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Assessing the Adaptation of Internet of Things (IoT) Barriers for Smart Cities' Waste Management Using Fermatean Fuzzy Combined Compromise Solution Approach

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ABSTRACT This study proposes a systematic methodology of the adoption of Internet of Things (IoT) barriers (IoTBs) that exist in the waste management structures of smart cities (SCs) in growing economies likely India. A hybrid multi-attribute decision-making (MADM) is applied and has recognized 15 IoTBs from literature and experts opinions obstructing the IoT adoption in SCs of India. The different IoTBs are studied using the similarity measure-based new weighting approach, and the combined compromise solution (CoCoSo) method. Considering that Fermatean fuzzy sets (FFSs) can represent this uncertainty, this paper proposes a decision-making framework for waste management system solutions based on the FFSs and builds a complete evaluation index system. Herein, we first combine the Archimedean Copula operations and Archimedean operations and term them as 'generalized Archimedean Copula operations' for FFSs. Based on these new operations, we develop the Fermatean fuzzy generalized Archimedean copula weighted averaging (FFGACWA) and Fermatean fuzzy generalized Archimedean copula weighted geometric (FFGACWG) operators. Then, we construct a decision algorithm based on FFWGAAC and FFWGGAC operators. Second, we propose new weighting procedure based on similarity measure to discuss the significance degree of IoTBs. Further, we apply this method to the evaluation and selection of a methodology of IoTBs in smart cities' waste management (SCWM) assignments, and prove the effectiveness of this method. The algorithm can represent the Fermatean fuzzy information in a complex environment. It cannot only consider the uncertainty of the decision-makers (DMEs) when giving the evaluation value but also synthesize the relationship between any numbers of evaluation criteria. Finally, the superiority of the methodology is discussed by sensitivity analysis and comparative study. The results show that the method can effectively handle the decision-making problems in complex environments. This paper will assist the representatives, stakeholders and government to know the importance of IoTBs affecting waste management processes, and it will certainly help them to take judgments for exterminating the IoTBs for an effective IoT employment in SCWM assignments.

INDEX TERMS Archimedean copula, CoCoSo, Fermatean fuzzy sets, IoT barriers, MCDM, similarity measure, smart cities, waste management.

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I. INTRODUCTION

In the developing nations, the "smart city (SC)" is shown as a prospective result to the barriers/concerns caused by the urbanization procedure. Over the last two decades, smart cities have risen as a vital requirement for developing countries with their progressive attitudes. Numerous scholars have made their effort to express the idea of an SC [1], [2] and most have intellectualized it as a multilayered structure that purposes to construct sustainable SCs [2]. The SCs require the combination of ''information & communication technology (ICT)'' and ''internet services (ISs)'' to reform their design in such variegated procedures as creative infrastructure, atmosphere, healthcare, governance, and various different disciplines of interest with a decisive objective to propose a sustainable structure [3]. A SC is the combination of ICTs, economic, social and technical assessment aspects of sustainability perspectives and the key shareholders are government, designers, populations and service providers [4], [5]. Over the aforementioned technological advances, the ''internet of things (IoT)'' turns as a key carter in SCs inventiveness all over the globe. IoT-facilitated structures treat as a substance in the renovation of urban cities to develop an advanced structure, ''waste management (WM)'', healthcare, and to the advancement social life [2], [6]. IoT systems in SCs should offer advance facilities and reshape extant procedures [7]. There are various aspects of ISs namely network, scalability, heterogeneity, and end-user involvement to the construction of an IoT-enabled smart city [8].

The ''united nation (UN)'' expects that around 2/3rd of population of the globe will be urbanized by 2050 [9]. Thus, organizational and further extensive facilities will become vital to achieve the requirements of the urbanized residents. If the population increases approximately 3-5% per annum, the quantity of produced waste will be doubled in each 10 years span, which evidently presents a serious concern for SCs and a massive financial liability for expenditures of assemble, landfills, and recycling [10]. The extant study has shown that treating the waste is a severe concern of urbanized people, and that emerging a sustainable environment is required to diminish the risk to urbanized life [11].

To attain the sustainable development and economic growth, the developed and growing countries are employing ISs [2], [12]. Though various aspects are in place, developing SCs is an evolving feature of economic growth and a system of satisfying the desires of urbanized population [2], [13]. Developed countries have innovative technology, appropriate resources, and a robust structure with which to build the SCs; additional, the SCs that previously develop to assist and guide them to make some innovative activities [14]. Nonetheless, the situation of growing nations is completely changed. Because of financial, technical, and economic aspects, growing nations tackle the problems in employing projects for SCs development. Developing nations such as, India, scrutinize to construct SCs to promote the life styles of their people and societies [15]. Next, Adapa [1] elucidated that growing nations have differences in their functioning atmospheres as related to developed nations; therefore, it is compulsory to propose an organized structure that could assist to efficiently utilize IoT-enabled environments in SCs. Aforementioned study exemplified that the aspects influencing the SC assignments are crucial to be investigated individually in growing countries [16].

The exciting situation has prepared IoT theories necessary to be executed in SCs, as it generates association between the items and connects to individuals in an intellectual mode [17]. IoT-based facility that suits more critical day by day is the effective ''smart cities waste management (SCWM)''. So far, WM operated the tools and prototypes namely ''geographical information system (GIS)'', improved ''routing & scheduling (R&S)'', and other procedures to enhance waste collection, storage, and disposal treatments. These methods have lack of modernism, but the IoT systems can tackle the concerns easily [18]. In the extant works, stakeholders have not studied an essential portion of IoT-enabled WM procedures; rather, they are measured independent entities [19].

To fulfill the requirements of urbanization, an IoT-facilitated smart city is a promising choice; it may carry various aids in elevating public facilities namely transport, WM, medical facilities and education, and it has the prospective to convert communities into smart societies [2]. Mineraud *et al.* [20] argued extra aids namely transparency, mobility, and adaptation from the SCD [21]. Alternatively, several challenges namely scalability, security concerns, architecture, governance to adopt the IoT structures [22]. There are very limited studied exist related to the IoT process and execution in perspective to waste management; they essentially emphasis on developing and enhancing IoT structures for waste collection procedures [23]. Despite of compost collection, there is a requirement is to explain the aspects that impact SCWM [2]. Consequently, this paper aims to propose an appreciative and investigating the impact of IoTBs for SCWM so that participants may take practical activities to impeccably utilize IoT-enabled structures. The systematic outline of smart city to adopt IoTBs for SCWM is discussed in Fig. 1. This paper is an inventiveness to handle the IoT implementation situation of SCs in growing nation likely India and the numerous barriers/concerns that may be faced through IoT adoption. Despite the technical intricacies, a perfect, consistent strategy for adopting the IoTBs and an appropriate way for smart city creativities has not so far been discussed.

A. CHALLENGES AND MOTIVATIONS

Recent literature presented the SCs ideas but various barriers faced by the SCs in IoT-facilitated waste management structures are not much studied. The situation in developing nations is completely diverse from developed nations as waste production is the key concern rising in urban regions. The promising result is IoT implementation to tackle waste resourcefully; therefore, the IoTBs may performance as complications and requirement to be recognized and investigated. Because of the modified requirements and the ambiguity of the considered situation, it is very tough to select the best smart city to adopt IoTBs for SCWM.

In order to deal with uncertainty of the real-life problems, Zadeh [88] initiated the concept of "*fuzzy set theory (FST)*" that has widely been utilized in practice. In FST, each element is assigned a membership grade (MG) lying between 0 and 1. Since in an FS, the non-membership grade (NG) of an element cannot be preferred independently, therefore, Atanassov [89] pioneered the notion of "*intuitionistic fuzzy set (IFS)*". In the theory of IFS, each element has a MG and a NG lying between 0 and 1, with their sum is restricted to unity. Besides, the theory of IFS has limitations in ambiguous decision-making contexts wherein the sum of MG and NG could exceed 1. Further, Pythagorean fuzzy set (PFS) [24], [25] an augmentation of intuitionistic fuzzy set (IFS), has attracted many potential researchers. In PFS, the membership and non-membership grades are in the [0,1] interval and the quadratic sum of MG and NG varies in the unit closed interval.

In several practical decision-making applications, sometimes this condition is not easy to satisfy. The following example will illustrate this problem. Suppose two professionals are asked to assess the same problem. They make decisions separately. One expert offered the MG as 0.9 for the problem, whilst another expert gave the NG as 0.6 for the same problem. In this case, $0.9 + 0.6 > 1$ and 0. 9^2 + 0.6^2 > 1. Hence, it is not appropriate to employ IFS and PFS to describe the evaluation information of this problem. To conquer with such situations, Senapati and Yager [26] initiated the notion of "*Fermatean fuzzy set (FFS)*". In FFS, the cube sum of MG and NG is in the unit interval, therefore it provides a more general perspective for FST. FFS is capable to deal with higher levels of uncertainties by assigning fuzzy parameters from a larger domain. It offers more liberty in expressing their beliefs about membership grades. Thus, in order to tackle the aforementioned problems and choose a suitable smart city to adopt the IoT barriers of waste management system, manuscript develops a decision-making algorithm under the FFS environment and studies its application in specific cases and proves the superiority of the algorithm through sensitivity analysis and comparative analysis.

In the literature, several multi-attribute decision-making (MADM) approaches have been studied to make the decisions in reality. However, the preference ordering of the alternatives acquired by some of the existing methods may vary significantly because of the change of weight distribution of criteria. In order to deal with such applications, the "*combined compromise solution (CoCoSo)* [40]" approach has been pioneered, which incorporates the combination of compromise decision-making procedure with aggregation operators to acquire a complicated compromise solution. In accordance with the existing studies, it has been proven that the CoCoSo approach has a high stability and reliability than the extant models. In the recent past, several studies have been presented to extend the classical CoCoSo approach under diverse uncertain environments but no one has extended from the Fermatean fuzzy perspective.

In summary, the research on the IoT barriers implementation in SCWM solutions is mainly based on design and optimization at the technical level. There is a lack of a systematic MADM methodology and a complete evaluation index system for the assessment and selection of solutions. Therefore, a systematic methodology is lacking for users to select appropriate solutions. The existing research on FFSs is also very rich, but there is no research for combining the FFSs, Archimedean operations and the Archimedean copula operations to solve MADM problems. Hence, the motivations of the paper are as follows.

- The SCWM solutions involve human health and safety problems. If they cannot be selected correctly, they may be dangerous to life and health and cause a high number of losses. Therefore, this paper plans a MADM algorithm utilizing the developed FFWGAAC and FFWGGAC AOs to solve the problem of the assessment and prioritize the IoTBs and smart city to adopt IoTBs for SCWM;
- Determine the main IoTBs and their impacts to develop the SCs for the SCWM. This paper develops a similarity measure-based weighting procedure to evaluate the various barriers to adopt IoT of SCWM.
- The existing information aggregation operators only deal with the information aggregation problem of a limited number of macro indicators and do not investigate the information aggregation problem of a multi-layer structure index system in which there are correlation characteristics between indicators. Therefore, this paper introduces the Archimedean copula operator, which can consider the correlation between any number of evaluation indicators and enhance the flexibility of decision-making;
- Most of the existing evaluation information representation problems use IFSs and PFSs which have limited information expression and cannot deal with the subjective uncertainty of the evaluator when giving an assessment value. Therefore, this paper chooses the FFSs to represent complex decision information.

B. CONTRIBUTIONS

The contributions of the study are given by

- A complete evaluation framework is established as the evaluation standard of IoT adoption barriers of SCWM solutions.
- A Fermatean fuzzy set is selected to represent the evaluation information of each index, which fully expresses the uncertainty of the evaluator when giving the evaluation value.
- A similarity measure is developed to evaluate the significance degree of each IoT adoption barrier of SCWM systems.
- Combining Archimedean Copula operations and Archimedean operations, some new operational laws (called generalized Archimedean Copula operations) are proposed for Fermatean fuzzy numbers. Next,

Fermatean fuzzy generalized Archimedean copula weighted averaging (FFGACWA) and Fermatean fuzzy generalized Archimedean copula weighted geometric (FFGACWG) operators are introduced which considers the correlation characteristics of the complex evaluation framework and is suitable for assessment and decision-making problems in FFSs setting.
- An evaluation and decision-making CoCoSo framework based on FFSs is constructed to support evaluation and decision-making in smart city evaluation to adopt the IoTBs of waste management system.

The remaining article is discussed as follows: Section 2 reviews and summarizes the literature about to SCWM, FFSs and "aggregation operators (AOs)". Section 3 briefly introduces the concepts of FFSs, and similarity measure. Section 4 proposes the FFGACWA and FFGACWG AOs and presents their properties and particular cases. Section 5 introduces the "multi-attribute decision making (MADM)" method using the proposed AOs and new weighting procedure. In section 6, the developed methodology is applied to the evaluation and selection of IoTBs and SCs for SCWM, and a sensitivity investigation and comparison with extant procedures are carried out to prove the effectiveness of the developed methodology on FFSs. Section 7 summarizes the research.

II. LITERATUE REVIEW

In this section, we present the literature of FFSs, CoCoSo and IoT for SCWM.

A. FERMATEAN FUZZY SETS

Since the appearance "intuitionistic fuzzy sets (IFSs)" and "Pythagorean fuzzy sets (PFSs)", various interesting works have been done for treating the uncertainty and ambiguity found in realistic circumstances [24], [25]. However, in several realistic MADM problems, there are some circumstances in which experts give their judgment in terms as (0.8, 0.7), where 0.8 is a "membership grade (MG)" and 07 is an "non-membership grade (NG)". Thus, IFSs and PFSs are incapable to treat with the circumstances as $0.8 + 0.7 > 1$ and $0.8^2 + 0.7^2 > 1$. To discuss the concern, Senapati and Yager [26] initiated the notion of "Fermatean fuzzy set (FFS)", which is described by the MG and NG with the condition that the cubes sum of MG and NG is ≤ 1. Therefore, the FFSs are more significant and operative tool than IFSs and PFSs in treating the complex MADM problems. For instance, Senapati and Yager [27] gave some operations and a MADM model on FFSs setting. Senapati and Yager [28] discussed various AOs to treat the MADM problems. Recently, Akram *et al.* [29] studied some AOs-based model for assessing the appropriate sanitizer to drop COVID-19 contamination. Ghorabaee *et al.* [30] discussed a MADM model on FFSs for solving and choosing the optimal the construction supplier. Mishra *et al.* [31] presented a hybrid model for determining "sustainable third party reverse logistics providers (S3PRLPs)" problem on FFSs. Hadi *et al.* [32] gave new operations on FFSs using Hamacher AOs for handling the MADM problem. Though, there is no work related to the desirable smart city evaluation to adopt the IoT barriers of waste management system under FFSs setting.

