subsection, the axiomatic skeleton of information measures (distance measure, similarity measure, entropy measure, inclusion measure/subsethood measure, correlation coefficients) are reviewed.

2.3.1 Similarity measure

The similarity measure indicates the similar degree of two objects. Wang (1983) initially proposed the concept of fuzzy sets' similarity measure and gave a computation formula. It has been applied to different settings such as intuitionistic fuzzy set (Peng et al. 2015b), hesitant fuzzy set (Xu and Xia 2011), Pythagorean fuzzy set (Peng et al. 2017d; Peng and Dai 2017b; Peng and Ganeshsree 2018), interval-valued fuzzy soft set (Peng and Yang 2017; Peng and Garg 2018).

In the following, some related similarity measures for NS and its extensions are reviewed, which is shown in Table 16.

2.3.2 Distance measure

Distance measure is an important tool for measuring the vague information which describes the difference between two objects and has become a hot topic in decision making, machine learning, and pattern recognition. In the following, some related distance measures for NS and its extensions are reviewed, which is shown in Table 17.

2.3.3 Entropy measure

Entropy is used to measure the uncertain degree of two objects and has been widely used in diverse domains. Several scholars have studied it from different points of view. For example, Luca and Termini (1972) developed some axioms which captured human's intuitive comprehension to describe the fuzziness degree of a fuzzy set.

In the following, some related entropy measures for NS and its extensions are reviewed, which are shown in Table 18.

2.3.4 Correlation coefficients

Correlation coefficient is employed to explore the nature of the relations between the variables, and also may be used to make inferences about any one of the variables on the basis of the others. Based on these concepts and their axiomatic definitions, some existing correlation coefficients are shown in Table 19.

2.3.5 Inclusion measure/subsethood measure

The inclusion measure (subsethood measure) of fuzzy sets indicates the degree to which a fuzzy set is contained in another fuzzy set. Zadeh (1965) initially developed the definition of a fuzzy set inclusion and pointed out that inclusion was a crisp relation. That is to say, a fuzzy set is either included or not included in another fuzzy set. After that, many scholars study the inclusion measure in diverse environment by the axiomatic approach. In the following, some related inclusion measures/subsethood measures for NS and its extensions are reviewed, which are shown in Table 20.

From above 5 kinds of information measures, we can know that the most of final destinations are to decision making. Also, some are used for image processing, medical diagnosis, pattern recognition. In the future, some research points are shown as follows.

Table 16 Distribution based on neutrosophic similarity measure.

Authors	Sets	Application scenes
Biswas et al. (2014b)	TNS	Decision making
Ali and Deli (2016)	NCS	Pattern recognition
Ye and Ye (2014)	SVNM	Medical diagnoses
Ye (2014c)	INS	Decision making
Majumdar and Samanta (2014)	SVNS	*
Broumi and Smarandache (2013c)	SVNS	*
Ye (2017h)	SVNS	Fault diagnosis
Ye (2014i)	SVNS	Clustering analysis
Ye (2014g)	SVNS	Decision making
Ye (2015b)	SNS	Medical diagnoses
Pramanik and Mondal (2015a)	RNS	Medical diagnoses
Ye (2014b)	SVNS	Decision making
Broumi and Smarandache (2014a)	NRS	Medical diagnoses
Guo et al. (2014)	SVNS	Image processing
Guo and Şengür (2014)	SVNS	Image processing
Ye and Zhang (2014)	SVNS	Decision making
Guo et al. (2016)	SVNS	Image processing
Ye and Fu (2016)	SVNS	Medical diagnoses
Pramanik and Mondal (2015d)	RNS	Decision making
Mondal and Pramanik (2015c)	NRS	Decision making
Pramanik and Mondal (2015b)	RNS	Medical diagnoses
Pramanik et al. (2017a)	SVNS	Decision making
Mukherjee and Sarkar (2014b)	NSS	Decision making
Peng and Liu (2017)	NSS	Decision making
Peng and Dai (2017a)	INS	Decision making
Mondal and Pramanik (2015d)	SVNS	Decision making
Ye et al. (2015)	SVNM	Medical diagnoses
Kong et al. (2015)	SVNS	Misfire fault diagnosis
Aydoğdu (2015b)	SVNS	Decision making
Mukherjee and Sarkar (2014a)	IVNSS	Pattern recognition
Mukherjee and Sarkar (2015)	NSS	Pattern recognition
Can and Ozguven (2017)	SVNS	PID tuning
Ye (2017g)	SVNS	Clustering analysis
Aydoğdu (2015a)	INS	*
Ye (2016d)	SVNS	Fault diagnoses
Amin et al. (2016)	SVNS	Classification analysis
Qi et al. (2016)	SVNS	Image processing
Mandal and Basu (2015)	SVNS	Decision making
Guo et al. (2017b)	SVNS	Image processing
Ye and Smarandache (2016)	NRS	Decision making
Sahin et al. (2017)	SVNS	Pattern recognition
Mandal and Basu (2016)	SVNS	Minimum spanning tree

Table 16 continued

Authors	Sets	Application scenes
Ye (2016c)	SVNS	Fault diagnoses
Guo et al. (2017a)	SVNS	Image processing
Ye (2016f)	SNS	Decision making
Şahin and Küçük (2014)	NSS	Decision making

"*" Denotes that it is only discussed its properties

Table 17 Distribution based on neutrosophic distance measure

Authors	Sets	Application scenes
Kandasamy (2018)	DVNS	Minimum spanning tree/clustering analysis
Broumi and Smarandache (2013c)	SVNS	*
Ye (2014b)	SVNS	Decision making
Ye et al. (2015)	SVNM	Medical diagnoses
Ye (2014e)	SVNS	Minimum spanning tree
Liu and Luo (2016c)	SVNS/INS	Decision making
Huang (2016)	SVNS	Decision making/clustering analysis

"*" Denotes that it is only discussed its properties

Table 18 Distribution based on neutrosophic Entropy measure

Authors	Sets	Application scenes
Deli et al. (2018)	ipnpiv-NSS	Decision making
Wu et al. (2016)	SNS	Decision making
Aydoğdu (2015b)	SVNS	Decision making
Aydoğdu (2015a)	INS	*
Şahin and Küçük (2014)	NSS	Decision making
Ye (2014d)	SVNS	Decision making
Guo and Cheng (2009)	SVNS	Image processing
Heshmati et al. (2016)	SVNS	Image processing
Şahin (2017a)	INS	Decision making
Sengur and Guo (2011)	SVNS	Image processing
Liu and Luo (2016a)	INS	*
Hu et al. (2017)	SVNS	Image processing
Mohan et al. (2013a)	SVNS	MRI denoising
Garg and Garg (2016)	SVNS	Decision making
Guo et al. (2009)	SVNS	Image processing
Tian et al. (2016a)	INS	Decision Making
Biswas et al. (2014c)	SVNS	Decision making
Wu and Wang (2017)	MVNS	Decision making

"*" Denotes that it is only discussed its properties

(1) Proposed some novel information measures (similarity measure, distance measure, entropy measure, inclusion measure/subsethood measure, correlation coefficients) formulae under the corresponding 4 axiomatic definitions;

Table 19 Distribution based on neutrosophic correlation coefficients

Authors	Sets	Application scenes
Ye (2016a)	INHFS	Decision making
Ye (2013b)	SVNS	Decision making
Broumi and Deli (2014)	NRS	Medical diagnosis
Broumi and Smarandache (2013a)	INS	*
Zhang et al. (2015)	INS	Decision making
Ye (2017b)	SVNS	Decision making
Ye (2014a)	SVNS/INS	Decision making
Hanafy et al. (2013)	SVNS	*
Ye (2013a)	SVNS	Decision making
Şahin and Liu (2017b)	NHFS	Decision making
Karaaslan (2016)	PNSS	*
Ye (2017c)	NNS	Decision making
Shi (2016)	SNS	Bearing fault diagnosis
Liu and Luo (2016d)	INHFS	Decision making

"*" Denotes that it is only discussed its properties

Table 20 Distribution based on neutrosophic Inclusion measure/subsethood measure

Authors	Sets	Application scenes
Sahin and Karabacak (2015)	INS	Decision making
Şahin and Küçük (2015)	SVNS	Decision making
Ji and Zhang (2016)	INS	*

"*" Denotes that it is only discussed its properties

(2) Utilized some existing formulae for decision making, image processing, medical diagnosis, pattern recognition;
(3) Suggested the systematic transformation of information measures for achieving their fundamental properties.

2.4 MCDM methods

Decision making is one of the most important and complex tasks for individuals or organizations and is an interdisciplinary research area attracting researchers from almost all fields from psychologists, economists, to computer scientists (Zhan and Alcantud 2018). As an important research branch of decision-making theory, multiple criteria decision making (MCDM) has gained great success. MCDM methods cover a wide range of quite distinct approaches. MCDM methods can be broadly classified into two categories: discrete MADM (multi-attribute decision making) and continuous MODM (multi-objective decision making) methods.

In MODM problems, the number of alternatives is effectively infinite, and the trade-offs among design criteria are typically described by continuous functions. MADM problems are distinguished from MODM problems, which involve the design of a best/optimal alternative by considering the trade-offs within a set of interacting design constraints and a set of quantifiable objectives. MADM refers to making selections among some courses of action in

Table 21 Summary of applications of the MCDM techniques

MCDM methods	Frequency of application	Percentage (%)
Aggregation operators	51	31.29
Information measures	32	19.63
Hybrid MCDM	16	9.82
TOPSIS	13	7.98
WASPAS	3	1.85
COPRAS	1	0.61
SWARA	1	0.61
VIKOR	3	1.84
ELECTRE	4	2.45
TODIM	3	1.84
QUALIFLEX	3	1.84
GRA	12	7.36
MULTIMOORA	1	0.61
PROMETHEE	1	0.61
Projection method	5	3.07
Other	14	8.59
Total	163	100

the presence of multiple, usually conflicting, attributes. Although Philosophers often make a distinction between properties and attributes, it is common that many scholars take MCDM and MADM as interchangeable and use MCDM to represent the discrete MCDM.

