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Research Article

Taxonomical Review of the Evolution from Deterministic to Fuzzy-Neutrosophic Inventory Models for Sustainable Supply Chain Optimization

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ABSTRACT

This study offers a pioneering synthesis of cutting-edge advancements in inventory and supply chain optimization, focusing on fuzzy logic, Intuitionistic, and Neutrosophic frameworks. Bridging theoretical rigor with real-world applicability, it traces the evolution from classical EOQ models to intelligent, AI-driven systems that thrive in uncertain, complex environments. This review provides a strong classification by navigating innovations on the demand models, integration of sustainability, financial constraints, and algorithm-based optimization. This paper elucidates that Neutrosophic logic enables sustainable, strategic, and transformational decision-making, which also provides a useful guide for future studies towards the third-generation inventory systems.

Keywords: Supply chain optimization, Fuzzy-Neutrosophic inventory Model.

INTRODUCTION

This manuscript provides an exemplary regulation and a cohesive account of some of the core research contributions in the field of state-of-the-art inventory management, supply chain logistics, and complex decision-making systems. It embraces a comprehensive study of research works that apply fuzzy logic, Neutrosophic set to tackle the common issues of uncertainty sustainability, and optimization methods in operation research works. All these methodologies can be applied in a variety of fields such as manufacturing, supply chain, and energy management among others, industries that require reliability, flexibility, and stability. The discipline of inventory management has come a long way, since simple deterministic models are applied and developed to a complex AI integrated systems necessary to address the issues of supply chains of the contemporary world. This is characteristic of the perpetural need to improve productivity and reduce costs as well as an attempt to develop strategies that would cope with the emerging complexity of business and advancements in technologies for increased commerce. The transition from classical inventory heuristic approaches to algorithmic ones is indicative of an enduring and determined effort to combine mathematical credentials with operational contingency in efforts to deploy and develop resilient as well as powerful inventory control these systems that are capable of handling contingencies of the real world complexities.

1.1. Direction Flow of the Paper:

In addition to the introductory section, this paper has seven more sections that are arranged as follows: Section 2 shows the advancements in inventory models**.** Section 3 documents conducting the literature review and developing the taxonomy. In Section 4, methodology is used to classify the reviewed papers. Section 5 presents research gap & scientific contribution and Section 6 discusses the results from the review. In Section 7, concludes the paper.

II. TRAJECTORY AND ADVANCEMENTS IN INVENTORY MODELS:

There has been a continuous evolution of the inventory models from deterministic models to complex and advanced models absorbing artificial intelligence and having ability to handle uncertainties. As of Fuzzy logic, intuitionistic fuzzy set, Neutrosophic set, the present day inventory systems manage to effectively handle impreciseness, uncertainty, and the complex and more of the supply chain. This evolution continuity has significantly enhanced the decision making strategy, better resource integration and enhanced flexibility in overall tactical inventory management in numerous commercial sectors..

2.1. Evolution of Inventory models:

The first models are the Economic Order Quantity (EOQ) model which was developed by Harris [15] in 1913, this model is still used as a basic model in analysing the right order quantity that is right for ordering the material to

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minimise the total inventory cost between the ordering cost and the holding cost. However, some of its postulates are ideal; for instance, infinite demand and availability of resources to fill the demand and no opportunity for competition that hampers operations. Wilson [30] extends the EOQ model in 1934 by formulating specific order sizes depending on the costs – making it more useful for industries. Since the demand and supplies in business activities were uncertain, theorists devised stochastic inventory models. The Newsvendor Model was introduced by Arrow, Harris & Marschak [3] in 1951 to manage inventory for perishable goods, minimizing the cost of overstocking and understocking through probabilistic demand forecasts. Later, (s, S) inventory policies were introduced by Scarf [24] in 1959. Where he introduced a reorder point system to dynamically manage inventory levels, making it suitable for industries with variable lead times. With the expansion of global supply chains, inventory models evolved to accommodate multi-stage networks that integrated suppliers, manufacturers, and distributors. The Base-Stock Inventory System was developed by Clark & Scarf [9], (1960) extended inventory optimization to multi-echelon supply chains, while Just-in-Time (JIT) [22] Inventory (Toyota, 1970s) revolutionized inventory management by minimizing waste and ensuring that materials arrived exactly when needed for production. Further advancements led to Material Requirements Planning (MRP) [23] and Enterprise Resource Planning (ERP) [29], which enabled businesses to synchronize inventory planning with production schedules through computerized systems, enhancing supply chain efficiency. In more recent years, inventory models have evolved to incorporate uncertainty modelling and intelligent decision-making techniques, integrating artificial intelligence, fuzzy logic, and real-time analytics to optimize inventory control in complex and dynamic environments.