B. COPULA OPERATOR

According to Tao *et al.* [33] "Copulas are functions that link more than one marginal distribution, which can reflect the correlation among variables and can also avoid information loss in the process of aggregation". Beliakov *et al.* [34] and Nelsen [35] discussed an organized overview of copula and its implementation in aggregating the information. Nather [36] utilized the copula to deal with probabilistic fuzzy information. Grabisch *et al.* [37] put forward several methods to construct AOs including copula. Bacigal *et al.* [38] categorized AOs preserving additive generators of Archimedean Coplulas. Han *et al.* [39] developed a MADM framework using the Archimedean Copula and "probabilistic unbalanced linguistic term sets (PULTSs)".

C. COCOSO APPROACH

In the recent times, Yazdani *et al.* [40] presented a novel MADM tool, called the "combined compromise solution (CoCoSo)" method, which integrates the AOs-based algorithm with the diverse balanced strategy functions to obtain the compromise degree. The CoCoSo framework is proposed using the combination of "simple additive weighting (SAW)" and "weighted product measure (WPM)" tools. Furthermore, the CoCoSo framework has good steadiness and consistency concerning the priority of options. The removal or addition of options has least influence on the overall preference outcomes obtained by CoCoSo tool than "TOPSIS (technique for order preference by similarity to ideal solution)", "VIKOR (visekriterijumska optimizacija i kompromisno resenje)", and other MADM tools. The TOPSIS, VIKOR and "measurement alternatives and ranking according to the compromise solution (MARCOS)" models provided the preference orders from the "ideal solution (IS)" and "anti-ideal solution (A-IS)". In TOPSIS, VIKOR and "multi-attributive border approximation area comparison (MABAC)" models, the discriminations are estimated without taking into consideration of their relative significance. Though, the reference solution could be a key issue in MADM, and to be much close to the IS is the motivation of human. The CoCoSo framework may be an appropriate way to obtain an overall compromise degree for MADM problems. Thus, it would be more significant to study the improved CoCoSo approach under FFSs for assessing and selecting the IoT adoption barriers for SCWM. The detailed ways to utilize the CoCoSo technique are presented in Table 1.

D. IoT FOR SCWM

IoT can be elucidated as an environment in such a way that numerous digitally embedded procedures associate with

TABLE 1. The extant studied related to the CoCoSo approach and its variants.

References	Benchmarks	Types of processing data	Application(s)
Yazdani et al. [40]	The novel CoCoSo approach	"Crisp numbers (CNs)"	Logistic provider assessment
Zoflani et al. [41]	Use BWM to obtain the attribute weights	CNs	Sustainable supplier assessment
Yazdani et al. [42]	Use DEMATEL and BWM to obtain attribute weights	Grey numbers	Construction management
Biswas et al. [43]	Apply CRITIC to obtain attribute weights	CNs	Battery-operated electric vehicles (BEVs) selection
Rani and Mishra [44]	Use similarity measure-based procedure to determine criteria weights	"Single-valued neutrosophic numbers (SVNNs)"	WEEE recycling partner selection
Biswas et al. [45]	Use CRITIC to obtain attribute weights	CNs	Automotive passenger vehicle selection
Liao et al. [46]	Apply Prospect Theory And Weighting Procedure	PFSs	Cold chain logistics distribution center assessment
Peng and Smarandache [47]	Use CRITIC to determine criteria weights	SVNNs	China's rare earth industry security assessment
Ecer and Pamucar [48]	Use BWM to obtain attribute weights	Fuzzy numbers	Sustainable supplier assessment
Mi and Liao [49]	Use stochastic multi-criteria acceptability analysis-CoCoSo	CNs	Renewable energy investments
Alrasheedi et al. [50]	Use similarity measure-based procedure to determine criteria weights	Interval-valued intuitionistic fuzzy numbers	Assessment the green growth indicators to attain sustainability
Mishra and Rani [51]	Use CRITIC to determine criteria weights	SVNNs	S3PRLPs selection
Mishra et al. [52]	Use discrimination measure-based procedure to obtain criteria weights	Hesitant fuzzy numbers	S3PRLPs selection
Liu et al. [24]	Use similarity measure-based procedure to obtain criteria weights	PFSs	Medical waste treatment technology selection
Torkayesh et al. [53]	Use BWM and LBWA to obtain attribute weights	CNs	Evaluation of healthcare performances
Cui et al. [54]	Use SWARA to determine criteria weights	PFSs	Evaluate barriers to adopt IoT in the manufacturing region

the help through ISs [2]. Bruneo *et al.* [55] discussed that procedures are known as "smart entities" and that they occur as features in procedures or automobiles in the environments. The IoT visualizes the globe as wholly linked where all entities are capable to interconnect with each other. This association indicates to the foundation of a digital domain where smart utilizations are executed to develop the smart societies with the use of ISs [56]. Nowadays, the development of ISs namely cloud computing, big data and IoT are taking into consideration in the SCs to produce a sustainable environment [2]. The utilization of IoT is exhilarated by "world foundation" for smart societies in SCs to satisfy the requirements of the global budget [57]. The effective WM is a prime issue in India because of increases in waste production, dumping, and landfills [3].

In recent times, SCWM has been concentrated by various researchers and literature reviews are discussed to illustrate prototypes of IoT facilitated presentations for waste collection procedures [58] that contain the following phases of process: waste assemble, recycle, and recovery. Numerous procedures are applied to remind and circulate data namely "RFID tags", sensors, "wireless sensors network (WSNs)", "near field communications (NFC)", and GPS in WM. Sensors are used to assess the volume, temperature and humidity [2]. The NFCs and WSNs are applied for data transmission. The GPS is utilized for site trailing of collection vehicles. The aforementioned tools have been applied in waste collection procedures, namely intelligent waste vessels

TABLE 2. The extant studies of IoT barriers implementation of SCWM.

Barriers	References
Security and privacy issues (I_1)	[2], [60], [61]
Lack of regulatory norms, policies and guidelines (I_2)	[2], [62], [63]
Operational cost and extended payback duration (I_3)	[1], [8], [64], [65]
Lack of transparency (I_4)	[2], [19], [14]
Limited skilled workforce (I_5)	[2], [66]
IoT devices' safety (I_6)	[2], [67]
High energy consumption (I_7)	[7], [64], [68]
Lack of common information system (I_8)	[66], [69], [70]
Lack of integration between IT networks and infrastructure (I_9)	[61], [55], [57], [71]
Lack of standardization of the infrastructure (I_{10})	[58], [63], [67], [72]
Lack of mobility (I_{11})	[2], [70]
Inadequate internet connectivity (I_{12})	[55], [73]
System failure issues (I_{13})	[73], [74]
Poor data availability (I_{14})	[8], [21], [75]
Lack of technical knowledge among developers (I_{15})	[76], [77]

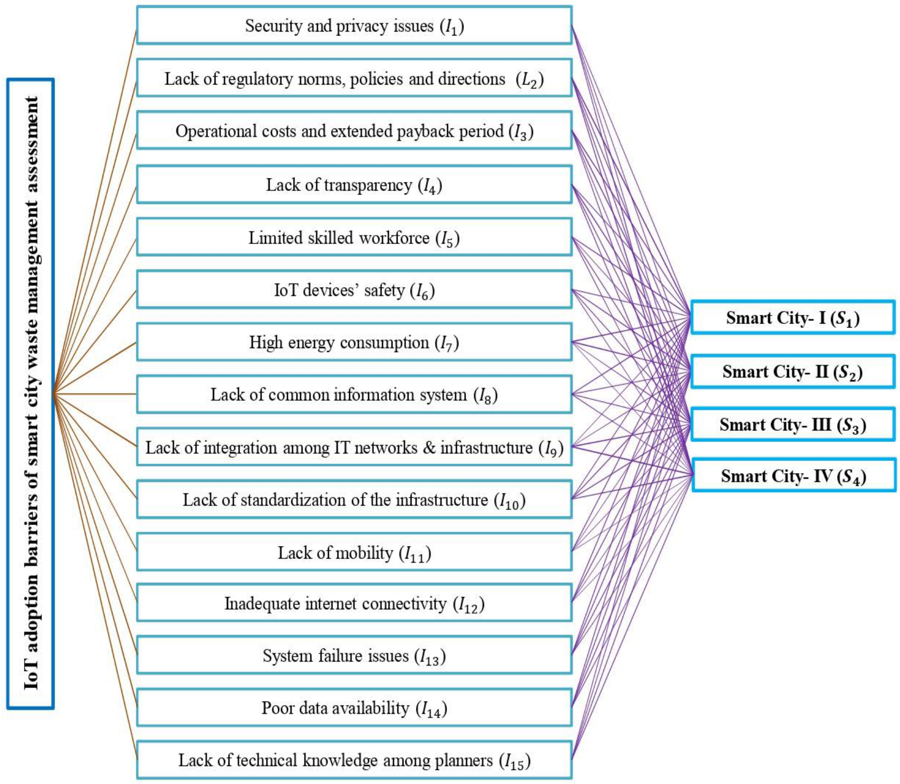

FIGURE 1. Hierarchical structure of IoT adoption barriers to SCWM.

that can recognize the amount of volume and optimum of path, and that information diminishes expenses and advances recycling. LoRa is applied to enlighten the collection structure once the waste containers are occupied [59]. Smart WM structures are an appropriate prioritization to be fitted in the SCs to tackle waste proficiently [17]. The IoTBs for SCWM are recognized from the extant literature and shown in Fig. 1 and Table 2.

III. NEW FERMATEAN FUZZY SIMILARITY MEASURE

In this section, first we discuss the some ideas related to the FFSs. Second, we suggest new similarity measure on FFSs to develop new weighting procedure.

A. BASIC CONCEPTS

Definition 3.1 ([26]): A FFS F on a discourse set T is defined as

$$F = \{\langle t_i,\ F(\mu_F(t_i),\ \nu_F(t_i))\rangle |\ t_i \in T\},$$

where $\mu_F, \nu_F : T \rightarrow [0, 1]$ Simply the MG and NG of an object $t_i \in T$ to F with the condition $0 \leq (\mu_F(t_i))^3 + (\nu_F(t_i))^3 \leq 1$. The indeterminacy grade is described by $\pi_F(t_i) = \sqrt[3]{1 - \mu_F^3(t_i) - \nu_F^3(t_i)},\ \forall t_i \in T$. For effortlessness, Senapati and Yager [26] termed as the "Fermatean fuzzy number (FFN)" $\alpha = (\mu_\alpha, \nu_\alpha)$ which satisfies $\mu_\alpha, \nu_\alpha \in [0, 1]$ and $0 \leq \mu_\alpha^3 + \nu_\alpha^3 \leq 1$.

Definition 3.2 ([26], [27]): Consider a FFN $\alpha = (\mu_\alpha, \nu_\alpha)$. Then,

$$\mathbb{S}(\alpha) = (\mu_\alpha)^3 - (\nu_\alpha)^3 \text{ and } \hbar(\alpha) = (\mu_\alpha)^3 + (\nu_\alpha)^3, \quad (1)$$

are called the score value and accuracy value of α, where $\mathbb{S}(\alpha) \in [-1, 1]$ and $\hbar(\alpha) \in [0, 1]$.

Since $\mathbb{S}(\alpha) \in [-1, 1]$, when several score values are combined with linear weighted assessment procedure, it possibly emerges that positive score values are align by negative score values. Consequently, the improved score value is defined by

Given a variable $\vartheta \in [-1, 1]$, if we consider a function $\xi(\vartheta) = \frac{\vartheta+1}{2}$, then $\xi(\vartheta)$ cannot only preserve the monotonicity of ϑ but also maps ξ to [0, 1]. Therefore, we revise the score value $\mathbb{S}(\alpha)$ as

Definition 3.3: Let $\alpha = (\mu_\alpha, \nu_\alpha)$ be an FFN. Then

$$\mathbb{S}^*(\alpha) = \frac{1}{2}(\mathbb{S}(\alpha) + 1) \quad (2)$$

is called an improved score value.

Definition 3.4 ([26], [27]): Let α, α_1 and α_2 be the FFNs. Then the operations on FFNs are defined by

(a) $\alpha^c = (\nu_\alpha, \mu_\alpha)$,

(b) $\alpha_1 \cap \alpha_2 = \left(\min\{\mu_{\alpha_1}, \mu_{\alpha_2}\},\ \max\{\nu_{\alpha_1}, \nu_{\alpha_2}\}\right)$,

(c) $\alpha_1 \cup \alpha_2 = \left(\max\{\mu_{\alpha_1}, \mu_{\alpha_2}\},\ \min\{\nu_{\alpha_1}, \nu_{\alpha_2}\}\right)$,

(d) $\alpha_1 \oplus \alpha_2 = \left(\sqrt[3]{\mu_{\alpha_1}^3 + \mu_{\alpha_2}^3 - \mu_{\alpha_1}^3 \mu_{\alpha_2}^3},\ \nu_{\alpha_1}\nu_{\alpha_2}\right)$,

(e) $\alpha_1 \otimes \alpha_2 = \left(\mu_{\alpha_1}\mu_{\alpha_2},\ \sqrt[3]{\nu_{\alpha_1}^3 + \nu_{\alpha_2}^3 - \nu_{\alpha_1}^3 \nu_{\alpha_2}^3}\right)$,

(f) $\lambda\alpha = \left(\sqrt[3]{1-\left(1-\mu_\alpha^3\right)^\lambda},\ (\nu_\alpha)^\lambda\right),\ \lambda > 0,$

(g) $\alpha^\lambda = \left((\mu_\alpha)^\lambda,\ \sqrt[3]{1-\left(1-\nu_\alpha^3\right)^\lambda}\right),\ \lambda > 0.$

Next, Sklar [78] initiated the notion of copula which is a useful mathematical way to aggregate probability distributions.