Table 21 shows frequency of both neutrosophic MCDM tools and approaches. Based on results presented in this table, a total of 163 studies have employed MCDM tools and approaches. This table shows that aggregation operators method (51 papers) has been used more than other tools and approaches. The second one is the method of information measures (32 papers) and traditional hybrid MCDM (16 papers) is the third in this ranking. Tables 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34 and 35 show implementation of each neutrosophic MCDM tools and approaches.

2.5 Image processing

2.5.1 Medical imaging processing

Image processing is processing of images using mathematical operations by using any form of signal processing for which the input is an image, a series of images, or a video, such as a photograph or video frame; the output of image processing may be either an image or a set of characteristics or parameters related to the image. Generally, the neutrosophic set (NS) approaches were applied successfully into image processing including image denoising, image thresholding, image classification, image clustering, and image segmentation . In the following, we will show the concrete details in Tables 36, 37, 38, 39 and 40.

Table 22 Distribution based on neutrosophic hybrid methods

Authors	Sets	Methods	Tools and approaches
Ye (2015a)	SVNLS	TOPSIS + SVNWA	Implemented of SVNLS-TOPSIS and aggregation operators for ranking possible companies
Tian et al. (2017b)	SNLS	MULTIMOORA + SNLWA	Suggested SNLS-MULTIMOORA and SNLWA for alternative selecting
Wu et al. (2016)	SNS	Cross entropy + SNPWA	Suggested cross entropy and SNPWA for alternative selecting
Peng et al. (2017a)	SNS	TOPSIS + SNWA	Extended SNS-TOPSIS and SNWA for MCGDM problem
Yang et al. (2018)	INS	Choquet integral + linear assignment method + GINFCA	Presented hybrid method for invest company selection
Peng and Liu (2017)	NSS	EDAS + level soft set	Applied the combined method for software development selection
Peng and Dai (2017a)	INS	EDAS + MABAC	Modified the combined method for teacher or company selection
Tian et al. (2016a)	INS	TOPSIS + entropy	Application of INS-TOPSIS and entropy for evaluation of investment appraisal project
Biswas et al. (2014c)	SVNS	GRA + entropy	Combined the SVNS-GRA and entropy for ranking possible companies
Pouresmaeil et al. (2017)	SVNS	TOPSIS + VIKOR	Implemented of SVNS-TOPSIS-VIKOR for supplier selection
Peng and Dai (2018)	SVNS	TOPSIS + MABAC	Proposed a SVNS-TOPSIS-MABAC for language selection
Tian et al. (2017a)	SNLS	TOPSIS + QUALIFLEX	Suggested a TOPSIS–QUALIFLEX for green product design
Rajeswara et al. (2016)	INS	TOPSIS + AHP	Developed INS-TOPSIS-AHP for ranking best supplier
Yang et al. (2017b)	MIVNS	Choquet integral + TOPSIS	Presented MIVNS-Choquet integral-TOPSIS for subway alternatives selection
Şahin and Liu (2016)	SVNS and INS	SVNWA + INWA + maximizing deviation	Extended hybrid method for selecting supplier
Ji et al. (2018)	MVNS	TODIM + Projection method	Implemented of MVNS–TODIM–Projection for personnel selection

Table 23 Distribution based on neutrosophic TOPSIS

Authors	Sets	Tools and approaches
Şahin and Yiğider (2014)	NS	Employed NS-TOPSIS for supplier selection
Chi and Liu (2013)	INS	Presented a new INS-TOPSIS for selection of a company
Broumi et al. (2015)	INULS	Applied INULS-TOPSIS for solving company selection problems
Biswas et al. (2016)	SVNS	Using a SVNS-TOPSIS approach for tablet selection
Dey et al. (2015b)	GNSS	Proposed a GNSS-TOPSIS approach for selection
Zhang and Wu (2014)	SVNS	Extended SVNS-TOPSIS for solving supplier selection problem
Pramanik et al. (2015)	NSES	Developed NSES-TOPSIS for an assistant teacher selection
Mondal et al. (2016)	RNS	Developed RNS-TOPSIS for logistic center location selection
Nădăban and Dzitac (2016)	SVNS	Provided a general view of SVNS-TOPSIS
Elhassouny and Smarandache (2016)	SVNS	Modified the SVNS-TOPSIS for simplifying the calculation
Pramanik et al. (2016)	RNS	Applied RNS-TOPSIS for tab selection in shop
Dey et al. (2016b)	BNS	Extended BNS-TOPSIS for car selection
Liu et al. (2016b)	INS	Application of INS-TOPSIS for evaluation of investment appraisal project

Table 24 Distribution based on neutrosophic GRA

Authors	Sets	Tools and approaches
Biswas et al. (2014a)	SVNS	Employed SVNS-GRA for ranking possible companies
Pramanik and Dalapati (2016)	GNSS	Developed GNSS-GRA for decision making
Dey et al. (2016c)	INULS	Proposed INULS-GRA for selecting optimal company
Pramanik and Mondal (2015c)	INS	Developed INS-GRA for suitable school selection
Dey et al. (2015a)	INS	Application of INS-GRA for selection of weaver
Mondal and Pramanik (2015e)	RNS	Presented RNS-GRA for solving the weights of criteria are unknown
Dey et al. (2016a)	NHFS	Suggested NHFS-GRA for selecting ideal company
Banerjee et al. (2017)	NCS	Extended of NCS-GRA for optimal alternative
Dey et al. (2016d)	NSS	Using NSS-GRA for selection of house
Mondal and Pramanik (2015a)	SVNS	Presented SVNS-GRA for clay-brick
Wang (2016)	INS	Applied INS-GRA for urban flood control and disaster reduction program evaluation
Mondal and Pramanik (2015b)	SVNS	Application of SVNS-GRA for school choice

Table 25 Distribution based on neutrosophic TODIM

Authors	Sets	Tools and approaches
Wang and Li (2015)	MVNS	Developed MVNS-TODIM for choosing optimal company
Wang and Zhang (2017)	PMVLNS	Applied PMVLNS-TODIM for a MCGDM problem
Zhang et al. (2016a)	SVNS	Presented SVNS-TODIM for choosing best investment project

Table 26 Distribution based on neutrosophic WASPAS

Authors	Sets	Tools and approaches
Zavadskas et al. (2015)	SVNS	Implemented of SVNS-WASPAS for alternative sites selection
Zavadskas et al. (2016)	SVNS	Presented SVNS-WASPAS for choosing lead-zinc flotation circuit design
Baušys and Juodagalvienė (2017)	SVNS	Employed SVNS-WASPAS for Garage location selection to residential house

Table 27 Distribution based on neutrosophic VIKOR

Authors	Sets	Tools and approaches
Bausys and Zavadskas (2015)	INS	Implemented of INS-VIKOR for location selection
Liu and Zhang (2017a)	NHFS	Developed NHFS-VIKOR for invest selection
Tan et al. (2017b)	SVNS	Applied SVNS-VIKOR for emergency decision making

Table 28 Distribution based on neutrosophic ELECTRE

Authors	Sets	Tools and approaches
Peng et al. (2017c)	MVNS	Implemented of MVNS-ELECTRE for location selection
Zhang et al. (2016c)	INS	Developed INS-ELECTRE for location selection
Peng et al. (2014)	SNS	Presented SNS-ELECTRE for diverse application selection
Liu et al. (2016a)	INS	Applied INS-ELECTRE for invest selection

Table 29 Distribution based on neutrosophic PROMETHEE

Authors	Sets	Tools and approaches
Wang and Liu (2016)	INS	Implemented of INS-PROMETHEE for energy storage alternative selection

Table 30 Distribution based on neutrosophic QUALIFLEX

Authors	Sets	Tools and approaches
Tian et al. (2017c)	SNLS	Suggested SNLS-QUALIFLEX for selecting green product design
Peng et al. (2017b)	MVNS	Employed MVNS-QUALIFLEX for selecting green supplier design
Peng et al. (2016b)	PMVNS	Developed PMVNS-QUALIFLEX for choosing logistics outsourcing

Table 31 Distribution based on neutrosophic COPRAS

Authors	Sets	Tools and approaches
Bausys et al. (2015)	SVNS	Suggested SVNS-COPRAS for selecting location of a liquefied natural gas

Table 32 Distribution based on neutrosophic MULTIMOORA

Authors	Sets	Tools and approaches
Stanujkic et al. (2017)	SVNS	Employed SVNS-MULTIMOORA for choosing comminution circuit designs

Table 33 Distribution based on neutrosophic SWARA

Authors	Sets	Tools and approaches
Stanujkic et al. (2016)	SVNS	Suggested SVNS-SWARA for restaurants selecting

Table 34 Distribution based on neutrosophic Projection method

Authors	Sets	Tools and approaches
Ye (2017a)	SVNS	Suggested SVNS-Projection for optimal alternative selection
Ye (2017f)	SNS	Employed SVNS-Projection for choosing best company
Pramanik et al. (2017b)	BNS	Presented BNS-Projection for car selection
Ye (2017e)	SVNS	Implemented of SVNS-Projection for design schemes selection
Chen and Ye (2016)	SVNS	Developed SVNS-Projection for clay-brick selection

2.5.2 Medical diagnosis

Medical diagnosis is the process of determining which disease or condition explains a person's symptoms and signs. It is most often referred to as diagnosis with the medical context being implicit. The information required for diagnosis is typically collected from experts' examination of the person seeking medical care. Often, one or more diagnostic procedures, such as diagnostic tests, are also done during the process. Sometimes Posthumous diagnosis is considered a kind of medical diagnosis. Diagnosis is often challenging, because many signs and symptoms are fuzzy. For accurate medical diagnosis, researchers are interested in developing new algorithms to handle the modalities variety output. Recently, a new trend is to use the NS approaches in the processing stages to achieve precise diagnoses from the captured images.

In the following, we will show the concrete details in Table 41.

