Journal of Intelligent Decision and Computational Modelling

www.jidcm.reapress.com

J. Intell. Decis. Comput. Model. Vol. 1, No. 1 (2025) 57–64.

Paper Type: Original Article

Intuitionistic Fuzzy Differential Equations and its Applications: A Review

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Citation:

Received: 13 June 2024 *Revised: 20 September 2024* *Accepted: 25 November 2024*	Salahshour, S., & Prasad Mondal, S. (2025). Intuitionistic fuzzy differential equations and its applications: A review. *Journal of intelligent decision and computational modelling, 1*(1), 57-64.

Abstract

This paper presents a systematic brief review of the topic Intuitionistic Fuzzy Differential Equation (IFDEs) and its applications, which an extension of fuzzy differential equations. The fundamental ideas, mathematical constructions, and solution tactics of IFDEs are drawn. Various existed procedures for handling uncertainty or impreciseness in dynamic systems using IFDEs are deliberated. The paper also mentions recent progressions and key applications in economics engineering, and decision sciences models associated with IFDE. Future research guidelines and existing challenges are briefly addressed lastly.

Keywords: Fuzzy set, Intuitionistic fuzzy sets, Fuzzy differential equation.

1 | Introduction

The concept of fuzzy set theory was coined by Zadeh [1] in the year 1965. It is an extension of classical set theory or crisp set theory. By considering an additional condition, called the membership function [2], which lies between 0 and 1 the idea of this set becomes a new interest with applications. A fuzzy set [3–5] is different from a crisp set, where every element is associated with a degree of membership value to represent the belongingness of the element in the set [6]. It has the capability to accommodate partial membership values which dealing with the uncertainty and vagueness concepts in real problems with associated models [7–9].

This useful set theory is especially helpful in frameworks where information is not precise in nature, such as natural language processing, complex optimization problems, control theory application, pattern recognition, weather forecasting, and decision-making. Fuzzy set theory has prompted the creation of multivalued fuzzy logic [7], fuzzy differential equations [10], fuzzy control systems [11], and fuzzy optimizations [12]. It delivers

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https://doi.org/10.48314/jidcm.v1i1.62

a way to handle real-world uncertainty and ambiguity modelling through the mathematical and statistical model in more operative ways. Over time, the ideology and concepts of fuzzy sets and fuzzy logic have been applied in numerous fields for better understating rather than crisp.

Fuzzy set theory is widely applied in various engineering, science and social sciences fields that involve single or multi valued logic under uncertainty and imprecision. It assistances to making precise decisions in complex uncertain problems where binary logic fails to take. The examples of application in decision making such as in image processing [13], supply chain management [14], data classification [15], and control systems [16], robotics and appliances [17]. In the field of medicine [18], fuzzy sets also simplify diagnosis by addressing vague symptoms and uncertain results. Furthermore, it helps to investigation risk assessment and customer satisfaction in business applications [19]. In general, fuzzy set theory has the capability to familiarize important various real-life problems [20–22].

1.1 | Intuitionistic Fuzzy Set Theory and Its Applications

Intuitionistic Fuzzy Sets (IFS) were first introduced by Atanassov [23] in 1986. The IFS [24], [25] is an extension of fuzzy sets where every element can be allied with two types graded membership functions, namely the membership function and the non-membership function. Here, every element has said types membership values to represent the uncertainty and vagueness of the element more explicitly and the lack of knowledge on the elements may be acknowledged.

IFS helps to modelled the real-world problems with a more beneficial representation of uncertainty when compared to conventional fuzzy sets theoretic approaches [25]. As per present day status IFS are mostly useful in important fields like pattern recognition [26], decision sciences [27], and real systems modelling [28] where data is vague or lacking. IFS has flexibility and expressiveness in complex situations rather than fuzzy sets approaches with more scientifically manner [29]. Therefore, IFS theory has drawn a lot of consideration in the theoretical as well as practical research.

Since Intuitionistic fuzzy set theory extends the formal fuzzy sets by considering the degree of membership function and non-membership function so it handles the uncertainty of the model and data set more appropriately.