Definition 3.5 ([78]): A copula is a mapping $\mathbb{C} : [0,1] \times [0,1] \to [0,1]$, which holds the following axioms:
(i) $\mathbb{C}(t,0) = \mathbb{C}(0,t) = 0,\ \mathbb{C}(t,1) = \mathbb{C}(1,t) = t\ \forall t \in [0,1]$
(ii)$\mathbb{C}(t_1,s_1) + \mathbb{C}(t_2,s_2) - \mathbb{C}(t_2,s_1) - \mathbb{C}(t_1,s_2) \geq 0$, for $t_1, s_1, t_2, s_2 \in [0,1]$ with $t_1 \leq t_2$ and $s_1 \leq s_2$.

Definition 3.6 ([35]): An Archimedean copula is a mapping $\mathbb{C} : [0,1] \times [0,1] \to [0,1]$ such that $\mathbb{C}(t,s) = \psi(\varphi(t) + \varphi(s))$ where $\eta : [0,1] \to [0,\infty)$ is a strictly decreasing and $\psi : [0,\infty) \to [0,1]$ is given as $\psi(t) = \begin{cases} \varphi^{-1}(t), & t \in [0,\ \eta(0)] \\ 0, & t \in [\eta(0),\ \infty]. \end{cases}$

An Archimedean copula is termed as a strict Archimedean copula if $\mathbb{C}$ is strictly increasing on $[0,1] \times [0,1]$ and ψ becomes identical with φ. In such a scenario $\mathbb{C}(t,s) = \varphi^{-1}(\varphi(t)+\varphi(s)).\mathbb{C}(t_1,s_1)+\mathbb{C}(t_2,s_2)-\mathbb{C}(t_2,s_1)-\mathbb{C}(t_1,s_2) \geq 0$for $t_1, s_1, t_2, s_2 \in [0,1]$ with $t_1 \leq t_2$ and $s_1 \leq s_2$.

Definition 3.7 ([79], [80]): A t-norm $\Delta(t,s)$ is said to be a strictly Archimedean t-norm if it is continuous, $\Delta(t,t) < t\ \forall t \in (0,1)$ and decreases strictly for $t, s \in (0,1)$.

Definition 3.8 ([79], [80]): A t-conorm $\nabla(t,s)$ is said to be a strictly Archimedean t-conorm if it is continuous, $\nabla(t,t) > t\ \ \forall t \in (0,1)$ and increases strictly for $t, s \in (0,1)$.

Definition 3.9 ([81]): Suppose $f : (0,1] \to R$ is a continuous such that f is strictly decreasing. Then a strictly Archimedean t-norm is given as

$\delta(t,s) = f^{-1}(f(t) + f(s))$ for $t, s \in (0,1]$.

Definition 3.10 ([81]): Suppose $g : [0,1) \to R$ is a continuous such that $g(l) = f(1-l),\ l \in [0,1)$ and f is strictly decreasing. Then a strictly Archimedean t-conorm is expressed by

$\rho(t,s) = g^{-1}(g(t) + g(s))$ for $t, s \in [0,1)$.

B. SIMILARITY MEASURE FOR FFSs

The concept of "similarity measure (SM)" is a significant and essential tool to quantifying the degree of closeness between any numbers of objects. As the FSs have been pioneered, copious scholars have worked on SMs in diverse fuzzy contexts and effectively utilized to handle the problems associated to image processing, texture analysis, pattern identification, disease diagnosis and decision-analysis [24], [82]–[84]. However, the notion of Fermatean fuzzy SM has less investigated in the literature [85]. As SMs have been extensively applied in realistic problems, the aim of the current section is to propose similarity measure and implement it to introduce a FF-CoCoSo approach.

Definition 3.11: Let $F, G, J \in FFSs(T)$. A real-valued mapping $S : FFS(T) \times FFS(T) \to [0,1]$ is said to be a similarity measure for FFSs if it fulfills the mentioned axioms:

(s1). $0 \leq S(F,G) \leq 1,$
(s2). $S(F,G) = S(G,F),$
(s3). $S(F,G) = 1 \Leftrightarrow F = G,$
(s4). $S(F,F^c) = 0 \Leftrightarrow F$ is a crisp set,
(s5). If $F \subseteq G \subseteq J$, then $S(F,J) \leq S(F,G)$ and $S(F,J) \leq S(G,J)$.

For $F = (\mu_F, \nu_F),\ G = (\mu_G, \nu_G) \in FFSs(T)$, we introduce new formula for calculating the similarity between two FFSs, presented as

$$S_1(F,G) = 1 - \frac{1-\exp\left[-\frac{1}{2n}\sum_{i=1}^{n}\left(|\mu_F^3(t_i)-\mu_G^3(t_i)|+|\nu_F^3(t_i)-\nu_G^3(t_i)|\right)\right]}{1-\exp(-1)}. \tag{3}$$

Lemma 3.1: If $\varphi(\lambda) = 1 - \frac{1-\exp(-\lambda)}{1-\exp(-1)}$, then $\max_{\lambda \in [0,n]} \varphi(\lambda) = \varphi(0) = 1$ and $\min_{\lambda \in [0,n]} \varphi(\lambda) = \varphi(n) = 0$.

Proof: Since $\varphi'(\lambda) = -\frac{\exp(-\lambda)}{1-\exp(-1)} < 0, \forall \lambda \in [0,n]$, therefore, $\varphi(\lambda)$ is decreasing in $[0,n]$.

Theorem 3.1: The function $S_1(F,G)$, expressed by Eq. (3), is a suitable FF-similarity measure.

Proof: To show this theorem, we have to verify the properties (s1)-(s5) of Definition 3.11.

(s1). For $F = (\mu_F, \nu_F),\ G = (\mu_G, \nu_G) \in FFSs(T)$,

$$\lambda = \frac{1}{2n}\sum_{i=1}^{n}\left(\left|\mu_F^3(t_i) - \mu_G^3(t_i)\right| + \left|\nu_F^3(t_i) - \nu_G^3(t_i)\right|\right). \tag{4}$$

Since $\lambda \in [0,n]$, therefore, $S_1(F,G) = \varphi(\lambda)$. Thus, in accordance with Lemma 3.1, we have $0 \leq S_1(F,G) \leq 1$.

(s2). From Eq. (3), if $F = G$, then $S_1(F,G) = 1$. Conversely, let $S_1(F,G) = 1$. Then, from Eq. (3), we obtain

$$1 - \frac{1-\exp\left[\frac{1}{2n}\sum_{i=1}^{n}\left(|\mu_F^3(t_i)-\mu_G^3(t_i)|+|\nu_F^3(t_i)-\nu_G^3(t_i)|\right)\right]}{1-\exp(-1)} = 1,$$

It implies that

$$\left|\mu_F^3(t_i)-\mu_G^3(t_i)\right|+\left|\nu_F^3(t_i)-\nu_G^3(t_i)\right| = 0, \quad \forall t_i \in T. \tag{5}$$

That means $\mu_F(t_i) = \mu_G(t_i),\ \nu_F(t_i) = \nu_G(t_i),\ \forall t_i \in T$. Hence, $F = G$.

(s3)-(s4). Both properties are obvious from the Eq. (3).

(s5). Given that $F \subseteq G \subseteq H$, and $\forall t_i \in T$, then $\mu_F^3(t_i) \leq \mu_G^3(t_i) \leq \mu_H^3(t_i)$ and $\nu_F^3(t_i) \geq \nu_G^3(t_i) \geq \nu_H^3(t_i)$.

Now,

$$\lambda_1 = \frac{1}{2n}\sum_{i=1}^{n}\left(\left|\mu_F^3(t_i) - \mu_G^3(t_i)\right| + \left|\nu_F^3(t_i) - \nu_G^3(t_i)\right|\right)$$
$$\leq \lambda_2 = \frac{1}{2n}\sum_{i=1}^{n}\left(\left|\mu_F^3(t_i) - \mu_H^3(t_i)\right| + \left|\nu_F^3(t_i) - \nu_H^3(t_i)\right|\right). \tag{6}$$

Consequently, by Lemma 3.1, we have $S_1(F, G) = \varphi(\lambda_1) \geq \varphi(\lambda_2) = S_1(F, H)$. Similarly, we can verify that $S_1(G, H) \geq S_1(F, H)$.

Furthermore, a new Fermatean fuzzy similarity measure is proposed based on the combination of $S_1(F, G)$ and a lattice. A lattice is a structure consisting of partially ordered set in which each pair of elements has a lub (supremum) and a glb (infimum).

Now, the proposed FF-similarity measure is presented as

$$S_2(F, G) = \sqrt{S_1(F, V_{FG}) \times S_1(G, V_{FG})}, \text{ where } V_{FG} = F \cup G. \tag{7}$$

Theorem 3.2: The function $S_2(F, G)$, expressed by Eq. (7), is a valid FF-similarity measure.

Proof: **(s1).** It is obvious, so that we have omitted the proof.

(s2). Consider $F = (\mu_F, \nu_F)$, $G = (\mu_G, \nu_G) \in FFSs(T)$ and $F = G$. Given that $V_{FG} = F \cup G$, this implies that $F = G = V_{FG}$ and thus, $S_1(F, G)$ holds the requirement (s2). As a result, $S_2(F, G) = 1$. Conversely, assume that $S_2(F, G) = 1$. That means that $S_1(F, V_{FG}) = S_1(G, V_{FG}) = 1$, where $V_{FG} = F \cup G$ and $S_1(F, G)$ satisfies (s2). Thus, $F = G = V_{FG}$.

(s3)-(s4). Both are obvious from Eq. (3) and Eq. (7).

(s5). Suppose $F, G, H \in FFSs(T)$ and $F \subseteq G \subseteq H$. Then $F \cup G = G$, $F \cup H = H$ and $G \cup H = H$.

Now,

$$S_2(F, H) = \sqrt{S_1(F, V_{FH}) \times S_1(H, V_{FH})}.$$

It implies that

$$S_2(F, H) = \sqrt{S_1(F, H) \times S_1(H, H)}.$$

Thus, $S_2(F, H) = \sqrt{S_1(F, H)}$. Similarly, we can verify that $S_2(F, G) = \sqrt{S_1(F, G)}$. Since $S_1(F, H)$ holds (s5), i.e., $S_1(F, G) \geq S_1(F, H)$, consequently, $S_2(F, G) \geq S_2(F, H)$. In a similar way, we can prove that $S_2(G, H) \geq S_2(F, H)$.

IV. FERMATEAN FUZZY ARCHIMEDEAN COPULA OPERATORS

In this section, we propose some new AOs combining the ideas of Copula and Archimedean operators to aggregate the Fermatean fuzzy information.

A. GENERALIZED ARCHIMEDEAN COPULA OPERATIONS

Definition 4.1: The generalized Archimedean Copula operations between the FFNs $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), j = 1, 2$ are defined by

(a) $$\alpha_1 \oplus \alpha_2 = \left\langle \sqrt[3]{g^{-1}\left(1 - \varphi^{-1}\left(\sum_{j=1}^{2} \varphi(1 - g(\mu_{\alpha_j}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{2} \varphi(f(\nu_{\alpha_j}^3))\right)\right)} \right\rangle,$$

(b) $$\alpha_1 \otimes \alpha_2 = \left\langle \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{2} \varphi(f(\mu_{\alpha_j}^3))\right)\right)}, \sqrt[3]{g^{-1}\left(1 - \varphi^{-1}\left(\sum_{j=1}^{2} \varphi(1 - g(\nu_{\alpha_j}^3))\right)\right)} \right\rangle,$$

(c) $$\lambda\alpha_1 = \left\langle \sqrt[3]{g^{-1}\left(1 - \varphi^{-1}\left(\lambda\varphi(1 - g(\mu_{\alpha_1}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\varphi(f(\nu_{\alpha_1}^3))\right)\right)} \right\rangle, \quad \lambda > 0,$$

(d) $$\alpha_1^\lambda = \left\langle \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\varphi(f(\mu_{\alpha_1}^3))\right)\right)}, \sqrt[3]{g^{-1}\left(1 - \varphi^{-1}\left(\lambda\varphi(1 - g(\nu_{\alpha_1}^3))\right)\right)} \right\rangle, \quad \lambda > 0.$$

Theorem 4.1: For the FFNs $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}) (j = 1, 2)$, then we obtain

(a) $\alpha_1 \oplus \alpha_2 = \alpha_2 \oplus \alpha_1$
(b) $\alpha_1 \otimes \alpha_2 = \alpha_2 \otimes \alpha_1$
(c) $\lambda(\alpha_1 \oplus \alpha_2) = (\lambda\alpha_1) \oplus (\lambda\alpha_2)$
(d) $(\alpha_1 \otimes \alpha_2)^\lambda = (\alpha_1^\lambda) \otimes (\alpha_2^\lambda)$
(e) $(\lambda_1 + \lambda_2)\alpha_1 = (\lambda_1\alpha_1) \oplus (\lambda_2\alpha_1)$
(f) $\alpha_1^{\lambda_1+\lambda_2} = (\alpha_1^{\lambda_1}) \otimes (\alpha_1^{\lambda_2})$

Proof: (a) and (b) are straight forward (8), as shown at the bottom of the next page. Next (9), as shown at the bottom of the next page.

Hence $\lambda(\alpha_1 \oplus \alpha_2) = (\lambda\alpha_1) \oplus (\lambda\alpha_2)$. (d)-(f) are similar to (c).

Here, corresponding to generalized Archimedean Copula operations on FFNs, we will develop the Fermatean fuzzy generalized Archimedean copula weighted averaging (FFGACWA) and Fermatean fuzzy generalized Archimedean copula weighted geometric (FFGACWG) operators. Also, we will present some elegant properties.