2.6 Graph

A graph is a convenient way of representing information involving relationship between objects. The objects are represented by vertices and the relations by edges. When there is vagueness in the description of the objects or in its relationships or in both, it is natural that we need to designe a fuzzy graph Model. The extension of fuzzy graph theory (Gani and Ahamed 2003) have been developed by several researchers including intuitionistic fuzzy graph (Akram and Davvaz 2012) considered the vertex sets and edge sets as intuitionistic fuzzy sets. Interval

Table 35 Distribution based on neutrosophic other methods

Authors	Sets	Tools and approaches
Nancy and Garg (2016a)	SVNS	Suggested SVNS based on score function for company selecting
Deli and Şubaş (2017a)	SVNS and TrNS	Using the concept of values and ambiguities to solve some MACM problems
Akram and Shahzadi (2017b)	NSS	Combined NSS with graph for house selection
Broumi et al. (2016e)	INS	Extended neutrosophic graph-based multicriteria decision making method to the case of INS-graph
Akram and Sitara (2018)	SVNS	Discussed new applications of SVN-graph structures in decision-making by proposed algorithms
Akram and Sarwar (2017)	BNS	Proposed the dominating and independent set of BN-graph to multiple attribute decision making
Ashraf et al. (2017)	SVNS	Introduced regular, edge regular, partially edge regular and full edge regular SVN-graph and SVN digraph for decision making
Akram and Shahzadi (2016)	INSS	Combined INSS with graph for multiple attribute decision making
Deli and Broumi (2015a)	NSS	Constructed a NSS matrix decision making method for car selection
Maji (2012)	NSS	Introduced multiobserver input parameter data set based on NSS for decision making
Mondal and Pramanik (2014)	SNS	Ranked teacher recruitment based on SNS hybrid score-accuracy functions
Maji (2015)	NSS	Combined comparison matrix with score of an object for decision making
Das et al. (2017)	NSS	Applied neutrosophic soft matrix and relative weights to business investment
Zavadskas et al. (2017)	SVNS	Applied neutrosophic MAMVA method for evaluating sustainable market valuation

valued fuzzy graphs (Akram 2012) considered the vertex sets and edge sets as interval valued fuzzy sets. In the following, we will review some neutrosophic graphs in Table 42.

From above references of graph, we can know that the most of final destination are widely used in diverse domains. In the future, some research points are shown as follows.

(1) Discussed some basic properties of neutrosophic graph or its extensions;
(2) Applied graph theory into more areas for solving more issues.

2.7 Algebraic structures

Algebraic structure is a set (called carrier set or underlying set) with one or more finitary operations defined on it that satisfies a list of axioms. Examples of algebraic structures include groups, rings, fields, and lattices. More complex structures can be defined by introducing multiple operations, different underlying sets, or by altering the defining axioms. In the following, we only review some neutrosophic algebraic structures or its extensions in Table 43.

Table 36 Distribution based on neutrosophic image denoising

Authors	Description
Mohan et al. (2013a)	Transformed the resulting nonlocal means filtered image into NS domain by applying three membership sets. And measured the indeterminacy by entropy. The Wiener filtering operation was applied on T and F by removing the noise and decreasing the set indeterminacy I. Compared to other denoising techniques, the proposed nonlocal NS Wiener filter produced superior de-noising results in terms of quantitative and qualitative measures
Guo et al. (2009)	Evaluated the indetermination by measuring the entropy in neutrosophic image domain and removed the image noise or indetermination by a γ -median-filtering operation. And the results established NS supportedimage de-noising for several scenarios, namely with different noise levels and with different noise kinds without knowing the noise type
Faraji et al. (2013)	Applied new NS based pre-processing technique for enhancing and removing noise form facial features in original face images
Mohan et al. (2012a)	Removed the Rician noise from simulated MRI from Brainweb database using NS approach with wiener filtering. And the NS entropy was employed to calculate the indeterminacy I and the ω-wiener filtering operation was applied on T and F in order to remove the noise and to decrease the set indeterminacy
Mohan et al. (2013b)	Developed the framework that can be used with any denoising filter using the NS. The NS provide efficient de-noising which can be independent on the noise type and/or level by the proposed filter. Some quality metrics can be measured including the PSNR, SSIM index, mean square error, and average difference when evaluated the de-noising process

Table 37 Distribution based on neutrosophic image clustering

Authors	Description
Guo and Sengur (2015)	Proposed a clustering algorithm based on the NS which membership T can be measured as the membership degree to determinant clusters, the other two memberships, namely I and F were used to define an ambiguity cluster and an outlier cluster, respectively
Yu et al. (2013)	Adopted mean shift clustering in NS domain to segment images, which makes it possible to detect constructions with a stable threshold
Akbulut et al. (2017)	Extended the idea of NCM for nonlinear-shaped data clustering by incorporating the kernel function into NCM. According to the obtained results, the proposed KNCM produced better results than KFCM

Table 38 Distribution based on neutrosophic image thresholding

Authors	Description
Guo et al. (2014)	Developed a new algorithm based on neutrosophic similarity score which defined to measure the degree to the ideal object to execute thresholding on image
Guo et al. (2009)	Transformed the images into NS domain using the three subsets, namely T, I and F with calculating the NS entropy to evaluate the indetermination. A new λ-mean operation was proposed to reduce the indetermination in the NS which can process clean images, images with different types of noise and images with multiple types of noise

Table 39 Distribution based on neutrosophic image segmentation

Authors	Description
Guo et al. (2009)	Integrated the *k*-means with the NS for image segmentation for achieving superior results with clean and noisy images. Nevertheless, it fail if the entropy is varying, which may cause boundaries and edges blur
Anter et al. (2014)	Proposed an enhanced segmentation method based on the NS and FCM by carring out to segment abdominal computerized CT images. The entropy in the NS was employed to evaluate the indeterminacy, and the abdominal CT images were segmented and the liver parenchyma was selected using connected componentapproach which has less sensitive to noise and performed superior performance with non-uniform CT images
Zhang et al. (2010b)	Applied the watershed algorithm to segment the image in the neutrosophic domain for providing superior results compared with that obtained by the existing techniques
Hanbay and Talu (2014)	Proposed a novel synthetic aperture radar (SAR) image segmentation algorithm based on the NS and improved artificial bee colony (I-ABC) algorithm. I-ABC optimization algorithm is presented to search for the optimal threshold value
Shan et al. (2012)	Proposed fully automatic and accurate breast lesion segmentation for ultrasound (BUS) images combined neutrosophic l-means clustering approach that was applied to detect the precise lesion boundary. A PMO algorithm was applied to improve the image quality by filtering the image in the frequency domain and manipulating the phase accumulationin the orientation with maximum energy
Zhao et al. (2016)	Proposed a novel segmentation algorithm based on NS and quantum-behaved particle swarm optimization (QPSO) for fulfilling side scan sonar (SSS) image segmentation accurately and efficiently
Guo and Sengur (2013)	Improved fuzzy c-means clustering method by integrating with NS and employed for the color image segmentation

Table 40 Distribution based on neutrosophic image classification

Authors	Description
Kraipeerapun et al. (2007)	Proposed medical binary classification using ensemble neural networks (NN) based on bagging technique and INS for improving the classification performance compared to the simple majority vote and averaging approaches which were applied only to the truth membership value. The results depicted that INS represented uncertainty information and supported the classification quite well
Ju (2011)	Applied an integrated NS into a reformulated support vector machine by segmenting by a two-stage self-organizing map (HSOM) using texture and color features. The results established the effectiveness and validity of the proposed NS technique for the input samples of SVM based on the distances between the sample and the class centers
Sayed and Hassanien (2017)	Presented an automatic mitosis detection approach of histopathology slide imaging based on using NS and moth-flame optimization (MFO) for obtaining fast, robust, efficient and coherent in early diagnostic suspicion of breast cancer

Table 41 Distribution based on neutrosophic medaical diagnosis styles

Medaical diagnosis styles	Authors	Description
CTI		
	Jayanthi (2016)	Discussed the possibility of different segmenting techniques for liver from the abdominal CTI to detect and classify liver regions by comparingdifferent segmentation algorithms such as the label connected, seeded region growing, and NS with thresholding
	Sayed et al. (2015)	Proposed a hybrid segmentation technique based on Neutrosophic logics and modified Watershed procedure for enhancing the attained truth image formed from the previous phase and extracting liver from the CT images
	Guo et al. (2013)	Developed an iterative neutrosophic lung segmentation (INLS) scheme to propose the EMM segmentation using the anatomic features of the lungs for improving segmentation accuracy
	Paras et al. (2012)	Presented an effective method for CT images denoising to remove the Additive white Gaussian Noise (AWGN) and to improve the images quality
MRI		
	Mohan et al. (2012b)	Implemented of a NS approach of MRI for denoising by reducing the Rician noise in the MR images. A validation based on structural similarity such as quality index based on local variance (QILV) and structural similarity index (SSIM) were carries out. The diagnostic and visual quality of the de-noised image was well preserved
	Elnazer et al. (2016)	Developed segmentation technique based on NS and modified non local fuzzy c-mean clustering by transforming Brain tumor MRI images intothe NS domain. Comparing with studies using Dice Coefficient and Jaccard Index, the results proved that the proposed technique was less sensitive to noise and performed superior performance on MRI brain images
UI		
	Shan et al. (2012)	Presented a new fully automatic technique for BUS images segmentation by using a novel neutrosophic clustering method to detect the accurate lesion boundary. The results established that the proposed technique generated the most similar boundaries to the radiologist's manual delineations
	Zhang et al. (2010a)	Developed the neutrosophy to fully automate an algorithm for breast ultrasound image segmentation. The results established that the proposed technique was effective, accurate, and robust
	Koundal et al. (2016)	The Spatial Neutrosophic Distance Regularized Level Set (SNDRLS) achieves the automatednodule boundary even for low-contrast, blurred, and noisy thyroid ultrasound images without any human intervention

CTI computed tomography imaging, *MRI* magnetic resonance imaging, *UI* ultrasound imaging