For more examples like the decision-making problem, incomplete or ambiguous information is frequent, where IFS help to deal with it. IFS is applied in numerous fields, including multi-criteria decision analysis [30], pattern recognition, graph theory [31], and medical diagnosis [32], education fields [33], social sciences [34] and economic modelling [35]. The IFS theory also improves the precision and flexibility of the systems for advanced uncertainty models.

Table 1 shows the comparative table between fuzzy set and intuitionistic fuzzy set and *Fig. 1* represent the pictorial comparison between crisp set, fuzzy set and Intuitionistic fuzzy set.

Table 1. Comparative table between fuzzy set and intuitionistic fuzzy set.

Feature	Fuzzy Set	Intuitionistic Fuzzy Set
Related functions	Defined by a single membership degree $\mu(x) \in [0,1]$	Defined by both membership $\mu(x) \in [0,1]$ and non-membership $\nu(x) \in [0,1]$
Hesitancy idea	Not considered	Explicitly considered as $\pi(x) = 1 - \mu(x) - \nu(x)$.
Total constraint limits	Not applicable	$0 \leq \mu(x) + \nu(x) \leq 1$
Information for data type capturing	Captures degree of belonging	Captures belonging, non-belonging

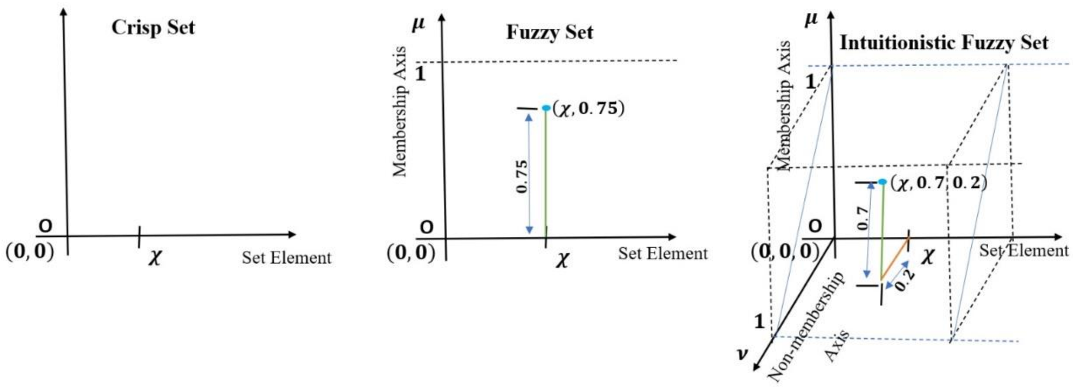

Fig. 1. Pictorial comparison between crisp set, fuzzy set and intuitionistic fuzzy set.

1.2 | Motivation of the Paper

The growing complexity and uncertainty or impreciseness in real-world systems modelling mandate more strong mathematical modeling tools and techniques. Intuitionistic Fuzzy Differential Equations (IFDEs) offer a sophisticated approach by combining both membership and non-membership functions. Despite their potentiality, IFDEs persist underexplored areas as compared to traditional fuzzy set-based models. This paper aims to link that gap by providing a inclusive overview of standing theories and real-world applications. The main goal is to stimulate further research and more practical application of IFDEs in various fields.

2 | Different Approaches for Intuitionistic Fuzzy Differential Equation

There exist several approaches for solving fuzzy differential equations. Anyone can extend the ideology for IFDE cases. Few approaches as follows:

I. Using the concept of intuitionistic fuzzy derivative. Here the derivative of intuitionistic fuzzy function is considered and corresponding parametric differential equation are solved.

II. The second approaches are Zadeh's extension principle. In this method first we solve the associated crisp differential equation and then we try to accommodate with intuitionistic fuzzy parameters.

III. The third approaches is the fuzzy problem transformed into a crisp problem using the (α, β)-cut and solve the crisp differential equation associate with the parameters α, β.

IV. The fourth one is the method base mathematical transform in intuitionistic fuzzy settings.

V. Another approach is numerical solution of this IFDE.

It should be noted that any one of the above said approaches may be taken after seeing the nature of IFDE.

3 | Review on Some published work based on Intuitionistic Fuzzy Differential Equation

Here is the comparison table with respect to different components of published work related to IFDE (See *Table 2*).

Table 2. Comparison of some published work on IFDE.