B. FFGACWA OPERATOR

Definition 4.2: Let $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), j = 1, 2, \ldots, n$, be the collection of FFNs. Let $w = (w_1, w_2, \ldots, w_n)^T$ is the weight value of α_j such that $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Then the FFGACWA is given by

$$FFGACWA(\alpha_1, \alpha_2, \ldots, \alpha_n) = \mathop{\oplus}_{j=1}^{n} w_j\alpha_j \tag{10}$$

Corresponding to Definition 4.2, Theorem 4.1 and Definition 4.1, we discuss the subsequent theorem as

Theorem 4.2: Let $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), j = 1, 2, \ldots, n$, be the collection of FFNs. Let $w = (w_1, w_2, \ldots, w_n)^T$ is the weight values of α_j such that $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Then the combined value is again an FFN, and

$$FFGACWA(\alpha_1, \alpha_2, \ldots, \alpha_n) = \left\langle \sqrt[3]{g^{-1}\left(1 - \varphi^{-1}\left(\sum_{j=1}^{n} w_j\varphi(1 - g(\mu_{\alpha_j}^3))\right)\right)}, \right.$$

$$\sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{n} w_j\varphi(f(\nu_{\alpha_j}^3))\right)\right)}\Bigg\rangle$$

Proof: Follows from Definition 4.1 and Theorem 4.1.

Based on Theorem 4.2, we deduce the following corollaries:

Property 4.1 (Idempotency): If any FFNs $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right), j = 1, 2, \ldots, n$, are identical, i.e., $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right) = (\mu, \nu) = \alpha$, then

$$FFGACWA\,(\alpha_1, \alpha_2, \ldots, \alpha_n) = \alpha.$$

Property 4.2 (Monotonicity): Let $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right)$ and $\alpha_j' = \left(\mu_{\alpha_j}', \nu_{\alpha_j}'\right), j = 1, 2, \ldots, n$, be two collection of FFNs satisfying $\mu_{\alpha_j} \leq \mu_{\alpha_j}'$ and $\nu_{\alpha_j} \geq \nu_{\alpha_j}'$. Then

$$FFGACWA\,(\alpha_1, \alpha_2, \ldots, \alpha_n) \prec FFGACWA\left(\alpha_1', \alpha_2', \ldots, \alpha_n'\right).$$

Property 4.3 (Boundedness): Let $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right), j = 1, 2, \ldots, n$, be a collection of FFNs. Then $\alpha^- \prec FFGACWA\,(\alpha_1, \alpha_2, \ldots, \alpha_n) \prec \alpha^+$, where

$$\alpha^- = \left\langle \min_j \mu_{\alpha_j}, \max_j \nu_{\alpha_j} \right\rangle \text{ and } \alpha^+ = \left\langle \max_j \mu_{\alpha_j}, \min_j \nu_{\alpha_j} \right\rangle.$$

C. FFGACWG OPERATOR

Definition 4.3: Let $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right), j = 1, 2, \ldots, n$ be the collection of FFNs. Let $w = (w_1, w_2, \ldots, w_n)^T$ is the weight values of α_j such that $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Then the FFGACWG operator is defined as

$$FFGACWG\,(\alpha_1, \alpha_2, \ldots, \alpha_n) = \bigotimes_{j=1}^{n} w_j\alpha_j \tag{11}$$

Corresponding to Definition 4.2, Theorem 4.1 and Definition 4.1, we discuss the subsequent theorem as

Theorem 4.3: Let $\alpha_j = \left(\mu_{\alpha_j}, \nu_{\alpha_j}\right), j = 1, 2, \ldots, n$ be the collection of FFNs. Let $w = (w_1, w_2, \ldots, w_n)^T$ is the weight

$$
\begin{aligned}
(c)\ \lambda(\alpha_1 \oplus \alpha_2) &= \lambda \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\sum_{j=1}^{2}\varphi(1-g(\mu_{\alpha_j}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{2}\varphi(f(\nu_{\alpha_j}^3))\right)\right)}\right\rangle \\
&= \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\lambda\varphi\left(1-1+\varphi^{-1}\left(\sum_{j=1}^{2}\varphi(1-g(\mu_{\alpha_j}^3))\right)\right)\right)\right)}, \right. \\
&\qquad \left. \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\varphi\left(\varphi^{-1}\left(\sum_{j=1}^{2}\varphi(f(\nu_{\alpha_j}^3))\right)\right)\right)\right)}\right\rangle \\
&= \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\lambda\sum_{j=1}^{2}\varphi(1-g(\mu_{\alpha_j}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\sum_{j=1}^{2}\varphi(f(\nu_{\alpha_j}^3))\right)\right)}\right\rangle.
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
(\lambda\alpha_1) \oplus (\lambda\alpha_2) &= \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\lambda\varphi(1-g(\mu_{\alpha_1}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\varphi(f(\nu_{\alpha_1}^3))\right)\right)}\right\rangle \\
&\quad \oplus \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\lambda\varphi(1-g(\mu_{\alpha_2}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\varphi(f(\nu_{\alpha_2}^3))\right)\right)}\right\rangle \\
&= \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\sum_{j=1}^{2}\varphi\left(1-1+\varphi^{-1}\left(\lambda\varphi(1-g(\mu_{\alpha_1}^3))\right)\right)\right)\right)}, \right. \\
&\qquad \left. \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{2}\varphi\left(\varphi^{-1}\left(\lambda\varphi(f(\nu_{\alpha_1}^3))\right)\right)\right)\right)}\right\rangle \\
&= \left\langle \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\lambda\sum_{j=1}^{2}\varphi(1-g(\mu_{\alpha_1}^3))\right)\right)}, \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\lambda\sum_{j=1}^{2}\varphi(f(\nu_{\alpha_1}^3))\right)\right)}\right\rangle.
\end{aligned} \tag{9}
$$

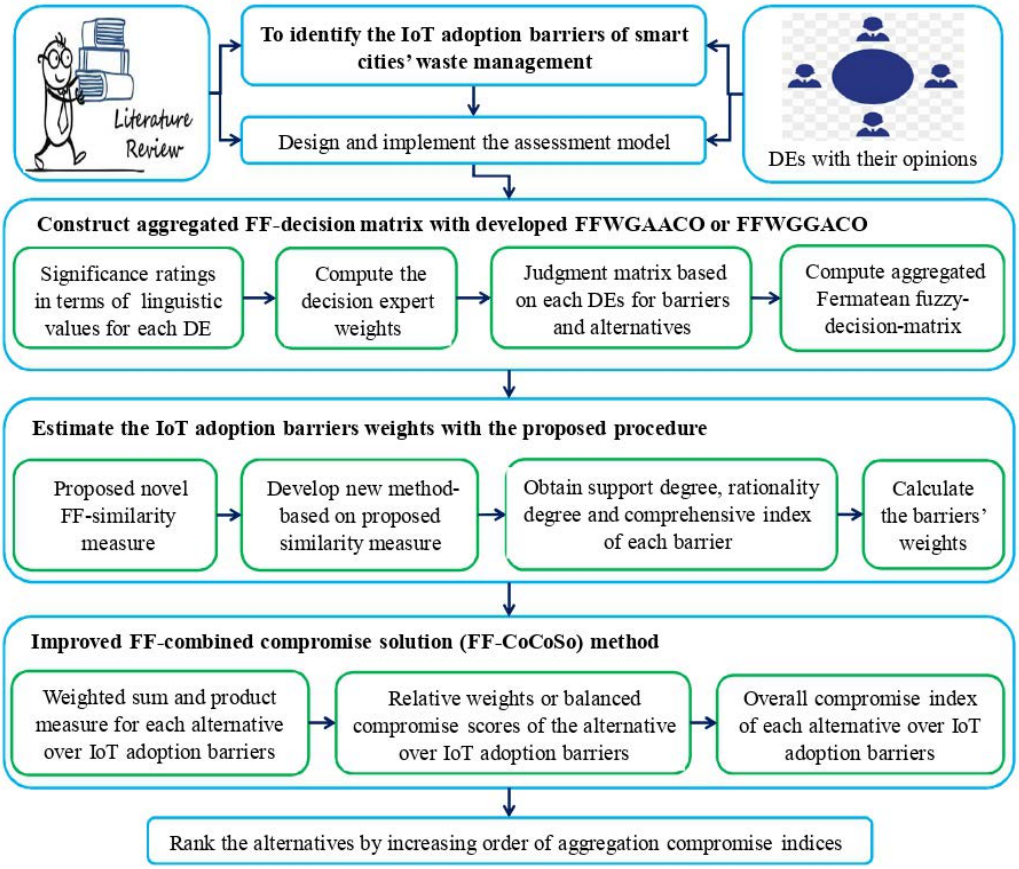

FIGURE 2. Assessment framework to adopt the IoTBs for SCWM.

values of α_j such that $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Then the combined value is again an FFN, and

$$FFGACWG(\alpha_1, \alpha_2, \ldots, \alpha_n) = \left\langle \sqrt[3]{f^{-1}\left(\varphi^{-1}\left(\sum_{j=1}^{n} w_j \varphi(f(\mu_{\alpha_j}^3))\right)\right)}, \sqrt[3]{g^{-1}\left(1-\varphi^{-1}\left(\sum_{j=1}^{n} w_j \varphi(1-g(\nu_{\alpha_j}^3))\right)\right)} \right\rangle.$$

Proof: Follows from Definition 4.1 and Theorem 4.1.

Based on Theorem 4.3, we deduce the following corollaries:

Property 4.4 (Idempotency): If any FFNs $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), j = 1, 2, \ldots, n$ are identical, i.e., $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}) = (\mu, \nu) = \alpha$, then

$$FFGACWG(\alpha_1, \alpha_2, \ldots, \alpha_n) = \alpha.$$

Property 4.5 (Monotonicity): Let $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j})$ and $\alpha'_j = (\mu'_{\alpha_j}, \nu'_{\alpha_j}), j = 1, 2, \ldots, n$ be two collection of FFNs satisfying $\mu_{\alpha_j} \leq \mu'_{\alpha_j}$ and $\nu_{\alpha_j} \geq \nu'_{\alpha_j}$. Then

$$FFGACWG(\alpha_1, \alpha_2, \ldots, \alpha_n) \prec FFGACWG(\alpha'_1, \alpha'_2, \ldots, \alpha'_n).$$

Property 4.6 (Boundedness): Let $\alpha_j = (\mu_{\alpha_j}, \nu_{\alpha_j}), j = 1, 2, \ldots, n$ be a collection of FFNs. Then $\alpha^- \prec FFGACWG(\alpha_1, \alpha_2, \ldots, \alpha_n) \prec \alpha^+$, where

$$\alpha^- = \left\langle \min_j \mu_{\alpha_j}, \max_j \nu_{\alpha_j} \right\rangle \text{ and } \alpha^+ = \left\langle \max_j \mu_{\alpha_j}, \min_j \nu_{\alpha_j} \right\rangle.$$

V. IMPROVED FF-CoCoSo METHODOLOGY FOR MADM PROBLEM

The CoCoSo approach is an influential tool to treat with MADM problems, which combines the EWP and the SAW models [42]. Furthermore, Mi and Liao [49] improved the CoCoSo model that considers the non-compensatory effect to the final compromise solution. To magnify the utilization of the CoCoSo approach, we develop an improved FF-CoCoSo framework with new weighting procedure using similarity measure for treating the uncertain and complex MADM problems. The structure of the developed approach (see Fig. 2) is discussed as

Step 1 (Define the MADM Problem): Assume that a set of alternatives $S = \{S_1, S_2, \ldots, S_m\}$ over a set of criteria $I = \{I_1, I_2, \ldots, I_n\}$. Let $P = (\alpha_{ij}), \forall i, j$ be the "linguistic decision matrix (LDM)" generated by l "decision experts (DEs)" $D = \{D_1, D_2, \ldots, D_l\}$, in which α_{ij} implies the assessment values of alternative S_i over attribute I_j in the terms of a "linguistic values (LVs)".

Step 2 (Obtain the DEs' Weights): In MADM procedure, the estimation of the expert's weight is a major issue. Here, let the expert weights are provided in term of LVs and then transformed into FFNs. To compute the k^{th} DEs' weight, consider (μ_k, ν_k) is an FFN of DEs, then weight value of DE is estimated as

$$\varpi_k = \frac{\left(\mu_k^3+\pi_k^3\times\left(\frac{\mu_k^3}{\mu_k^3+\nu_k^3}\right)\right)}{\sum_{k=1}^{\ell}\left(\mu_k^3+\pi_k^3\times\left(\frac{\mu_k^3}{\mu_k^3+\nu_k^3}\right)\right)}, \quad \varpi_k \geq 0,$$
$$\sum_{k=1}^{\ell}\varpi_k = 1, \quad k = 1\,(1)\,\ell. \tag{12}$$

Step 3 (Find the "Aggregated FF-Decision Matrix (AFF-DM)"): To obtain the AFF-DM, the FFGACWA operator (or FFGACWG operator) is implemented, and then the AFF-DM A $= (\iota_{ij})_{m\times n}$ is found, where

$$\iota_{ij} = (\mu_{ij}, \nu_{ij}) = FFGACWA_{\varpi}\left(\alpha_{ij}^{(1)}, \alpha_{ij}^{(2)}, \ldots, \alpha_{ij}^{(\ell)}\right)$$

or

$$\iota_{ij} = (\mu_{ij}, \nu_{ij}) = FFGACWG_{\varpi}\left(\alpha_{ij}^{(1)}, \alpha_{ij}^{(2)}, \ldots, \alpha_{ij}^{(\ell)}\right) \tag{13}$$

Step 4 (Proposed Weighting Procedure for Criteria Weights Estimation): To estimate the weight of attribute, an innovative formula is introduced by means of the proposed similarity measure. Firstly, we assume that each criterion has diverse importance. Let $w = (w_1, w_2, \ldots, w_n)^T$ such that $\sum_{j=1}^{n} w_j = 1$ and $w_j \in [0, 1]$ be the weight vector of the criteria set I. Here, we propose new weighting procedure is given by

Step 4a: Obtain the "support degree (SD)" $\sup(\iota_{ij}, \iota_{it})$ between the attributes I_j and I_t using the AFF-DM as follows:

$$\sup(\iota_{ij}, \iota_{it}) = S(\iota_{ij}, \iota_{it}), \quad i = 1\,(1)\,m, j, \ t = 1\,(1)\,n, \ j \neq t, \tag{14}$$

where $S(\iota_{ij}, \iota_{it})$ signifies the proposed similarity measure in Eq. (3).