Table 42 Distribution based on neutrosophic graph

Authors	Sets	Description
Broumi et al. (2016e)	INS	Extended neutrosophic graph-based multicriteria decision making method to the case of INS-graph
Akram and Sitara (2018)	SVNS	Discussed new applications of SVN-graph structures in decision-making by proposed algorithms
Akram and Sarwar (2017)	BNS	Proposed the dominating and independent set of BN-graph to multiple attribute decision making
Akram and Shahzadi (2016)	INSS	Combined INSS with graph for multiple attribute decision making
Broumi et al. (2016c)	TNS	Applied TN-graph for solving shortest path problem
Akram and Nasir (2017)	INS	Modified the definition of an IN-graph for presenting new operations and discussing complete graphs
Akram and Sitara (2017)	BNS	Presented the construction methods of BN-graph to investigate their properties
Chalapathi and Kumar (2017)	SVNS	Combined finite groups with SVN-graph to discuss basic properties
Akram and Shahzadi (2017a)	SVNS	Explored interesting properties of SVN-graph by level graph and applied it to social network
Broumi et al. (2017)	BNS	Developed SVN-graph for finding the shortest path on a network
Hamidi and Saeid (2017)	SVNS	Derived SVN-graph from SVNS hypergraph via strong equivalence relation
Akram and Shahzadi (2017b)	NSS	Introduced the concept of NS-graph to apply it in decision making
Mehra and Singh (2017)	SVNS	Proposed new concept of SVNS singedgraphs for examining by some examples
Naz et al. (2017)	SVNS	Provided new operations for forming SVNG disgraph in travel time
Broumi et al. (2016b)	BNS	Introduced the BN-graph, strong BN-graph, complete BN-graph for discussing their properties
Broumi et al. (2016d)	SVNS	Examined the properties of various types of degrees, order and size of SVN-graphs
Broumi et al. (2016a)	SVNS	Proved for a SVN-graph to be an isolated SVN-graph
Akram (2016)	SVNS	Extended SVN-graph to multigraphs, planar graphs and dual graphs
Shah and Hussain (2016)	NSS	Established a link between graphs and NSS for further discussing strong NSS-graph
Shah and Broumi (2016)	SVNS	Discussed neighbourly irregular and highly irregular SVN-graphs to be equivalent
Malik et al. (2016)	SVNS	Defined the regular and totally regular SVN-hypergraphs for extending work on completeness
Akram (2017)	BNS	Presented some m-step BN-graphs
Akram et al. (2017)	SVNS	Designed a SVN-graph decision making algorithm for optimal alternative selection
Anitha and Gunavathi (2016)	SVNS	Applied SVN cognitive maps for classifying musical features

Table 42 continued

Authors	Sets	Description
Dutta (2016)	NS	Analysis of side effects of chemotheraphy treatment for cancer patientsusing neutrosophic cognitive graphs (NCG)
Akram and Luqman (2017)	SVNS	Introduced SVN-directed hypergraphs for certain networks models

Table 43 Distribution based on neutrosophic Algebraic Structures

Authors	Sets	Used structures
Singh (2017)	SVNS	Three-way concept lattice
Bera and Mahapatra (2017)	NSS	Ring, subring, normal soft ring, ideal
Yang et al. (2016)	SVNS	SVN-relations
Deli and Broumi (2015b)	NSS	NSS-ralations
Broumi et al. (2014b)	INSS	INSS-ralations
Lupiáñez (2008)	SVNS	SVNS-relations
Lupiáñez (2009a)	INS	INS-relations
Lupiáñez (2009b)	SVNS	SVNS-relations
Lupiáñez (2010)	SVNS	SVNS-relations
Broumi and Smarandache (2014b)	SVNS	SVNS-relations
Broumi and Smarandache (2015)	INS	Opeations
Cetkin and Aygun (2015)	SVNS	Subgroup
Borzooei et al. (2014)	SVNS	BL-algebras

From above neutrosophic algebraic structures, we can know that the most used sets are SVNS and INS due to their special properties. In the future, the main research point is to explore more algebraic structures such as group-like (semigroup, group, Abelian group, Quasigroup), ring-like structures (semiring, near-ring, lie ring, boolean ring, field), lattice structures (complete lattice, bounded lattice, complemented lattice, modular lattice, distributive lattice), Hybrid structures (topological group, Lie group, ordered groups, ordered rings, ordered fields, Archimedean group).

3 Analyses

3.1 Data and method

3.1.1 Web of Science™ core collection: all

Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index-Science (CPCI-S), Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH) , four widely used citation indexes of Thomson Reuters Web of Science, were chosen for raw bibliographic data collection in this research compared with only SCIE/SSCI. In order to retrieve the neutrosophic-related publications, we used the following search strategy. We retrieved our data on June 22, 2017, and the search returned 212 hits.

$$\text{Title} = (\text{neutrosophic}); \text{Indexes} = *; \text{Timespan} = 1998-2017.$$

3.1.2 Web of Science^{TM} Core Collection: SCIE/SSCI

In order to retrieve the neutrosophic-related publications by SCIE/SSCI, we used the following search strategy. We retrieved our data on June 22, 2017, and the search returned 137 hits.

$$\text{Title} = (\text{neutrosophic}); \text{Indexes} = \text{SCIE, SSCI}; \text{Timespan} = 1998-2017.$$

In the following paper, we mainly take SCIE/SSCI into consideration.

3.2 Annual trends and possible explanations

Figure 1 plots the annual trends of neutrosophic-related publications. Since the classical reference (book) of Smarandache (1998), the neutrosophic-related research obtained no essential journals' papers over the first 7 years (most papers are conference papers shown in Fig. 2 when 2001 and 2005). However, when entering into the 2008, more and more scholars paid attentions to this area. This leds to the steady and stable increase in neutrosophic-related publications. As the neutrosophic set theory became more and more influential in scientific community, the publication records even received exponential increase at the beginning of the year 2013. There are many possible reasons resulting in this strong increase. Firstly, the great development of economic and Internet makes it easy to obtain different kinds of references and materials on neutrosophic theory. Meanwhile, more and more scholars worldwide, especially in China, have joined into this research field. The widely spread of neutrosophic publications shows the success of neutrosophic theory in practical applications. In addition, the increase in neutrosophic publications should also owe to the creation of journals and other related ones that were recently accepted neutrosophic publications which is indexed by SCIE/SSCI in Web of Sciences. This is apparently reflected in Fig. 1. Observe that many journals have expanded their issues to accommodate more papers. This also leads to the increase in neutrosophic records.

It should be noted that the number of publications will be far more than 48 at the end of 2017 (The current publications are 27).

Figure 2 is more than the number of papers in Fig. 1 for the conference papers. That is to say, in the early period, conference papers are main way due to its fast publish.

3.3 Country level

Our data shows that researchers from over 15 countries/territories were involved in the neutrosophic-related knowledge production during our total study period, but over 80% of the publications were contributed by authors from the top 4 active countries/territories. China, as a rising power in scientific research, is the largest producer of neutrosophic publications. Researchers from China have published 69 publications in this domain with a share of 50.36%. The India is the second prolific producer in this field with 11.68% of the world total publications; however, its share is far behind its Chinese counterpart. Following China

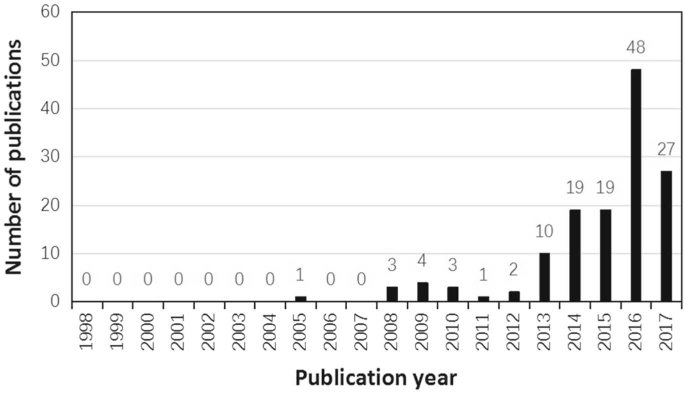

Fig. 1 Annual trends of neutrosophic-related publications by SCIE/SSCI

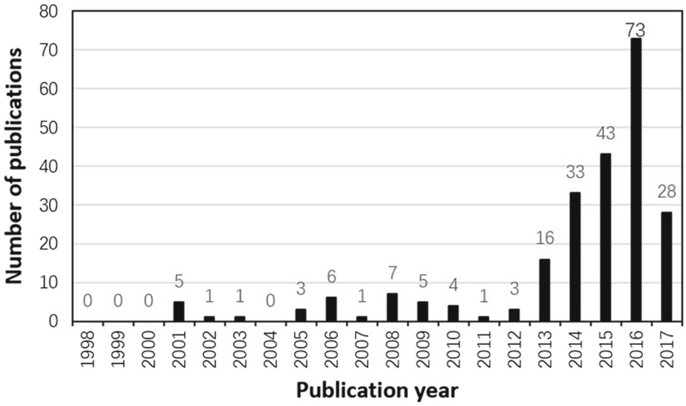

Fig. 2 Annual trends of neutrosophic-related publications by ALL

and the India, Turkey, and USA are also prolific actors ranked between 3rd and 4th with the publication shares of 10.95% and 10.22%, respectively.

Table 44 depicts the top 15 most prolific regions of neutrosophic-related knowledge production. It is quite surprising that some small or developing economies such as India, and Turkey are among the top players in this research domain. The main actors in this research domain are significantly different from those in other fields such as nanotechnology (Chen et al. 1991), biomass-based bioenergy (Liu et al. 2014b). To further explore this issue, we calculate the shares of all SCIE/SSCI publications in all research fields in 2017 named as Share *B* in Table 44 for these 15 regions.