Sl. No.	Citations	Types of Differential Equation	Approaches Used	Theoretical/ Applied
1	Nirmala and Pandian [36]	First order IFDE	Euler method (Numerical solution)	Both
2	Ettoussi et al. [37]	First order intuitionistic fuzzy initial value problem	Successive approximations (Numerical method)	Theoretical

Table 2. Continued.

Sl. No.	Citations	Types of Differential Equation	Approaches Used	Theoretical/ Applied
3	Wang and Guo [38]	First-order fuzzy differential equations with intuitionistic fuzzy initial value	Differentiability of intuitionistic fuzzy number-valued functions	Theoretical
4	Amma and Chadli [39]	First order fuzzy differential equation with intuitionistic fuzzy initial value	Runge–Kutta method of order four (Numerical method)	Theoretical
5	Biswas et al. [40]	IFDEs with linear differential operator	Adomian decomposition method (Numerical method)	Theoretical
6	Nirmala et al. [41]	Intuitionistic fuzzy Cauchy problem	Runge-Kutta method (Numerical method)	Theoretical
7	Akin and Bayeg [42]	System of intuitionistic fuzzy differential equation	GH differentiability concepts and Zadeh's extension principle interpretation	Theoretical
8	Geetha and Sangeetha [43]	Second order linear Intuitionistic fuzzy ODE	Generalized Hukuhara differentiability	Theoretical
9	Ettoussi et al. [44]	Second order Intuitionistic fuzzy differential equations	Intuitionistic fuzzy Laplace transforms	Theoretical
10	Melliani et al. [45]	Intuitionistic fuzzy differential equations with linear differential operator	Homotopy Analysis method (Numerical method)	Theoretical
11	Man et al. [46]	Intuitionistic fuzzy partial differential equations	Finite difference method	Theoretical
12	Rahaman et al. [47]	IFDEs of first order	Intuitionistic fuzzy derivative	Applications
13	Harir et al. [48]	Intuitionistic fuzzy fractional differential equation	Generalized conformable fractional derivative	Applications
14	Acharya et al. [49]	System of IFDE	Generalized Hukuhara derivative	Applications
15	Ceylan [50]	Second order IFDE	(α, β)-level set and Zadeh's extension principle	Theoretical
22	Singh et al. [51]	fuzzy differential equation in intuitionistic fuzzy metric spaces	Generalized contraction theorems	Theoretical
23	Ben Amma et al. [52]	Intuitionistic fuzzy partial functional differential equations	Banach fixed point theorem	Theoretical
24	Sadiki et al. [53]	Intuitionistic fuzzy linear fractional partial differential equations	Homotopy Analysis method	Theoretical
25	Amma et al. [54]	Intuitionistic fuzzy Cauchy problem	Nystrom method	Theoretical
26	Aslaoui et. [55]	Second-order IFDE	Banach fixed point theorem	Theoretical

4 | Future Research Scope of Intuitionistic Fuzzy Differential Equation

Although there are several developments for studying IFDE, still there is lots of scope to extend the existing concepts and apply in several new domains. Here is the future research scope of IFDE:

I. Development of efficient new numerical methods where exact solution is very tough to finding.

II. Extension to higher order nonlinear systems for better study of the associated system.

III. Hybrid models and method integration such as mathematics and statistical tools which may give better understanding to the solutions.

IV. Several real-world applications in social science, engineering sciences and biological science problem.

V. Use of software tools and upgraded simulations techniques for finding the solution solutions.

VI. Perform comparative studies with respect to several imprecise settings and parameters.

5 | Conclusion

The review paper conclude that IFDEs also deliver a powerful context for dealing with impreciseness based theoretical study and uncertainty modelling with better flexibility than traditional fuzzy differential equation modelling systems. This review process has brief key theoretical developments and solution methods in the said fields. Real life applications across varied domains reveal their practical relevance and potential benefits. Still there is more gaps for theoretical studies and have lots of scope for modelling. Continuous research is crucial to enhance their adoptability, applicability and effectiveness in complex systems for taking precise accurate decisions.

Conflict of Interest

The authors declare no competing interests.

Data Availability

The datasets generated and analyzed during this study are available from the corresponding author upon reasonable request.

Funding

No funding was received for conducting this study.

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