Step 4b: Define the "total support degree (TSD)" $T(\iota_{ij})$ for each attribute as follows:

$$T(\iota_{ij}) = \sum_{t=1;\, j\neq t}^{n} \sup(\iota_{ij}, \iota_{it}). \tag{15}$$

Step 4c: Compute the "rationality degree (RD)" δ_j of each attribute using

$$\delta_j = \frac{1}{m(n-1)}\sum_{i=1}^{m}\sum_{j=1}^{n} T(\iota_{ij}); \quad \delta_j \in [0, 1]. \tag{16}$$

Step 4d: Obtain the "comprehensive index (CI)" ξ_j of each attribute using

$$\xi_j = \frac{\delta_j}{\sum_{j=1}^{n}\delta_j}; \ 0 \leq \xi_j \leq 1. \tag{17}$$

Step 4e: Assess the "importance degree (ID)" (κ_j) of each attribute

To obtain the ID, we consider the individual ID-matrix (σ^k) for k^{th} expert using the procedure

$$\sigma^k = \begin{bmatrix}\sigma_1^k\\ \sigma_2^k\\ \vdots\\ \sigma_n^k\end{bmatrix}_{1\times n}, \quad j = 1\,(1)\,n, \ k = 1\,(1)\,l. \tag{18}$$

where σ_j^k signifies the assessment information of attribute provided by k^{th} expert. To compute the combined weight information, we utilize the proposed AOs as

$$\kappa_j = (\bar{\mu}_j, \bar{\nu}_j) = FFGACWA_{\varpi}\left(\sigma_j^1, \sigma_j^2, \ldots, \sigma_j^l\right) \tag{19}$$

Or

$$\kappa_j = (\bar{\mu}_j, \bar{\nu}_j) = FFGACWG_{\varpi}\left(\sigma_j^1, \sigma_j^2, \ldots, \sigma_j^l\right), \tag{20}$$

where $\sigma^k = (\mu_{\sigma^k}, \nu_{\sigma^k})$ is the assessment value of k^{th} expert.

Step 4f: Estimate the "overall importance degree (OID)" (η_j) of each attribute

The score value $\mathbb{S}^*(\kappa_j)$ of ID using Eq. (1). Therefore, we find the OID (η_j) and is presented by

$$\eta_j = \frac{\mathbb{S}^*(\kappa_j)}{\sum_{j=1}^{n}\mathbb{S}^*(\kappa_j)}; \quad j = 1\,(1)\,n. \tag{21}$$

Step 4g: Assess the combined weight of each attribute

From Eq. (14)–Eq. (21), the attribute weights is estimated using

$$w_j = \vartheta\xi_j + (1-\vartheta)\,\eta_j, \tag{22}$$

where ξ_j symbolizes the RD, η_j signifies the ID of the j^{th} attribute, ϑ $(0 \leq \vartheta \leq 1)$ indicates the strategy coefficient and the choice can be made with the real constraint of MADM such that we obtain $0 \leq w_j \leq 1$.

Step 5 (Make the "Normalized APF-DM (NAFF-DM)"): Corresponding to the AFF-DM A $= (\iota_{ij})_{m\times n}$, the NAFF-DM $\mathbb{R} = [\varsigma_{ij}]_{m\times n}$ is obtained using

$$\varsigma_{ij} = \left(\widehat{\mu}_{ij}, \widehat{\nu}_{ij}\right) = \begin{cases}\iota_{ij} = (\mu_{ij}, \nu_{ij}), & \text{for benefitcriterion,}\\ (\iota_{ij})^c = (\nu_{ij}, \mu_{ij}), & \text{for costcriterion.}\end{cases} \tag{23}$$

Step 6 (Estimate the "Weighted Sum Measure (WSM)" and "Weighted Product Measure (WPM)"): From Eq. (11) and Eq. (13), the WSM $\left(\mathbb{C}_i^{(1)}\right)$ and WPM $\left(\mathbb{C}_i^{(2)}\right)$ for each option is obtained using

$$\mathbb{C}_i^{(1)} = \bigoplus_{j=1}^{n} w_j\,\varsigma_{ij}, \tag{24}$$

$$\mathbb{C}_i^{(2)} = \bigotimes_{j=1}^{n} \varsigma_{ij}^{w_j}. \tag{25}$$

Step 7 (Relative or Average Compromise Degrees of Each Alternatives): The different average compromise degrees of each alternative are estimated using

$$\mathbb{Q}_i^{(1)} = \frac{\mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right) + \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}{\sum_{i=1}^{m}\left(\mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right) + \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)\right)}, \tag{26}$$

$$\bar{\mathbb{Q}}_i^{(2)} = \frac{\mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right)}{\min_i \mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right)} + \frac{\mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}{\min_i \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}, \tag{27}$$

$$\mathbb{Q}_i^{(3)} = \frac{\gamma\, \mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right) + (1-\gamma)\, \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}{\gamma \max_i \mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right) + (1-\gamma) \max_i \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}, \tag{28}$$

where γ is the decision precision coefficient and $\gamma \in [0, 1]$. Generally, we take $\gamma = 0.5$. It is deduced that Eq. (26)-Eq. (28) describe the mean value, relative degrees associated with worst solution and stable compromise degree, respectively.

Let us examine the zero-value condition for $\mathbb{C}_i^{(1)}$ and $\mathbb{C}_i^{(2)}$, if $\mathbb{C}_i^{(1)} = 0$ or $\mathbb{C}_i^{(2)} = 0$ then the relative degree of i^{th} alternative' over the attribute is the worst. Moreover, the zero-value cannot be considered since the denominator values are zero in Eq. (27). To evade the concern that consider zero-value in Eq. (27) can be changed by assuming the maximum degree as follows:

$$\mathbb{Q}_i^{(2)} = \frac{\mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right)}{\max_i \mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right)} + \frac{\mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}{\max_i \mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)}, \tag{29}$$

Step 8 (Assess the "Overall Compromise Degree (OCD)" of Each Alternative): The OCD $\left(\mathbb{Q}_i'\right)$ is determined of each alternative by decreasing OCD in the following expression

$$\mathbb{Q}_i' = \left(\mathbb{Q}_i^{(1)}\mathbb{Q}_i^{(2)}\,\mathbb{Q}_i^{(3)}\right)^{1/3} + \frac{1}{3}\left(\mathbb{Q}_i^{(1)} + \mathbb{Q}_i^{(2)} + \mathbb{Q}_i^{(3)}\right). \tag{30}$$

The reasonable and robust OCD comprises two advantages: eliminating the dominance situation in Eq. (30) for the OCD of options, and considering the non-compensatory feature besides two extant fully compensatory and partially compensatory viewpoints. The compensatory outcome symbolizes that a small degree of an option over one attribute can be reimbursed by the highest degree of the options over the attributes. This might occur to an issue that the appropriate option possesses a very less OCD on one attribute, which is not favored in realistic situations. To treat with the concern, we utilize the non-compensatory feature and are presented as follows:

$$\mathbb{Q}_i = \frac{1}{3}\left(\mathbb{Q}_i^{(1)} + \mathbb{Q}_i^{(2)} + \mathbb{Q}_i^{(3)}\right) + \left(\mathbb{Q}_i^{(1)}\,\mathbb{Q}_i^{(2)}\,\mathbb{Q}_i^{(3)}\right)^{1/3} - \max_\alpha \left|\max_i \mathbb{Q}_i^\alpha - \mathbb{Q}_i^\alpha\right|, \quad \alpha = 1, 2, 3, \tag{31}$$

Algorithm 1 Pseudo Code Representation of FF-CoCoSo for IoT Adoption Barriers for SCWM

Input: m, n, l, where m is the number of alternatives, n is number of attributes and l is number of decision experts (DEs)
Output: Rank the IoTBs and smart city to adopt the IoTBs for SCWM
Begin
Step 1: Input linguistic decision-matrix (LDM) ***P*** and weight of each DEs in terms of LVs
Step 2: Convert the LDM ***P*** and weight of each DEs into FFNs with the help of Table 3
Step 3: For $k = 1$ to l
  Compute the expert weight ϖ_k using Eq. (12).
  End for
Step 4: For *i*=1 to *m*
  For *j*=1 to *n*
  Use FFGACWA (or FFGACWG) to output the ***AFF-DM A*** using Eq. (13).
  End for
  End for
Step 5: For *i*=1 to *m*
  For *j*= 1 to *n*
  If(*i* !=*j*)
  Calculate the $\boldsymbol{Sup_{ij}}$ using Eq. (14) with the proposed similarity measure between criteria i and j.
  End if
  End for
  Calculate the rationality degree δ_j using Eq. (16).
  Compute the comprehensive index ξ_j using Eq. (17).
  Estimate the individual importance degree κ_j using the FFGACWA (or FFGACWG) operator.
  Calculate the overall importance degree η_j using Eq. (21).
  Compute the weight $\boldsymbol{w_i}$ using Eq.(22) over the adjustment coefficient ϑ $(0 \leq \vartheta \leq 1)$.
  End for
Step 6: For *i*=1 to *m*
  For *j*= 1 to *n*
  Calculate the normalized ***AFF-DM*** $\mathbb{R}$ using Eq. (23).
  End for
  End for
Step 7: Use FFWGAACO to output ***WSM*** $\mathbb{C}_i^{(1)}$ and FFWGGACO to ***WPM*** $\mathbb{C}_i^{(2)}$ using Eq. (24) and Eq. (25).
Step 8: Use WSM $\mathbb{C}_i^{(1)}$ and WPM $\mathbb{C}_i^{(2)}$ to output appraisal scores $\mathbb{Q}_i^{(1)}$, $\mathbb{Q}_i^{(2)}$ and $\mathbb{Q}_i^{(3)}$ w. r. t. decision mechanism coefficient $\gamma \in [0, 1]$ using Eq. (26)-Eq. (28).
Step 9: Evaluate the overall compromise degree $\mathbb{Q}_i$ w. r. t. decision mechanism coefficient $\gamma \in [0, 1]$
Step 10: Rank the IoTBs and smart city to adopt the IoTBs for SCWM in decreasing compromise degree $\mathbb{Q}_i$
End.

where $\max_\alpha \left|\max_i \mathbb{Q}_i^\alpha - \mathbb{Q}_i^\alpha\right|$ represents the regret degree in selecting any relative compromise degree among $\mathbb{Q}_i^{(1)}, \mathbb{Q}_i^{(2)}, \mathbb{Q}_i^{(3)}$ and $\alpha = 1, 2, 3$.

Step 9 End:

VI. CASE STUDY

Numerous existing studies have recognized the main IoT adoption barriers in perspective to diverse sectors [2], [8], [19]. To accomplish the requirement of the SCs in developing

TABLE 3. Linguistic ratings of the alternatives over IoTBs for SCWM.

LVs	FFNs
Absolutely important (AI)	(0.95, 0.20)
Very very important (VVI)	(0.90, 0.30)
Very important (VI)	(0.85, 0.40)
Slightly important (SI)	(0.80, 0.50)
Important (I)	(0.75, 0.60)
Fair (F)	(0.60, 0.70)
Unimportant (U)	(0.50, 0.80)
Slightly unimportant (SU)	(0.40, 0.85)
Very unimportant (VU)	(0.30, 0.90)
Very very unimportant (VVU)	(0.20, 0.95)

TABLE 4. The LDM for IoTBs for SCWM.

Barriers	S_1	S_2	S_3	S_4
I_1	(SI, I, I, SI)	(U, F, F, U)	(SI, I, F, SI)	(F, F, U, I)
I_2	(F, F, I, U)	(U, I, U, F)	(SI, I, SI, SI)	(I, SI, I, SI)
I_3	(F, I, F, SI)	(VI, I, F, SI)	(U, I, SI, U)	(VI,F,VI,SI)
I_4	(F, I, SI, F)	(I, F, I, VI)	(SI, F, I, U)	(SI, I, F, U)
I_5	(U, F, F, SI)	(SU,F,SI,U)	(F,SU,VU,F)	(SI, I, F, F)
I_6	(SI, I, SI, U)	(U,SU,I, F)	(SI, I, F, I)	(SI, SI, I, U)
I_7	(F, I, SI, U)	(I, I, VI, I)	(F, I, SI, U)	(SI,SU,SI,I)
I_8	(I, F, SI, U)	(I, F, VI, F)	(SI, I, SU, I)	(SI,SI,F, U)
I_9	(I, F, SI, F)	(VVI,I, F, I)	(F, U, I, U)	(VI, U, I, F)
I_{10}	(SI, I, F, SI)	(F, F, VI, I)	(U,F,SU,SU)	(SI,I,F, SU)
I_{11}	(U, I, F, SI)	(SI,F,SI,SU)	(SI, U, I, SU)	(VI, SI, I, I)
I_{12}	(F, I, U, SI)	(U, F, SI, F)	(SI, F, U, SI)	(I,SU,SI,U)
I_{13}	(I, F, F, SI)	(VI, I, F, I)	(F, I, SI, F)	(SI,I,U,SU)
I_{14}	(F, U, I, U)	(U,VU,F, I)	(SI, VI, I, F)	(SI, U, I, U)
I_{15}	(F, I, I, SU)	(I, U,VU, F)	(SI, U, I, U)	(U, F, VI, I)

nations, it is vital to illustrate the IoTBs to implement and rank the smart cities, which influences SCWM [2], [86].

Corresponding to the professionals' viewpoints, let {(0.80, 0.55), (0.85, 0.50), (0.70, 0.65), (0.75, 0.60)} be the importance ratings of DMEs. Table 3 shows LVs and their associated FFNs by DMEs with ten points from "Absolutely important (AI)" to "Very very unimportant (VVU)". Next, each option is evaluated by four DMEs over various key IoTBs. Thus, Table 4 describes the FF-linguistic decision-matrix.