The shares of neutrosophic publications of all the study period (Share *A*) and the shares of all SCIE/SSCI publications in 2017 (Share *B*) are quite different for almost all the top regions. Lithuania contributed 0.11% to the world total SCIE/SSCI publications in 2017; however, 26.55% of the neutrosophic publications were authored from the affiliations in Lithuania. This demonstrates that researchers from Lithuania are relatively active in publishing in this domain compared to their contribution to all the research fields. Turkey, Pakistan, and Serbia are also similar to Lithuania. On the contrary, researchers from some developed economies such as the USA, Spain, and Australia are relatively unlikely to contribute to this domain than to other research fields.

Table 44 Author distribution by country level

Rank	Regions	Publications	Share A (%)	Share B (%)	Share A/Share B
1	China	69	50.36	17.05	2.95
2	India	16	11.68	3.95	2.96
3	Turkey	15	10.95	1.90	5.76
4	USA	14	10.22	26.02	0.39
5	Spain	4	2.92	3.86	0.76
6	Lithuania	4	2.92	0.11	26.55
7	Pakistan	3	2.19	0.51	4.29
8	Iran	2	1.46	1.85	0.79
9	Australia	2	1.46	3.92	0.37
10	Egypt	2	1.46	0.61	2.39
11	Saudi Arabia	2	1.46	0.73	2
12	Serbia	1	0.73	0.22	3.31
13	Taiwan	1	0.73	1.84	0.11
14	England	1	0.73	6.46	0.11
15	Italy	1	0.73	4.45	0.16

Share A, the share of global neutrosophic-related publications; Share B, the share of global SCIE/SSCI publications in 2017

Only four document types (articles, letters, notes, reviews) were included

3.4 Institutional level

After identifying the top producers from the country level, we further recognize the top actors in the institutional level. Shaoxing University from China leads with 28 publications and a share of 30.10% of all the global publications. Following Shandong University of Finance and Economics University and Central South University also from China, are shared as the second producers with 10 publications. Table 45 lists the details of the top 20 most prolific institutions who are active in neutrosophic-related knowledge production. Among the top 20 active institutions, China (8 institutions), Turkey (5 institutions), India (2 institutions), USA (1 institution), Lithuania (1 institution), Pakistan (1 institution), Spain (1 institution), and Australia (1 institution) are the main countries/territories that these institutions affiliated to. This echoes the previous finding that these countries/territories are active in neutrosophic research.

3.5 Publishing journals

Over 50 SCIE/SSCI journals have published neutrosophic research work. *Journal of Intelligent and Fuzzy Systems* is the largest outlet which has published 36 neutrosophic publications, followed by *Neural Computing and Applications* (12), *Applied Soft Computing* (6), *International Journal of Machine Learning and Cybernetics* (4), and *Kybernetes* (4). The leading journal, *Fuzzy Sets and Systems*, also publishes 1 neutrosophic-related papers. Table 46 lists the top 52 publication outlets for neutrosophic research.

We further detect the publication outlet preference of the top 6 productive countries/territories among these important outlets as shown in Table 46. Chinese researchers have published in more than 25 journals for their 69 publications. *Journal of Intelligent*

Table 45 Author distribution by institutional level

Rank	Institution	Regions	Publications	Share (%)
1	SHAOXING UNIV	China	28	30.10
2	SHANDONG UNIV FINANCE ECON	China	10	10.75
3	CENT S UNIV	China	10	10.75
4	UNIV ILLIONIS	USA	5	5.38
5	VILNIUS GEDIMINAS TECH UNIV	Lithuania	5	5.38
6	UNIV COMPLUTENSE	Spain	4	4.30
7	CIVIL AVIAT UNIV CHINA	China	3	3.23
8	BAYBURT UNIV	Turkey	3	3.23
9	ATATURK UNIV	Turkey	3	3.23
10	FIRAT UNIV	Turkey	2	2.15
11	HUBEI UNIV AUTOMOT TECHNOL	China	2	2.15
12	CANKIRI KARATEKIN UNIV	Turkey	2	2.15
13	UNIV PUNJAB	Pakistan	2	2.15
14	PANJAB UNIVERSITY	India	2	2.15
15	SHANXI UNIV	China	2	2.15
16	THAPAR UNIV	India	2	2.15
17	KILIS 7 ARALIK UNIV	Turkey	2	2.15
18	NORTHEAST FORESTRY UNIV	China	2	2.15
19	MURDOCH UNIV	Australia	2	2.15
20	CHINESE ACAD SCI	China	2	2.15

and Fuzzy Systems, with relatively low impact factors in recent years, was Chinese scholars' first choice to publish its outputs. 36 out of 69 publications of China were published in this journal. Among all the 36 publications in this journal, 28 papers were published in recent 3 years (2015–2017). This may due to the quick rising of publication volume of this journal in recent 3 years. Besides, *Neural Computing and Applications* (7), *International Journal of Fuzzy Systems* (5), and I*nternational Journal of Systems Science* (3) were also Chinese researchers' main outlets to publish. India also has published 12 different journals which is narrower than their Chinese counterparts, but is wider than other countries.

The publication outlet preference of researchers from the Spain was quite different from other regions. Although with only 4 publications, Spain scholars have published in one journal (*Kybernetes*).

From 2013, a specialized neutrosophic journal named "*Neutrosophic Sets and Systems*" has been created by Smarandache. Although it has not been indexed by SCIE, it has a certain influence in neutrosophic domain. We also believe that it will be indexed by SCIE in our neutrosophic researchers' endeavour.

3.6 Highly cited papers

To roughly identify the most influential scientific minds in neutrosophic-related research, we select the top 11 highly cited papers and 1 hot paper of neutrosophic publications from Web of Science which are ranked by total number of citations. Table 47 illustrates these highly

Table 46 Main publication outlets

Rank	IF (2016)	Journal	Publications	China	India	Turkey	USA	Spain	Lithuania	Pakistan	Iran
1	1.261	Journal of Intelligent and Fuzzy Systems	36	22	3	6					1
2	2.505	Neural Computing and Applications	12	7	2	2	1				
3	3.541	Applied Soft Computing	9	1	2	3	2				
4	2.198	International Journal of Fuzzy Systems	6	5		1					
5	1.699	International Journal of Machine Learning and Cybernetics	4	2	1	1					
6	0.811	Kybernetes	4					4			
7	2.503	Computer Methods and Programs in Biomedicine	3	1			2				
8	1.056	Informatica	3	2							
9	2.285	International Journal of Systems Science	3	3							
10	0.802	Mathematical Problems in Engineering	3	2	1						
11	3.441	Cognitive Computation	2	2							
12	0.299	Economic Computation and Economic Cybernetics Studies and Research	2						2		
13	1.044	IET Image Processing	2		1						1
14	1.019	International Journal for Uncertainty Quantification	2		2						
15	1.140	International Journal of Computational Intelligence Systems	2								

Table 46 continued

Rank	IF (2016)	Journal	Publications	China	India	Turkey	USA	Spain	Lithuania	Pakistan	Iran
16	2.359	Measurement	2								
17	2.617	Medical Physics	2				1				
18	4.582	Pattern Recognition	2	1			1				
19	1.130	Springerplus	2	2							
20	2.718	Fuzzy Sets and Systems	1								
21	0.754	Journal of Electronic Imaging	1			1					
22	1.570	Computers and Electrical Engineering	1				1				
23	3.083	Journal of Classification	1	1							
24	1.082	Optical Engineering	1				1				
25	3.317	Neurocomputing	1								
26	1.281	Shock and Vibration	1	1							
27	2.350	Applied Mathematical Modelling	1	1							
28	0.279	University Politehnica of Bucharest Scientific Bulletin-Series-A-Applied Mathematics and Physics	1						1		
29	3.110	Signal Processing	1								
30	2.214	Biomedical Signal Processing and Control	1		1						
31	0.556	Journal of Systems Science and Complexity	1	1							
32	*	Group Decision and Negotiation	1	1							
33	1.627	Marine Geophysical Research	1	1							
34	4.529	Knowledge-Based Systems	1		1						

Table 46 continued

Rank	IF (2016)	Journal	Publications	China	India	Turkey	USA	Spain	Lithuania	Pakistan	Iran
35	2.009	Artificial Intelligence in Medicine	1		1						
36	xx	Applied Mathematics and Information Sciences	1			1					
36	2.164	Journal of Visual Communication and Image Representation	1	1							
37	2.472	Soft Computing	1	1							
38	0.695	Filomat	1	1							
39	1.789	Sustainability	1						1		
40	0.344	Spectroscopy and Spectral Analysis	1	1							
41	2.929	International Journal of Intelligent Systems	1	1							
42	0.557	Journal of Scientific and Industrial Research	1		1						
43	1.180	Expert Systems	1								
44	2.476	Biomed Research International	1								
45	1.694	Circuits Systems and Signal Processing	1				1				
46	0.769	Acta Montanistica Slovaca	1						1		
47	0.835	Optik	1	1							
48	2.498	Computer Vision and Image Understanding	1				1				
49	1.930	Journal of Parallel and Distributed Computing	1	1							

Table 46 continued

Rank	IF (2016)	Journal	Publications	China	India	Turkey	USA	Spain	Lithuania	Pakistan	Iran
50	1.664	International Journal of Information Technology and Decision Making	1	1							
51	1.344	Measurement Science Review	1		1						
52	xx	Scientific World Journal	1	1							

Rank	IF (2016)	Journal	Publications	Australia	Egypt	Saudi Arabia	Serbia	Taiwan	England	Italy
1	1.261	Journal of Intelligent and Fuzzy Systems	36		2	2				
2	2.505	Neural Computing and Applications	12							
3	3.541	Applied Soft Computing	9						1	
4	2.198	International Journal of Fuzzy Systems	6							
5	1.699	International Journal of Machine Learning and Cybernetics	4							
6	0.811	Kybernetes	4							
7	2.503	Computer Methods and Programs in Biomedicine	3							
8	1.056	Informatica	3				1			
9	2.285	International Journal of Systems Science	3							
10	0.802	Mathematical Problems in Engineering	3							

Table 46 continued

Rank	IF (2016)	Journal	Publications	Australia	Egypt	Saudi Arabia	Serbia	Taiwan	England	Italy
11	3.441	Cognitive Computation	2							
12	0.299	Economic Computation and Economic Cybernetics Studies and Research	2							
13	1.044	IET Image Processing	2							
14	1.019	International Journal for Uncertainty Quantification	2							
15	1.140	International Journal of Computational Intelligence Systems	2							
16	2.359	Measurement	2							
17	2.617	Medical Physics	2							
18	4.582	Pattern Recognition	2							
19	1.130	Springerplus	2							
20	2.718	Fuzzy Sets and Systems	1							1
21	0.754	Journal of Electronic Imaging	1							
22	1.570	Computers and Electrical Engineering	1							
23	3.083	Journal of Classification	1							
24	1.082	Optical Engineering	1							
25	3.317	Neurocomputing	1	1						
26	1.281	Shock and Vibration	1							
27	2.350	Applied Mathematical Modelling	1							

Table 46 continued

Rank	IF (2016)	Journal	Publications	Australia	Egypt	Saudi Arabia	Serbia	Taiwan	England	Italy
28	0.279	University Politehnica of Bucharest Scientific Bulletin-Series-A-Applied Mathematics and Physics	1							
29	3.110	Signal Processing	1							
30	2.214	Biomedical Signal Processing and Control	1							
31	0.556	Journal of Systems Science and Complexity	1							
32	*	Group Decision and Negotiation	1							
33	1.627	Marine Geophysical Research	1							
34	4.529	Knowledge-Based Systems	1							
35	2.009	Artificial Intelligence in Medicine	1							
36	xx	Applied Mathematics and Information Sciences	1							
36	2.164	Journal of Visual Communication and Image Representation	1							
37	2.472	Soft Computing	1							
38	0.695	Filomat	1							
39	1.789	Sustainability	1							
40	0.344	Spectroscopy and Spectral Analysis	1							

Table 46 continued

Rank	IF (2016)	Journal	Publications	Australia	Egypt	Saudi Arabia	Serbia	Taiwan	England	Italy
41	2.929	International Journal of Intelligent Systems	1							
42	0.557	Journal of Scientific and Industrial Research	1							
43	1.180	Expert Systems	1		1					
44	2.476	Biomed Research International	1				1			
45	1.694	Circuits Systems and Signal Processing	1							
46	0.769	Acta Montanistica Slovaca	1							
47	0.835	Optik	1							
48	2.498	Computer Vision and Image Understanding	1							
49	1.930	Journal of Parallel and Distributed Computing	1							
50	1.664	International Journal of Information Technology and Decision Making	1							
51	1.344	Measurement Science Review	1							
52	xx	Scientific World Journal	1							

“xx” denotes that it is deleted from Web of Science. “*” denotes that it is SSCI-indexed journal

Table 47 Highly cited papers

Rank	Authors	Year	Region	Journal	Title	Citations
1	Zhang et al. (2014)	2014	China	*Scientific World Journal*	Interval neutrosophic sets and their application in multicriteria decision making problems	77
2	Ye (2013b)	2013	China	*International Journal of General Systems*	Multicriteria decision-making method using the correlation coefficient under single-valued neutrosophic environment	67
3	Ye (2014c)	2014	China	*Journal of Intelligent and Fuzzy Systems*	Similarity measures between interval neutrosophic sets and their applications in multicriteria decision-making	66
4	Ye (2014c)	2014	China	*Journal of Intelligent and Fuzzy Systems*	A multicriteria decision-making method using aggregation operators for simplified neutrosophic sets	54
5	Ye (2014d)	2014	China	*Applied Mathematical Modelling*	Single valued neutrosophic cross-entropy for multicriteria decision making problems	45
6	Peng et al. (2016a)	2016	China	*International Journal of Systems Science*	Simplified neutrosophic sets and their applications in multi-criteria group decision-making problems	31
7	Zhang et al. (2016c)	2016	China	*Neural Computing and Applications*	An outranking approach for multi-criteria decision-making problems with interval-valued neutrosophic sets	26
8	Peng et al. (2015a)	2015	China	*International Journal of Computational Intelligence Systems*	Multi-valued neutrosophic sets and power aggregation operators with their applications in multi-criteria group decision-making problems	23
9	Tian et al. (2016b)	2016	China	*Filomat*	Simplified neutrosophic linguistic normalized weighted Bonferroni mean operator and its application to multi-criteria decision-making problems	16
10	Zhang et al. (2016d)	2016	China	*Cognitive Computation*	A neutrosophic normal cloud and its application in decision-making	9
11	Tian et al. (2016a)	2016	China	*International Journal of Systems Science*	Multi-criteria decision-making method based on a cross-entropy with interval neutrosophic sets	9
12	Wu et al. (2016)	2016	China	*International Journal of Fuzzy Systems*	Cross-entropy and prioritized aggregation operator with simplified neutrosophic sets and their application in multi-criteria decision-making problems	**5** (hot paper)

Hot paper was published in the past 2 years and received enough citations to place it in the top 0.1% of papers in the academic field of Engineering
Highly cited paper received enough citations to place it in the top 1% of its academic field based on a highly cited threshold for the field and publication year

cited papers in neutrosophic decision research in terms of author(s), region, journal name, publication year, title and citations.

The highest cited neutrosophic reference (Google Scholar with 470 citations), written by Smarandache (1998) (who is the “father of neutrosophic logic”), can be seen as the pioneering work for neutrosophic set as it firstly introduced the neutrosophic logic theory and thus opened a new research direction.

From Table 47, we can find an interesting phenomenon that highly cited papers are all from China. This phenomenon is credited with the numerous Chinese scholars and pioneering works. The top 1 paper, originally by Zhang et al. (2014), can be seen as the pioneering work for netrosophic aggregation operators. This paper published in the *Scientific World Journal* (open access journal) and gained much more citations than others highly cited papers. All the following highly cited papers developed different types of aggregation operators or information measures for decision making, such as aggregation operators (in the 4th, 6th, 7th, 8th, 9th, 10th and 12th papers), information measures (in the 2nd, 3rd, 5th and 11th papers). These methods and techniques were regarded as the indispensable and integral parts of neutrosophic decision research and thus gained more and more citation frequency. It is noted that all these highly cited papers are published in famous journals. It is also interesting to note that the authors of these highly cited papers mainly come from two teams (Ye, Jun and Wang, Jianqiang). It is too hard to find the highly cited papers from other authors or teams.

3.7 Research landscape

The neutrosophic research is not limited to the field of “Computer Science” or “Mathematics,” but covers over 20 Web of Science categories. This indicates the wide applications of neutrosophic theories and methods in various fields. “Computer Science, Artificial Intelligence” is the largest category with nearly one-second of all the neutrosophic-related publications. The followings are “Computer Science, Interdisciplinary Applications” and “Computer Science, Theory Methods,” each with over 10 publications and sharing of 12.409% and 8.029%, respectively.

Table 48 lists the main Web of Science categories that neutrosophic-related publications belong to. Besides computer science and mathematics-related categories, the neutrosophic-related publications were also found to be widely appeared in engineering-, management-, neurosciences, optics, and imaging science related categories. It shows the extensive applications of neutrosophic set in these fields.

3.8 The keywords analysis of research hot spots on NS

In this subsection, we explore the research hot spots by analyzing the distribution of keywords. The keywords co-occurrence network map, the top 10 keywords in NS publications and the keywords density visualization map will be presented. Keywords co-occurrence can effectively reflect the research hot spots in the discipline fields, offering efficacious support for scientific research (Liao et al. 2018). In all the 137 NS-related publications, we achieved 587 keywords altogether.

The keyword co-occurrence network of NS(see Fig. 3) was established by the VOSviewer software. The size of the nodes and words in Fig. 3 denotes the weights of the nodes. The bigger the node and word are, the larger the weight is. The distance between two nodes reports the strength of the relation between two nodes. A shorter distance usually indi-

Table 48 Main Web of Science categories

Rank	Web of Science category	Publications	Share (%)
1	Computer Science, Artificial Intelligence	84	61.314
2	Computer Science, Interdisciplinary Applications	17	12.409
3	Computer Science, Theory Methods	11	8.029
4	Mathematics, Interdisciplinary Application	10	7.299
5	Automation, Control Systems	9	6.569
6	Engineering, Electrical, Electronic	9	6.569
7	Mathematics, Applied	7	5.109
8	Computer Science, Information Systems	6	4.380
9	Engineering, Biomedical	5	3.650
10	Computer Science, Cybernetics	4	2.920
11	Medical Informatics	4	2.920
12	Operations Research, Management Science	4	2.920
13	Imaging Science, Photographic Technology	3	2.190
14	Instruments, Instrumentation	3	2.190
15	Multidisciplinary Sciences	3	2.190
16	Optics	3	2.190
17	Economics	2	1.460
18	Mechanics	2	1.460
19	Neurosciences	2	1.460
20	Radiology Nuclear, Medicine, Medical Imaging	2	1.460

cates a stronger relation. The line between two keywords denotes that they have appeared together. The thicker the line is, the more co-occurrence they have. The nodes with the same color classified as a cluster. VOSviewer divided the keywords of NS-related publications into 5 clusters. The keyword "intuitionistic fuzzy set" has a highest frequency of 53. Other keywords with a high frequency include "neutrosophic set" (41), "aggregation operators" (30), "entropy" (27), "similarity" (25), and "multicriteria decision-making" (21).

The link strength between two nodes denotes the frequency of co-occurrence. It can be used as a quantitative index to describe the relationship between two nodes (Pinto et al. 2014). The total link strength of a node is the sum of link strengths of this node over all the other nodes. The node, "intuitionistic fuzzy set", has thicker lines with "neutrosophic set" (14), "aggregation operators" (20), "entropy" (15), "similarity" (16), "multicriteria decision-making" (13), and "correlation coffeicient"(15). These are all the nodes whose link strengths are more than 13. The relationships between "intuitionistic fuzzy set" and "neutrosophic set" imply the close integration of extension. The relationships between "intuitionistic fuzzy set" and "entropy", "similarity" and "correlation coffeicient" reflect that the neutrosophic set study needs the support from some information measure techniques. The relationships between "intuitionistic fuzzy set" and "aggregation operators" as well as "multicriteria decision-making" show the development trends of application environments. The top 10 keywords with their frequencies and total link strengths are shown in Table 49.