Applying Eq. (13), the DMEs' weight is obtained as $\varpi_1 = 0.2693$, $\varpi_2 = 0.2965$, $\varpi_3 = 0.1982$ and $\varpi_4 = 0.2360$. To combine the single decision-matrix, we utilize Eq. (14) on Table 4 and therefore, the AFF-DM (Taking $f(t) = -\ln t\ (t>0)$, $g(t) = -\ln(1-t)\ (0<t<1)$, $\varphi(t) = -\ln(t)\ (t>0)$ and $\theta = 1$) is shown in Table 5.

To compute IoTBs' weights, firstly the RD and CI of AFF-DM are computed in Table 6. Table 7 presents the score degrees and overall significance values of the criteria.

Next, corresponding to Tables 6-7 and Eq. (15)-Eq. (19) (for $\vartheta = 0.5$), the criteria weights for IoT barriers of SCWM assessment is obtained and depicted in Fig. 3.

w_j = (0.0691, 0.0700, 0.0614, 0.0664, 0.0699, 0.0673, 0.0581, 0.0661, 0.0666, 0.0664, 0.0575, 0.0622, 0.0758, 0.0733, 0.0699).

Since, all IoTBs are of benefit types, there is no need generate the NAFF-DM. Thus, required NAFF-DM is presented in Table 5.

By utilizing Eq. (20)-Eq. (25), the results of FF-CoCoSo method has been computed and shown in Table 8. Based on the compromise degree $\mathbb{Q}_i$, the prioritization of options is $S_4 \succ S_1 \succ S_3 \succ S_2$ and therefore, S_4 is the best smart city of IoTBs for SCWM.

A. COMPARISON WITH EXTANT MODELS

To exhibit the usefulness and display the unique merits of developed improved FF-CoCoSo methodology, the FF-TOPSIS [26] and FF-WASPAS [30] approaches are taken to treat the aforementioned MADM problem.

1) FF-TOPSIS APPROACH

The steps of FF-TOPSIS approach are presented as

Steps 1-4: Similar to the FF-CoCoSo methodology

Step 6: Estimate the "Fermatean fuzzy ideal solution (FF-IS)" and "Fermatean fuzzy anti-ideal solution (FF-AIS)" using the expression

$$\eta^{+} = \begin{cases} \max\limits_{i} \mu_{ij}, & \text{for benefit criterion } I_b \\ \min\limits_{i} \nu_{ij}, & \text{for } \cos t \text{ criterion } I_n \end{cases} \quad \text{for } j = 1\,(1)\,n, \tag{32}$$

$$\eta^{-} = \begin{cases} \min\limits_{i} \mu_{ij}, & \text{for benefit criterion } I_b \\ \max\limits_{i} \nu_{ij}, & \text{for } \cos t \text{ criterion } I_n \end{cases} \quad \text{for } j = 1\,(1)\,n. \tag{33}$$

TABLE 5. The AFF-DM of IoTBs for SCWM.

Barriers	S_1	S_2	S_3	S_4
I_1	(0.780, 0.551, 0.710)	(0.557, 0.755, 0.735)	(0.769, 0.574, 0.709)	(0.645, 0.702, 0.728)
I_2	(0.665, 0.683, 0.729)	(0.642, 0.727, 0.705)	(0.789, 0.531, 0.711)	(0.781, 0.548, 0.710)
I_3	(0.727, 0.629, 0.716)	(0.809, 0.550, 0.672)	(0.703, 0.700, 0.676)	(0.827, 0.523, 0.663)
I_4	(0.719, 0.636, 0.718)	(0.793, 0.590, 0.666)	(0.717, 0.664, 0.698)	(0.727, 0.654, 0.695)
I_5	(0.680, 0.692, 0.707)	(0.649, 0.745, 0.679)	(0.522, 0.801, 0.700)	(0.733, 0.622, 0.714)
I_6	(0.760, 0.616, 0.690)	(0.602, 0.765, 0.694)	(0.754, 0.597, 0.711)	(0.766, 0.607, 0.689)
I_7	(0.712, 0.667, 0.699)	(0.798, 0.564, 0.679)	(0.712, 0.667, 0.699)	(0.751, 0.657, 0.664)
I_8	(0.709, 0.669, 0.700)	(0.773, 0.623, 0.667)	(0.747, 0.625, 0.697)	(0.752, 0.628, 0.689)
I_9	(0.716, 0.639, 0.719)	(0.819, 0.549, 0.691)	(0.616, 0.742, 0.710)	(0.785, 0.651, 0.622)
I_{10}	(0.769, 0.574, 0.709)	(0.771, 0.626, 0.667)	(0.508, 0.800, 0.710)	(0.724, 0.674, 0.680)
I_{11}	(0.720, 0.664, 0.694)	(0.732, 0.668, 0.677)	(0.703, 0.718, 0.656)	(0.835, 0.520, 0.652)
I_{12}	(0.722, 0.655, 0.700)	(0.668, 0.699, 0.712)	(0.743, 0.635, 0.694)	(0.693, 0.728, 0.656)
I_{13}	(0.724, 0.632, 0.717)	(0.802, 0.573, 0.666)	(0.719, 0.636, 0.718)	(0.718, 0.698, 0.661)
I_{14}	(0.616, 0.742, 0.710)	(0.606, 0.788, 0.661)	(0.813, 0.546, 0.670)	(0.707, 0.700, 0.672)
I_{15}	(0.746, 0.608, 0.712)	(0.625, 0.765, 0.676)	(0.707, 0.700, 0.672)	(0.766, 0.662, 0.638)

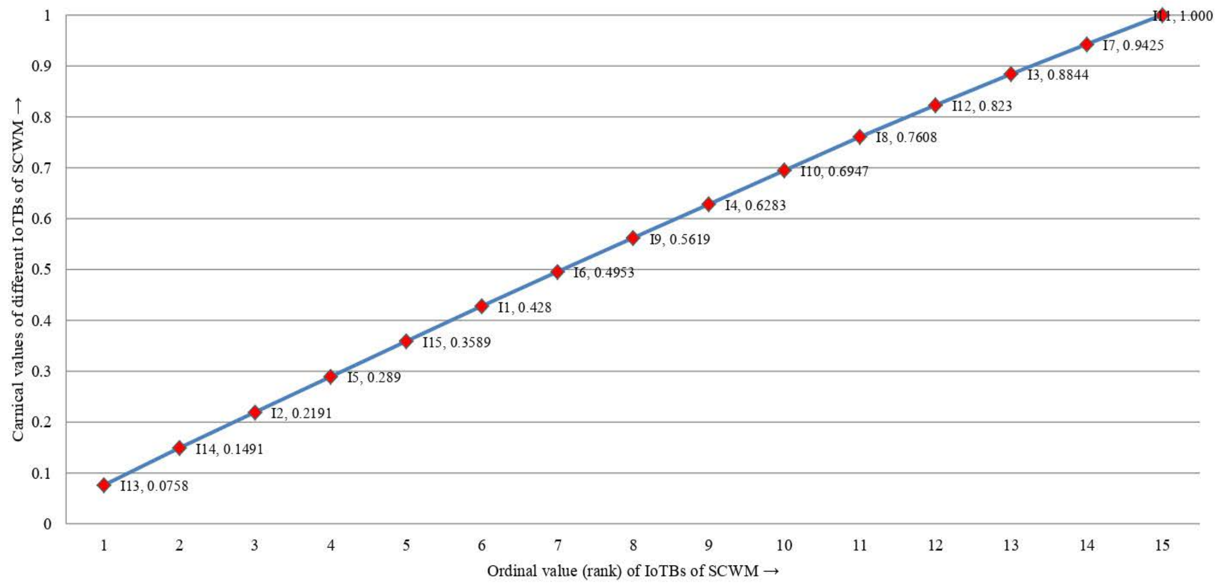

FIGURE 3. A model of ordinal priority value with different IoTBs for SCWM.

TABLE 6. Rationality degree of AFF-DM of IoTBs for SCWM.

Barriers	S_1	S_2	S_3	S_4	δ_j	ξ_j
I_1	13.8374	13.6065	13.7387	13.8024	0.9819	0.0663
I_2	13.9246	13.7828	13.6115	13.8224	0.9847	0.0665
I_3	13.9588	13.6283	13.8510	13.7377	0.9853	0.0666
I_4	13.9614	13.7388	13.8677	13.9263	0.9910	0.0670
I_5	13.9240	13.7546	13.3999	13.9191	0.9821	0.0664
I_6	13.9396	13.6518	13.7916	13.9164	0.9875	0.0667
I_7	13.9560	13.6771	13.8683	13.9289	0.9898	0.0669
I_8	13.9542	13.8073	13.8348	13.9303	0.9915	0.0670
I_9	13.9618	13.7260	13.7383	13.9071	0.9881	0.0668
I_{10}	13.8876	13.8128	13.3791	13.9146	0.9820	0.0664
I_{11}	13.9568	13.8583	13.8211	13.7191	0.9885	0.0668
I_{12}	13.9612	13.8335	13.8464	13.8046	0.9901	0.0669
I_{13}	13.9601	13.6927	13.8522	13.8812	0.9890	0.0668
I_{14}	13.7662	13.5717	13.6194	13.8750	0.9791	0.0662
I_{15}	13.9410	13.6793	13.8496	13.9174	0.9891	0.0668

Step 6: The assessment of discrimination values of options from FF-IS and FF-AIS is obtained using the expression

$$d\left(S_i,\eta^+\right) = \frac{1}{2}\sum_{j=1}^{n}\left[w_j(|\mu_{ij}^3-\mu_{\eta_j^+}^3|+|\nu_{ij}^3-\nu_{\eta_j^+}^3|+|\pi_{ij}^3-\pi_{\eta_j^+}^3|)\right] \tag{34}$$

$$d\left(S_i,\eta^-\right) = \frac{1}{2}\sum_{j=1}^{n}\left[w_j(|\mu_{ij}^3-\mu_{\eta_j^-}^3|+|\nu_{ij}^3-\nu_{\eta_j^-}^3|+|\pi_{ij}^3-\pi_{\eta_j^-}^3|)\right]. \tag{35}$$

Step 7: Obtain the ''relative closeness index (RCI)'' using the expression

$$C\left(S_i\right) = \frac{d\left(S_i,\eta^-\right)}{d\left(S_i,\eta^+\right)+d\left(S_i,\eta^-\right)},\quad i=1\,(1)\,m. \tag{36}$$

Step 8: Corresponding to the RCI, the smart city alternatives over IoTBs for SCWM are ranked.

For the aforementioned IoTBs adoption and smart city alternative for SCWM problem, the FF-IS and FF-AIS solutions are obtained using Eq. (32)-Eq. (33) as

$\eta^+ = \{(0.780, 0.551, 0.710), (0.789, 0.531, 0.711), (0.827, 0.523, 0.663), (0.793, 0.590, 0.666), (0.733, 0.622, 0.714), (0.766, 0.607, 0.689), (0.798, 0.564, 0.679), (0.773, 0.623, 0.667), (0.819, 0.549, 0.691), (0.769, 0.574, 0.709), (0.835, 0.520, 0.652), (0.743, 0.635, 0.694), (0.802, 0.573, 0.666), (0.813, 0.546, 0.670), (0.746, 0.608, 0.712)\}$,

$\eta^- = \{(0.557, 0.755, 0.735), (0.642, 0.727, 0.705), (0.703, 0.700, 0.676), (0.717, 0.664, 0.698), (0.522, 0.801, 0.700), (0.602, 0.765, 0.694), (0.712, 0.667, 0.699), (0.709, 0.669, 0.700), (0.616, 0.742, 0.710), (0.508, 0.800, 0.710), (0.703, 0.718, 0.656), (0.693, 0.728, 0.656), (0.718, 0.698, 0.661), (0.606, 0.788, 0.661), (0.625, 0.765, 0.676)\}$.

According to the Table 9, the priority of the smart city options for SCWM is $S_2 \succ S_4 \succ S_1 \succ S_3$. Thus, the optimal option is smart city-II (S_2).

2) FF-WASPAS APPROACH

Steps 1-6: Similar to aforementioned approach

Step 7: Evaluate the overall degree of the WASPAS for each alternative using

$$\mathbb{C}_i = \lambda\,\mathbb{C}_i^{(1)} + (1-\lambda)\,\mathbb{C}_i^{(2)}, \tag{37}$$

where 'λ' signifies the coefficient of strategic precision, where $\lambda \in [0, 1]$ (when $\lambda = 0$ and $\lambda = 1$, WASPAS is reformed into the WPM and WSM).

Step 9: Corresponding to the score degrees of $\mathbb{C}_i$, prioritize the choices.

TABLE 7. Weight values of IoTBs for SCWM by the DEs.

Criteria	DMEs				Aggregated FFNs	$\mathbb{S}^*(\kappa_j)$	η_j
	S_1	S_2	S_3	S_4			
I_1	I	I	F	F	(0.706, 0.646, 0.723)	0.542	0.0719
I_2	SI	I	F	U	(0.727, 0.654, 0.695)	0.553	0.0734
I_3	SU	F	I	F	(0.623, 0.733, 0.714)	0.424	0.0563
I_4	F	I	F	F	(0.666, 0.672, 0.737)	0.496	0.0659
I_5	F	F	I	SI	(0.716, 0.639, 0.719)	0.553	0.0735
I_6	U	SI	F	F	(0.697, 0.682, 0.701)	0.511	0.0679
I_7	SU	SU	F	I	(0.601, 0.780, 0.676)	0.372	0.0494
I_8	SU	SI	F	F	(0.692, 0.704, 0.684)	0.491	0.0653
I_9	F	SU	I	SI	(0.702, 0.701, 0.677)	0.500	0.0665
I_{10}	SU	F	SI	I	(0.698, 0.699, 0.683)	0.500	0.0664
I_{11}	F	VU	I	U	(0.598, 0.788, 0.668)	0.362	0.0482
I_{12}	SI	SU	F	SU	(0.666, 0.755, 0.649)	0.433	0.0575
I_{13}	F	VI	SI	U	(0.800, 0.618, 0.632)	0.638	0.0847
I_{14}	SU	VI	F	I	(0.792, 0.660, 0.599)	0.605	0.0803
I_{15}	VI	U	SU	F	(0.770, 0.710, 0.570)	0.549	0.0730

TABLE 8. The OCD of smart cities for IoTBs adoption for SCWM.