VOSviewer can have density visualization (see Fig. 4). Each node in the keywords density visualization plat has a color that relies on the density of items at that node. That is to say,

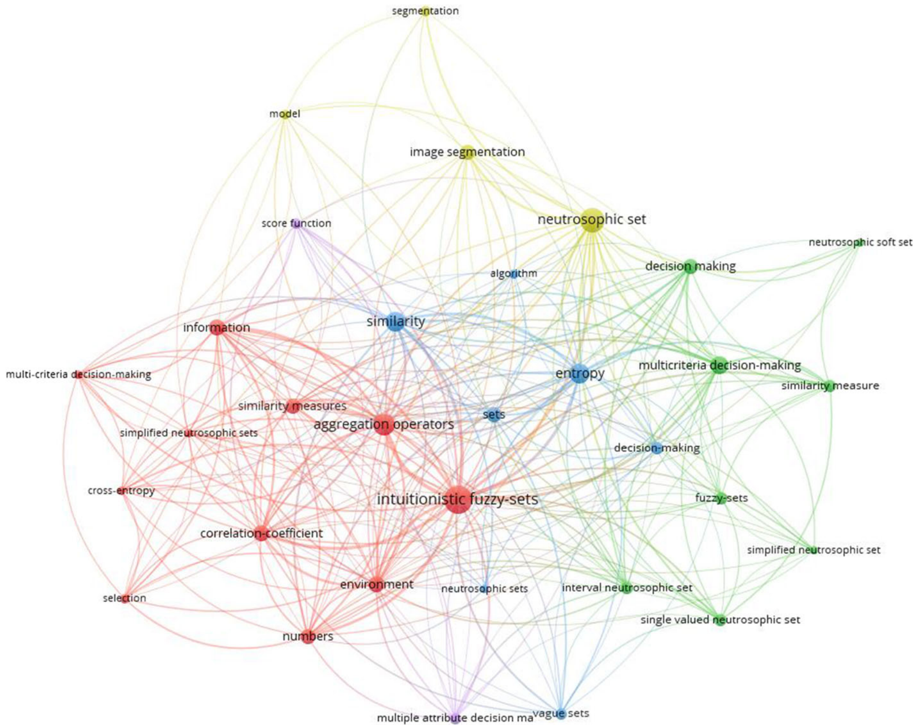

Fig. 3 Keywords co-occurrence network of NS-related publications

Table 49 The top 10 keywords of the NS-related publications

Rank	Keywords	Frequency	Total link strength
1	Inutitionistic fuzzy set	53	207
2	Neutrosophic set	41	105
3	Aggregation operators	30	127
4	Entropy	27	104
5	Similarity	25	102
6	Multicriteria decision-making	21	68
7	Information	18	76
8	Environment	18	84
9	Correlation-coefficient	18	100
10	Image segmentation	16	36

the color of a node depends on the number of items in the neighborhood of the node. The keywords in red color area appear more frequently. On the contrary, the keywords in yellow color area appear less frequently. Density visualization are quite useful for understanding the overall structure of a map and drawing attention to the most important areas in the map. From Fig. 4, we can see the research focuses of neutrosophic set study intuitively. “intuitionistic

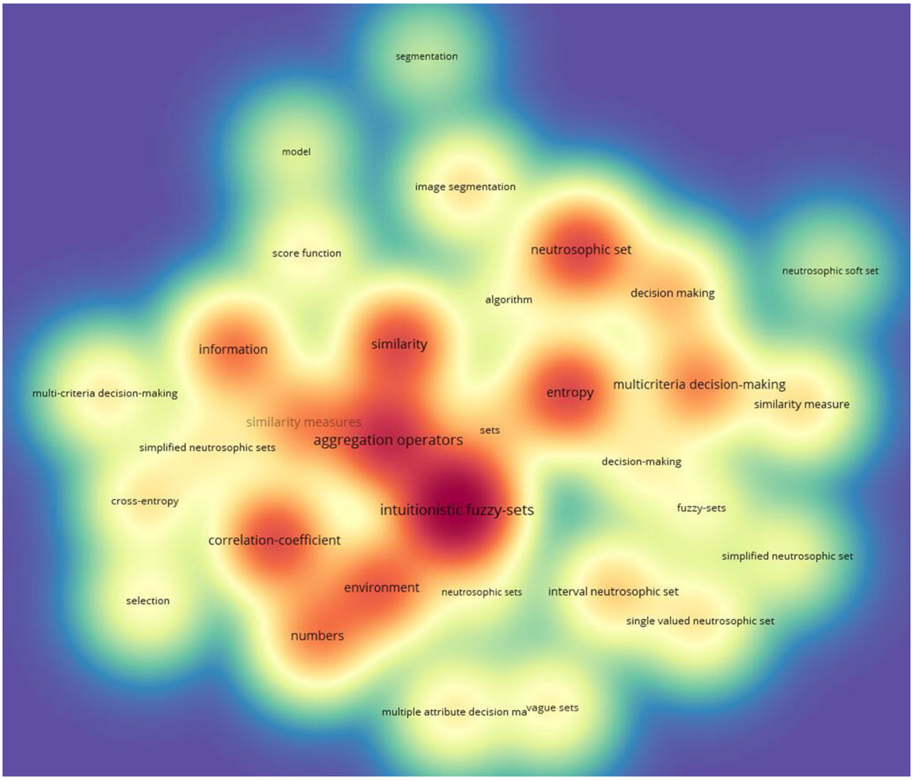

Fig. 4 Keywords density visualization map of NS-related publications

fuzzy set", "neutrosophic set", "aggregation operators", "entropy" turn out to be important. These keywords are the core keywords in the NS study.

3.9 The co-authorship analysis on NS

It is hard for people to accomplish a research on a certain subject individually. Most of research projects or work need collaborative strength to fulfill. Co-authorship research is an important content of bibliometrics and the level of research collaboration is an index to evaluate the current status of research in a specific domain (Reyes et al. 2016). In this subsection, we mainly give the country co-authorship analysis and the institute co-authorship analysis on NS-related publications. We make the co-authorship network by means of the VOSviewer software.

3.9.1 The country co-authorship analysis

Country co-authorship analysis is an important form of co-authorship analysis which can report the degree of communication between countries as well as the influential countries in this field. The country co-authorship network of NS-related publications is presented in Fig. 5. There are different colors in the map, which shows the diversification of research directions. The big nodes denote the influential countries. The links between nodes indicate

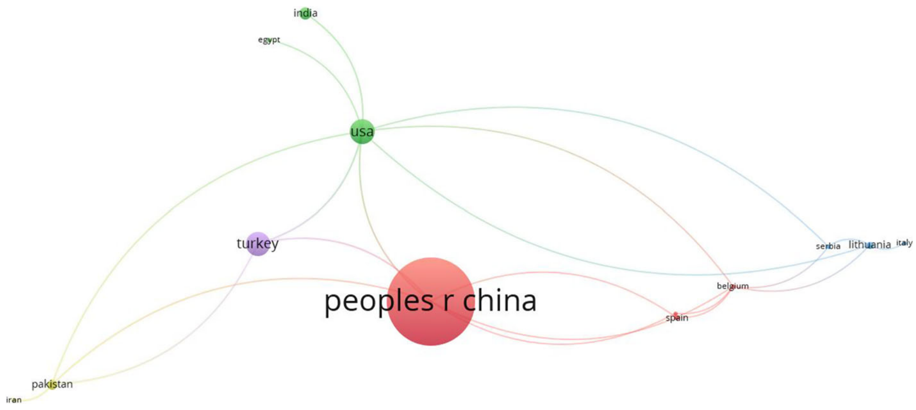

Fig. 5 The country co-authorship network of NS-related publications

Fig. 6 The institute co-authorship network of NS-related publications

the cooperative relationships among countries. The distance between the nodes and the thickness of the links denotes the level of cooperation among countries. In Fig. 5, we can easily know that the research center in the field of NS is in the China. The link strength between the China and USA is 7, between the China and Turkey being 5. While the link strength between Turkey and Pakistan is 1. It demonstrates that geographical advantage is not the key factor that influences the cooperative relationship in country level.

3.9.2 The institute co-authorship analysis

The institute co-authorship network is shown in Fig. 6. The Shaoxing University from the China is the top influential institutes of the NS-related publications. Although so many institutes have published their papers, the relationship among all institutes has not been well or effectively linked. It indicates that the cooperative relationships among institutes have not been well formed.

3.10 The co-citation analysis on NS-related publications

When two items (such as documents, journals and authors) are cited in a citing item's reference list, they have a co-citation relationship. Small (1973) developed a co-citation analysis to investigate the relationship and structure of academic domains. Since then the co-citation analysis has been extensively used to reveal the relationship and structure of authors, articles and journals in academic fields. In this subsection, the reference co-citation analysis, the journal co-citation analysis, and the author co-citation analysis are shown.