Options	$\mathbb{C}_i^{(1)}$	$\mathbb{C}_i^{(2)}$	$\mathbb{S}^*(\mathbb{C}_i^{(1)})$	$\mathbb{S}^*(\mathbb{C}_i^{(2)})$	$\mathbb{Q}_i^{(1)}$	$\mathbb{Q}_i^{(2)}$	$\mathbb{Q}_i^{(3)}$	$\mathbb{Q}_i$	Ranking
S_1	(0.725, 0.646, 0.705)	(0.719, 0.652, 0.705)	0.555	0.547	0.2517	1.9011	0.9505	0.1541	2
S_2	(0.737, 0.676, 0.663)	(0.717, 0.698, 0.663)	0.545	0.514	0.2418	1.8256	0.9130	0.14821	4
S_3	(0.729, 0.668, 0.679)	(0.710, 0.692, 0.677)	0.545	0.514	0.2416	1.8242	0.9123	0.14822	3
S_4	(0.763, 0.644, 0.662)	(0.749, 0.653, 0.670)	0.588	0.572	0.2648	2.0000	1.0000	0.1622	1

The priority of the smart city alternatives is found with the use of Eq. (1). The outcomes the WSM, WPM, WASPAS models, score degrees, and overall rank are presented in Table 10. The overall preference order of the smart city alternatives is $S_4 \succ S_1 \succ S_2 \succ S_3$. Thus, the optimal smart city is (S_4) to adopt IoTBs for SCWM.

Apparently, the outcomes are slightly different with introduced and extant methods. So far, the FF-CoCoSo approach is more resilient and stable than FF-WASPAS and FF-TOPSIS approaches and thus has wider applicability. In a comparison of the outcomes of the developed FF-CoCoSo methodology with those of the above-mentioned approaches, it was found that the developed methodology was superior to the others. In the following, the most important advantages of the developed method are presented (See also Fig. 4):

- The indeterminacy degree of DMEs can be reflected more objectively by FFSs than any other conventional extensions of FSs. For that reason, the FF-CoCoSo method can more flexibly express the uncertainty in assessing the IoTBs to the adoption SCWM.
- The proposed weighting procedure is responsible for assessing the weights of the IoTBs to the adoption SCWM, which considers both objective and subjective weights of IoTBs. It gives higher levels of reliability, efficiency, and sensibility to FF-CoCoSo. In [32], the "simple multi-attribute rating technique (SMART)" is applied to compute the subjective weights of IoTBs, and in FF-TOPSIS [26], the criteria weights are assumed.
- The FF-CoCoSo approach applies a comparability procedure using the two measures: the WPM and the WSM. To certify the prioritization, we define three different assessment degrees for each option and a combined procedure discusses the priorities. There is no other approach among the extant MCDM tools associate this kind of aggregation. Each comparability procedure provides a priority order, which would be improved by all-inclusive prioritization. In [32], an aggregation of two procedures, namely the WPM and the WSM, is utilized and in [26], the TOPSIS is used based on an aggregating function demonstrating "closeness to the ideal", which coined in the compromise programming approach. Thus, the proposed FF-CoCoSo approach is fulfilling the existing gap in the study of adaptation of IoTBs of SCWM assessment.

TABLE 9. Results of FF-TOPSIS to adopt IoTBs for SCWM.

Options	$d(S_i,\eta^+)$	$d(S_i,\eta^-)$	$C(S_i)$	Ranking
S_1	0.134	0.093	0.4104	3
S_2	0.069	0.150	0.6833	1
S_3	0.151	0.070	0.3169	4
S_4	0.121	0.102	0.4585	2

B. COMPARISON WITH SOME EXTANT AGGREGATION OPERATORS

Next, we utilize the existing AOs namely "Fermatean fuzzy weighted averaging (FFWA)" [28], "Fermatean fuzzy weighted geometric (FFWG)" [28], "Fermatean fuzzy Hamacher weighted averaging (FFHWA)" [32], "Fermatean fuzzy Hamacher weighted geometric (FFHWG)" [32], "Fermatean fuzzy Einstein weighted averaging (FFEWA)" [87]

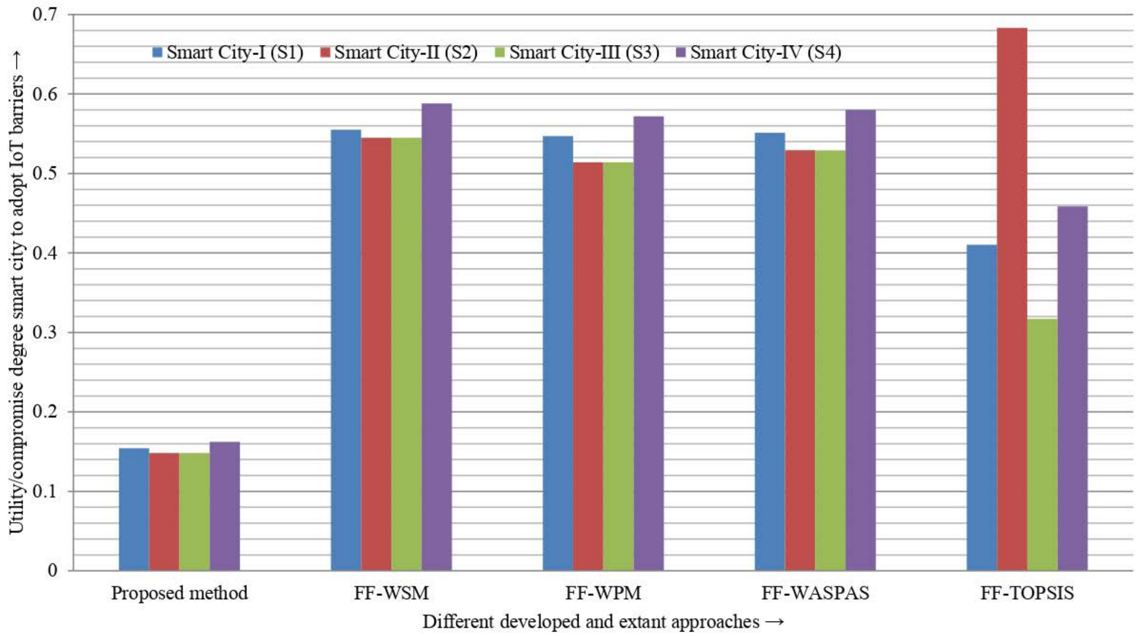

FIGURE 4. Comparison of compromise degree of each smart city option over different IoTBs.

TABLE 10. The FF-WASPAS approach to adopt IoTBs for SCWM.

Options	WSM		WPM		WASPAS measure $\mathbb{C}_i(\lambda)$	Ranking
	$\mathbb{C}_i^{(1)}$	$\mathbb{S}^*\left(\mathbb{C}_i^{(1)}\right)$	$\mathbb{C}_i^{(2)}$	$\mathbb{S}^*\left(\mathbb{C}_i^{(2)}\right)$		
S_1	(0.725, 0.646, 0.705)	0.555	(0.719, 0.652, 0.705)	0.547	0.5513	2
S_2	(0.737, 0.676, 0.663)	0.545	(0.717, 0.698, 0.663)	0.514	0.5295	3
S_3	(0.729, 0.668, 0.679)	0.545	(0.710, 0.692, 0.677)	0.514	0.5291	4
S_4	(0.763, 0.644, 0.662)	0.588	(0.749, 0.653, 0.670)	0.572	0.5800	1

TABLE 11. Outcomes of proposed and existing AOs.

Author(s)	Aggregation operators used	Utility values				Ranking order
		S_1	S_2	S_3	S_4	
Senapati & Yager [28]	FFWAAO and FFWGAO	0.1529	0.14686	0.14703	0.1601	$S_4 \succ S_1 \succ S_3 \succ S_2$
Hadi et al. [32]	FFHWAAO and FFHWGAO	0.1527	0.14658	0.14685	0.1599	$S_4 \succ S_1 \succ S_3 \succ S_2$
Rani and Mishra [87]	FFEWAAO and FFEWGAO	0.1528	0.14663	0.14687	0.1599	$S_4 \succ S_1 \succ S_3 \succ S_2$
Proposed method	FFGACWA and FFGACWG	0.1541	0.14821	0.14822	0.1622	$S_4 \succ S_1 \succ S_3 \succ S_2$

and, "Fermatean fuzzy Einstein weighted geometric (FFEWG)" [87] AOs to the same case study (Section 6) discussed earlier. The final OCDs and preference order of options are presented in Table 11 and Fig. 5. In accordance with Table 11, it can be verified that the most optimal smart city to adopt IoTBs for SCWM obtained by the developed AOs is S_4 which is exactly the same as obtained by utilizing the existing AOs. This means that the developed AOs are credible.

C. SENSITIVITY ANALYSIS

The current section offers the sensitivity investigation to exhibit the performance of introduced improved FF-CoCoSo approach. For this, we have taken various criteria weight sets over the variation of decision parameter ϑ and depicted in Table 12 and Fig. 6. Corresponding to the Table 12 and Fig. 6, system failure issues (I_{13}) has the highest importance degree, poor data availability (I_{14}) has second highest weight value followed by Lack of regulatory norms, policies and guidelines (I_2) and others, while lack of mobility (I_{11}) has minimum importance degree for $\vartheta \in [0, 1]$. Then, an elegant attribute weights sets are made to investigate the sensitivity of the presented methodology over different values of ϑ.

Further, we have estimated the OCD for each smart city option to adopt IoTBs for SCWM over diverse values of coefficient 'ϑ' where $\vartheta \in [0, 1]$ with fixed value of decision

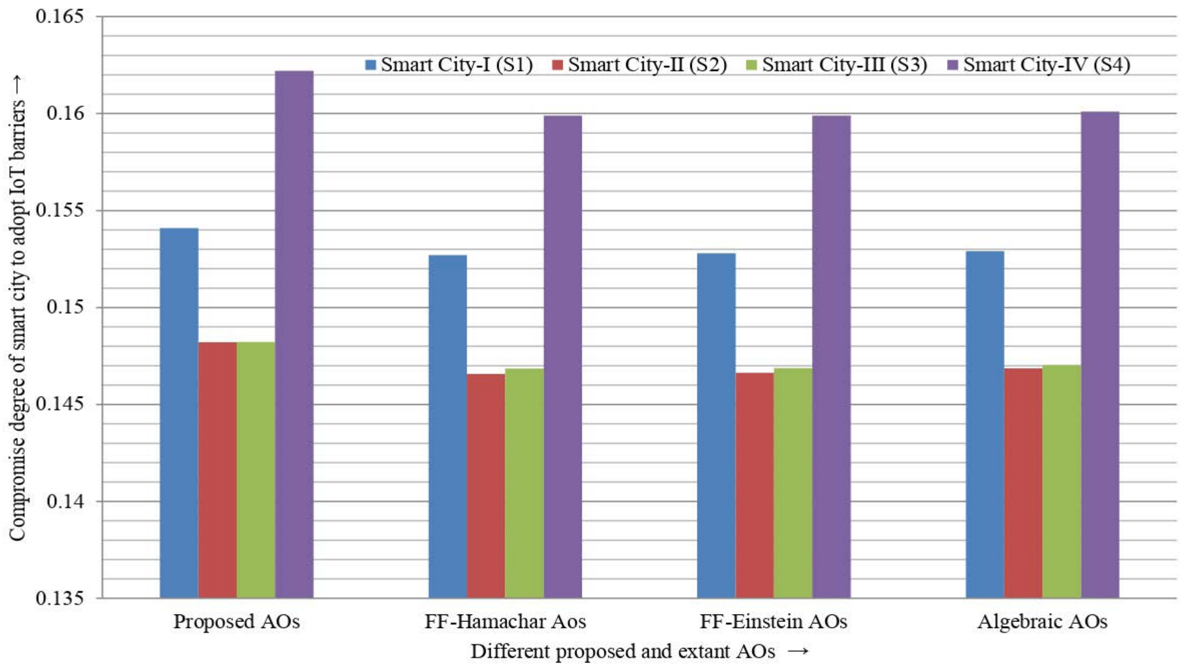

FIGURE 5. Variation of compromise degree of each smart city to adopt IoTBs for SCWM over different AOs.

TABLE 12. The weight values of IoTBs for SCWM with respect to parameter ϑ.

ϑ	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
I_1	0.0719	0.0714	0.0708	0.0703	0.0697	0.0691	0.0686	0.0680	0.0675	0.0669	0.0663
I_2	0.0734	0.0727	0.0720	0.0713	0.0707	0.0700	0.0693	0.0686	0.0679	0.0672	0.0665
I_3	0.0563	0.0573	0.0583	0.0594	0.0604	0.0614	0.0625	0.0635	0.0645	0.0655	0.0666
I_4	0.0659	0.0660	0.0661	0.0662	0.0663	0.0664	0.0665	0.0666	0.0667	0.0668	0.0670
I_5	0.0735	0.0728	0.0721	0.0714	0.0707	0.0699	0.0692	0.0685	0.0678	0.0671	0.0664
I_6	0.0679	0.0678	0.0676	0.0675	0.0674	0.0673	0.0672	0.0671	0.0670	0.0668	0.0667
I_7	0.0494	0.0511	0.0529	0.0546	0.0564	0.0581	0.0599	0.0616	0.0634	0.0651	0.0669
I_8	0.0653	0.0654	0.0656	0.0658	0.0660	0.0661	0.0663	0.0665	0.0667	0.0668	0.0670
I_9	0.0665	0.0665	0.0665	0.0665	0.0666	0.0666	0.0666	0.0667	0.0667	0.0667	0.0668
I_{10}	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664	0.0664
I_{11}	0.0482	0.0500	0.0519	0.0537	0.0556	0.0575	0.0593	0.0612	0.0631	0.0649	0.0668
I_{12}	0.0575	0.0584	0.0593	0.0603	0.0612	0.0622	0.0631	0.0641	0.0650	0.0660	0.0669
I_{13}	0.0847	0.0830	0.0812	0.0794	0.0776	0.0758	0.0740	0.0722	0.0704	0.0686	0.0668
I_{14}	0.0803	0.0789	0.0775	0.0761	0.0747	0.0733	0.0718	0.0704	0.0690	0.0676	0.0662
I_{15}	0.0730	0.0723	0.0717	0.0711	0.0705	0.0699	0.0693	0.0687	0.0681	0.0674	0.0668

TABLE 13. Priority of smart city options with FF-CoCoSo method for various parameter ϑ values ($\gamma = 0.5$).