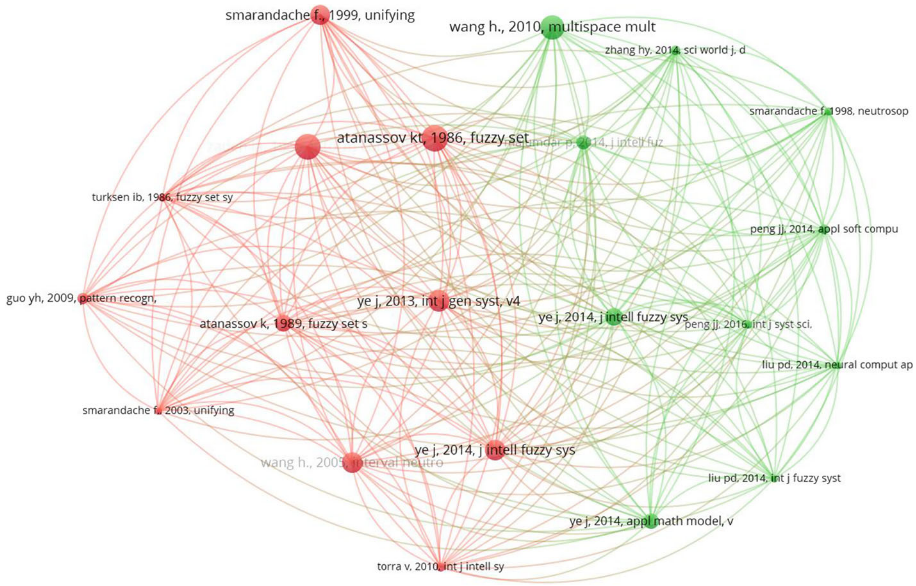

Fig. 7 The reference co-authorship network of NS-related publications

3.10.1 The reference co-citation analysis

When two papers emerged simultaneously in the third paper's citations, it is considered that the two papers built a co-citation relationship (Tang et al. 2018). Reference co-citation analysis is a significant way to investigate the structure and evolution path of a specific filed. Co-citation analysis is a kind of citation network analysis method. It is different from another citation analysis method, that is to say, the citation quantity analysis method. The citation quantity analysis method is to evaluate the quality of the subjects (journal, author, country, document, type of document, etc.) by the number of citations. Co-citation analysis chooses some representative literatures as the analysis object, and then employs the network analysis method to divide these literatures into several clusters. In this way, we can get the structure and characteristics of a specific filed. In the reference co-citation network, the importance of nodes does not reveal the high number of citations, but illustrates the research themes that are closely related to NS-related research. Figure 7 presents the reference co-citation network in the field of NS study. From Fig. 7, we can easily see that the biggest node is Atanssov (1986). His paper entitled "Intuitionistic fuzzy sets" published in FSS (Fuzzy Sets and Systems) proposed that the novel extension of fuzzy sets may be an important way to deal new extension of intuitionistic fuzzy set (neutrosophic set).

Table 50 lists the top 10 most co-cited documents related to NS study.

3.10.2 The journal co-citation analysis

The journal co-citation analysis is not only an effective way to explore the structure and characteristics of a subject, but also reveals the overall structure of the subject and the characteristics of a journal (Hu et al. 2011). The VOSviewer software is used to plot the journal co-citation network. Figure 8 presents the journal co-citation network with 45 nodes. The

Table 50 The top 10 most co-cited documents of NS-related study

Rank	Frequency	Author	Year
1	75	Atanassov	1986
2	72	Zadeh	1965
3	68	Wang	2010
4	61	Ye	2013
5	59	Ye	2013
6	58	Wang	2005
7	57	Smarandache	1999
8	50	Ye	2014
9	47	Atanassov	1989
10	43	Ye	2014

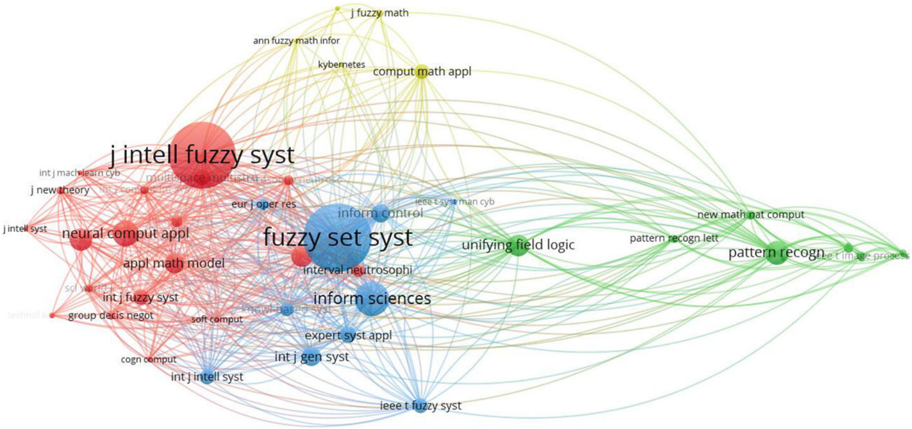

Fig. 8 The journal co-authorship network of NS-related publications

size of node denotes the activity of the journal and the number of published papers. The distance between two nodes is also quite important. Generally speaking, the smaller the distance between two nodes is, the higher the citation frequency is. As the visualization illustrated in Fig. 8, each cluster has a color that denotes the group to which the cluster is allocated. It can be easily seen that all these journals are divided into four clusters. The blue cluster contains Fuzzy Sets and Systems, Information Sciences and IEEE Transactions on Fuzzy Systems, etc. This cluster represents top journals. The red cluster contains Journal of Intelligent and Fuzzy Systems, Neural Computing and Applications and Applied Mathematical Modelling. This cluster denotes science and technology journals. The green cluster represents information journals.

3.10.3 The author co-citation analysis

Author co-citation analysis is an important and efficacious citation analysis method, since it was initially developed in 1981 (White and Griffith 1981), it has received wide attention and researches from scholars (Wang et al. 2016b). By drawing out the co-citation relations

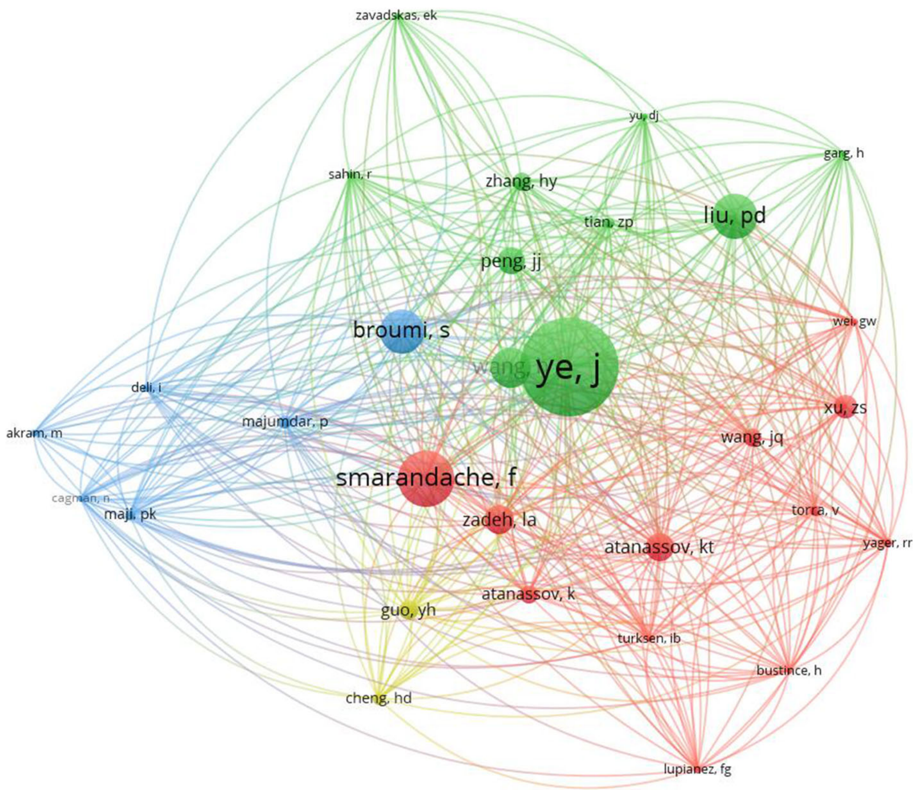

Fig. 9 The author co-authorship network of NS-related publications

between the authors of the academic literature, author co-citation network can be obtained and used to guide the scientific research (Koseoglu et al. 2015). In the following, VOSviewer was adopted to draw out the author co-citation map on NS researches and it was shown in Fig. 9. It consists of 30 nodes and 400 edges. Unsurprisingly, the node demonstrates that Ye J is the biggest one among all the nodes. Furthermore, the nodes indicate that Ye J and some others with purple rings express high centrality in NS researches.

4 Conclusions

We focus on seven parts (extensions style, aggregation operators, information measures, MCDM methods, image processing, graph, algebraic structures) to review the whole development of NS and discuss their future directions. Meanwhile, a total of 137 neutrosophic set publication records from Web of Science (WoS) are analyzed. Many interesting results with regard to the annual trends, the top players in terms of country level as well as institutional level, the publishing journals, the highly cited papers, and the research landscape are yielded and explained in-depth. Moreover, the co-authorship analysis of the country and institution, the co-citation analysis of the journal, reference and author, and the co-occurrence analysis of the keywords are presented by VOSviewer software. It has yielded the following results:

(1) Our analyses have demonstrated that the academic publications in neutrosophic research domain have fluctuated at low level during the initial periods of 1998–2008, but have grown rapidly over the last ten year.
(2) Quite different from other research domains, some small or developing economies such as India, and Turkey were also among the largest contributors.
(3) Our data have also showed that the scholars from China, and India were relatively active in publishing in this domain compared to their contribution to all the research fields.
(4) The highly cited papers were mainly published in famous journals and contributed all by authors from China.
(5) The most frequently cited work in neutrosophic set area is Atanssov (1986). FSS-Fuzzy Sets and Systems is most influential in neutrosophic set domain.
(6) Through the analysis of keywords, we have found that intuitionistic fuzzy set is the most core keyword. At the same time, the technical support of neutrosophic set study is the key direction that people need to combine the two kinds of extention of fuzzy set. They can share with common decision making methods, aggregation operators, information measure and so on.
(7) In neutrosophic set domain, the phenomenon of cooperation among multiple authors is widespread. More than 66% publications with the highest number of citations were completed with more than one author. However, the international cooperation is not universal. The future research can focus more on the impact of the research in this field and probe the reasons why some small economies are keen on academic research in this field.

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Author contributions Peng analyzed the existing data and wrote the manuscript; Dai drew the beautiful figures.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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