Options	$\vartheta = 0.0$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
S_1	0.1532	0.1534	0.1536	0.1537	0.1539	0.1541	0.1543	0.1544	0.1546	0.1548	0.1550
S_2	0.14650	0.14685	0.14719	0.14753	0.14787	0.14821	0.14855	0.14888	0.14922	0.14956	0.14989
S_3	0.14798	0.14803	0.14808	0.14813	0.14818	0.14822	0.14826	0.14830	0.14834	0.14838	0.14842
S_4	0.1607	0.1610	0.1613	0.1616	0.1619	0.1622	0.1626	0.1629	0.1632	0.1635	0.1638

TABLE 14. Priority smart city options with FF-CoCoSo method for various parameter τ values ($\vartheta = 0.5$).

Options	$\gamma = 0.0$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
S_1	0.1582	0.1574	0.1566	0.1557	0.1549	0.1541	0.1533	0.1525	0.1517	0.1509	0.1501
S_2	0.13988	0.14157	0.14324	0.14491	0.14656	0.14821	0.14984	0.15146	0.15307	0.15467	0.15626
S_3	0.13986	0.14156	0.14324	0.14491	0.14657	0.14822	0.14986	0.15149	0.15310	0.15471	0.15630
S_4	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622	0.1622

parameter γ, and found that the prioritization of smart city options is identical in $\vartheta \in [0, 1]$. The results are shown in Table 13 and Fig. 7. From Fig. 7, for fixed $\gamma = 0.5$, we obtain that the option S_4 has obtained the first rank for all

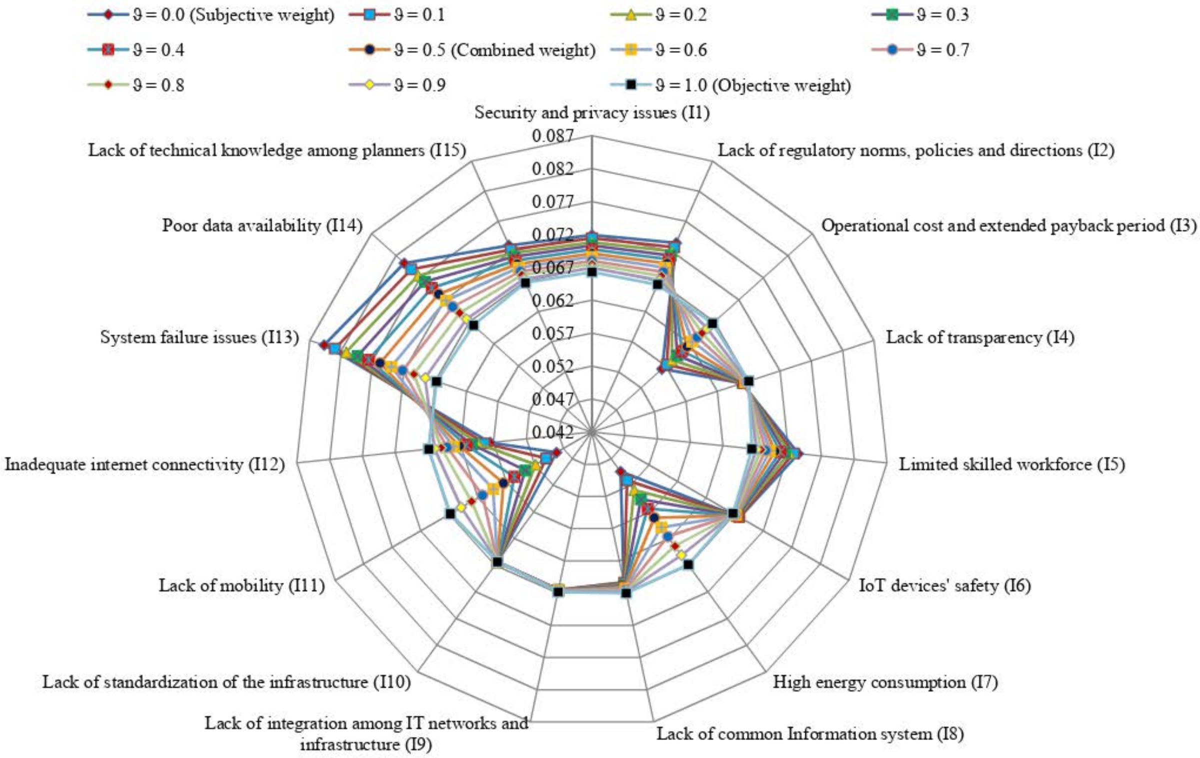

FIGURE 6. Variation of weights of different IoTBs for SCWM with respect to parameter (ϑ) values.

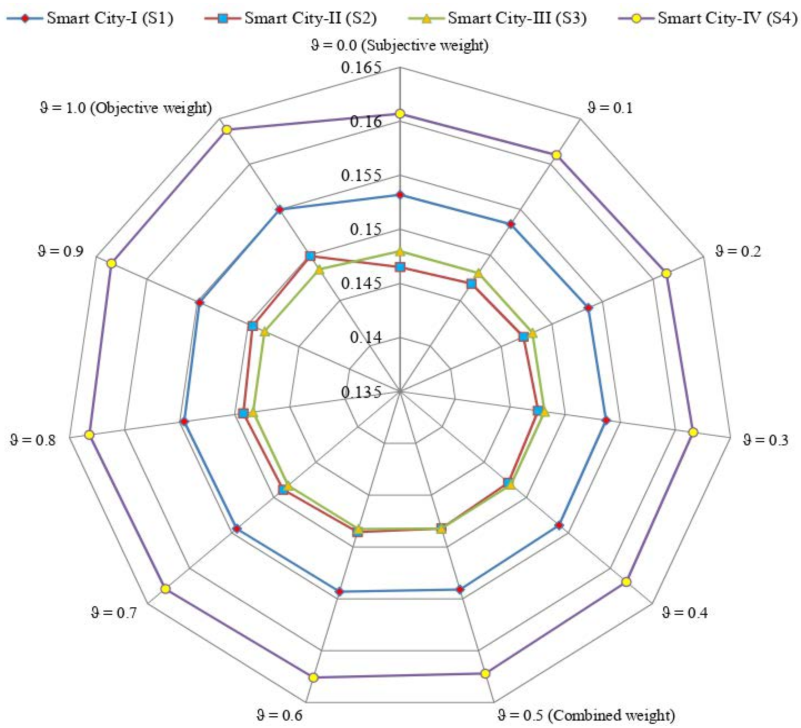

FIGURE 7. Variation of OCD over different values of parameter (ϑ).

values of ϑ, while S_2 has obtained the last rank for $\vartheta = 0.0$ to $\vartheta = 0.5$ and S_2 has obtained the last rank for $\vartheta = 0.6$ to $\vartheta = 1.0$. Consequently, we accomplish that the IoT barriers of SCWM selection are reliant on and sensitive over parameter 'ϑ'. On similar way, we have estimated the overall compromise degree for each smart city option over different

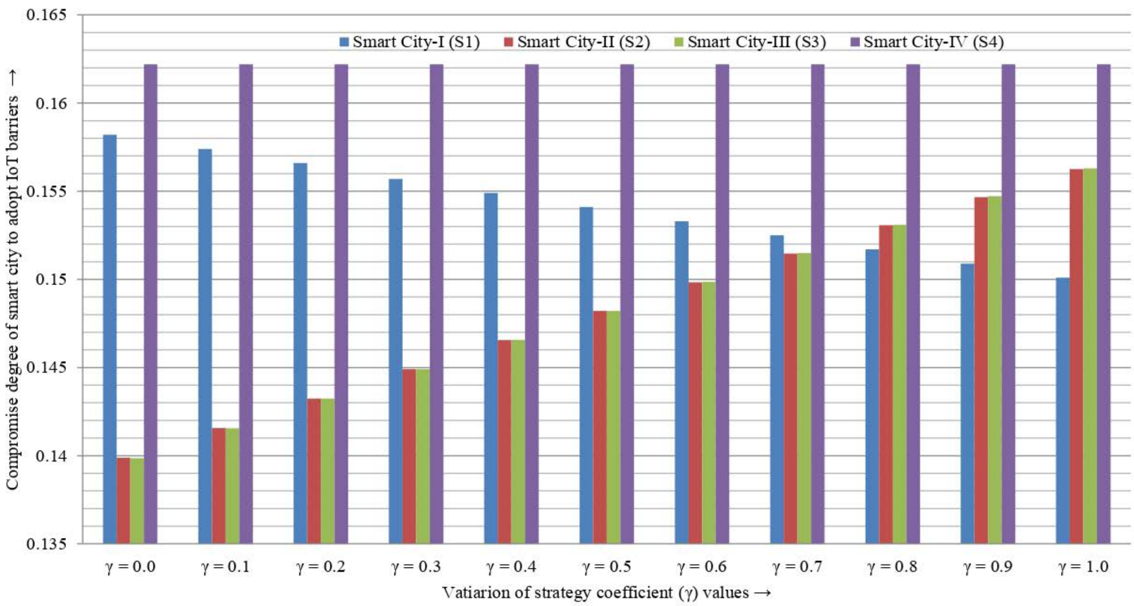

FIGURE 8. **Variation of compromise degree over different values of strategy coefficient (γ).**

values of coefficient 'γ' where $\gamma \in [0, 1]$ with fixed value of decision parameter ϑ, and found that the prioritization of smart city options is identical in $\gamma \in [0, 1]$. The results are discussed in Table 14 and Fig. 8. From Fig. 8, for fixed $\vartheta = 0.5$, we obtain that the option S_4 has obtained the first rank for all values of γ, while S_2 has obtained the last rank for $\gamma = 0.0$ to $\gamma = 0.5$ and S_2 has obtained the last rank for $\gamma = 0.6$ to $\gamma = 1.0$. Consequently, we accomplish that the smart city selection are reliant on and sensitive over parameter 'γ'. Thus, the proposed methodology has an adequate solidity over the variation of 'γ' and 'ϑ'. From this investigation, we conclude that the proposed method is independent from any favoritism and results in this work are stable in nature.

VII. CONCLUSION

To improve the quality of life and achieve sustainability, the adoption of IoT technologies plays a key driver for the efficient and sustainable development of smart cities. Over the decades, the SCWM is considered to be the most significant concern in developing nations. This study recognizes and ranks the IoTBs and smart city to adopt IoTBs for SCWM to assess the sustainability in Indian perspective. A review of extant literature discussed that main 15 IoTBs to adopt SCWM are considered. The decision-making process of choosing the most appropriate smart city to adopt IoTBs for SCWM for users is very important, but the existing research lacks such a decision-making framework. In order to comprehensively consider the complexity and uncertainty of decision information and the performance of smart medical solutions, this paper proposes the similarity measure-based new weighting procedure and FFGACWA and FFGACWG operators, studies its properties and proposes a MADM methodology using these operators, which is applied to the assessment and selection of IoTBs and rank the smart city to adopt IoTBs for SCWM for verification. In addition, this study also analyzes the impact of the variation of parameters in the proposed methodology on the decision results. The conclusions are as follows:

- In this article, the FFS is implemented to solve the problem of the representation of assessment information in complex and uncertain settings. The FFSs cannot only express multiple views at the same time but can also solve the uncertainty of people's subjective evaluation by using an interval form, which is helpful to improve the accuracy of decision-making in complex environments;
- The established evaluation index system solves the problem that the existing research cannot provide a reasonable solution evaluation index. In this paper, a multi-layer evaluation index system including 15 barriers to the adoption of IoT of SCWM is established for the evaluation and selection of smart city option to adopt IoT barriers and enhancing the accuracy of decision-making;
- This paper combines FFSs with the Archimedean copula operator, Archimedean operations and similarity measure and recommends a decision-making FF-CoCoSo methodology with the help of the FFGACWA and FFGACWG operators, providing decision support for the selection of smart city option to adopt IoTBs and helping people to choose an optimal solution. The test shows that the method is practical and flexible for solving MADM problems in complex environments.

Based on the shortcomings of this paper and the existing research, future study can be carried out the subsequent facets:

- This paper only discusses the role of the FFGACWA and FFGACWG AOs in MADM. In the future, we will combine FFSs with other operators, namely Bonferroni Mean operator, Hamy mean operator, Heronian mean operator and Maclaurin symmetric mean operator to develop various new hybrid operators to deal with diverse MADM methods.
- The paper applies the proposed methodology to the evaluation and selection of smart city waste management systems. In the future, we can explore the role of this method in other areas and fields, such as the selection of medical and health devices, the evaluation of medical companies, the selection of smart medical products, etc.
- The key steps of the decision algorithm discussed in this work are sometimes complex and not easy to perform.
- The FFSs can be combined with other information, for instance, the probabilistic interval-valued hesitant fuzzy [89]; and can evaluation and selection of smart city waste management systems under FFS information with other decision-making method, such as MULTIMOORA [90], [91], COPRAS [92] and others.

However, the proposed study is unable to deal with the new generation of smart applications with more complex sets of heterogeneous information, data, systems, sensors, devices, etc. Also, this study has not included several open technical and social challenges. In the future, an automatic evaluation decision system can be developed based on this method to achieve the function of obtaining decision results according to the input variables, providing more convenience for users and promoting the application of this method in various fields. In addition, the further research can focus towards collecting data from other relevant sources including surveys and various field stakeholders dealing with IoT barriers for smart cities' waste management to present further outcomes concerning the critical parameters. The qualitative analysis can further be done using different qualitative methods to provide the identification of barriers more exclusively.

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