2.2. Evolution of Fuzzy Inventory models

The fuzzy inventory systems developed from the conventional inventory models due to feedback of the existence vagueness and imprecision in real life. Some of the traditional modelling principles working with assumptions of clear cut demand, lead time and costs are often not very much realistic. The development of fuzzy inventory began with Lotfi A. Zadeh's, [31] publication of fuzzy set theory in 1965 to imbue the mathematical capability to manage the imprecise data. Fuzzy logic was introduced into EOQ and EPQ models in 1980's since the precise demand and cost cannot be estimated in an organization. From the 1990s, inventory new models started being developed based on the fuzzy models with the concept of parameters being replaced by the fuzzy numbers and one of such works includes that of Zimmermann [32] (1991) on the fuzzy optimization of inventory control. Incorporation of fuzzy adjacent with optimization technique made through the GA, ANN and PSO in 2000s leading to the fuzzy stochastic inventory model which consist of probability and fuzziness factors. Over the last few years, some improvements like intuitionistic fuzzy sets and type 2 fuzzy logic were developed to consider higher levels of vagueness; AI-based supply chain management solutions have used fuzzy logic in decision making. In addition, it has been integrated with blockchain [17] and IoT based inventory systems [7] to advance the progressive inventory control. Fuzzy logic system plays a vital role within the inventory management since it deals with the uncertainties, weak demand prediction, and practical application in the supply chain.

2.3. Evolution of Intuitionistic Fuzzy Inventory models

The transition from fuzzy sets FS to IFS was initiated when certain inadequacies of FS in dealing with uncertainties and hesitation, with the IFS taking over as the more suitable for such a purpose. H:I received from Lotfi A. Zadeh in 1965, the concept of fuzzy sets that enables a certain degree of membership in a set of numbers restricted to the interval 0 ∪ 1, the concept did not include non-membership or hesitation. To overcome this limitation, in 1986 Krassimir T. Atanassov [4] proposed the Intuitionistic Fuzzy Sets IFS that include an additional function of non-membership together with the membership function, that represents hesitation. In an IFS each element is characterised by its membership degree (μ), the non-membership degree (v) and the hesitation degree (π) where $\pi = 1 - (\mu + v)$. This gives a higher accuracy for dealing with real-life vagueness than that of the classical fuzzy sets. IFS has been implemented in many fields such as; decision making, diagnostics, supply chain and furthermore artificial intelligence in which delay is an inevitable part of. Hence, the introduction of IFS over Fuzzy sets has improved uncertainty modelling in a way that makes it more appropriate in solving scenarios that involve ambiguous real life decisions..

2.4. Evolution of Neutrosophic Fuzzy Inventory models

Neutrosophic Fuzzy Inventory models extend higher uncertainty and indeterminacy than the fuzzy methodology. The integration of Neutrosophic logic ushers these models to improve the decision-making process in the inventory system. The migration from IFS to NS was proposed by Florentin Smarandache in 1998 [25] for dealing higher levels of uncertainty, inconsistency, and indeterminacy of the real-life problems. However, IFS improved upon the existing concept of fuzzy sets by providing the idea of non-membership and hesitation, it also restrained the sum of membership and non-membership to 1 that was not able to address contradiction. To address this challenge, Smarandache [26] proposed NS in 1999 so as to incorporate more definite uncertainty in a broader view.

III. COMPREHENSIVE SYNOPSIS OF THE LITERATURE REVIEW:

The evolution of inventory models through the time progressed from deterministic models to the stochastic systems, which include uncertainty, sustainability and computational intelligence systems. Here, a considerable amount of existing work has been reviewed pertaining to several essential areas of consideration for inventory optimisation viz., type of inventory, demand factors, measure of uncertainty, algorithm progress and approach towards uncertainty management.

- Inventory management is fundamentally influenced by the tangible attributes of products, which affect storage conditions, order frequency, deterioration rates and discount factors. These characteristics classify inventory items into regular items that remain stable, deteriorating items that decay over time, and special items like growing, evaporating, or cold-sensitive products that require unique storage and replenishment strategies.

- Demand factors further complicate inventory optimization, with deterministic, stochastic, seasonal, and uncertain demand patterns influencing stock levels, necessitating predictive approaches such as machine learning and PHF fuzzy logic.

- The integration of green supply chain practices has become crucial, emphasizing carbon footprint reduction, reverse logistics, and sustainable sourcing to align inventory management with environmental sustainability.

- Modern supply chains with their complex nature benefit from multiple criteria decision-making methodologies including AHP, TOPSIS, LOPCOW, ARAS and fuzzy MCDM to achieve cost efficiency and demand and sustainability targets.

- Indeed, metaheuristic methods such as PSO, DE, ANFIS, and other algorithms for current inventory management improve flexibility in complicated contexts like uncertain and dynamic conditions; hybrid techniques and genetic algorithms. Quality control is also paramount, as defective items require strategies for estimation, inspection, and rework to ensure reliability and minimize losses.

- Financial aspects such as credit periods influence ordering behaviour and cash flow optimization, making credit-based inventory models essential.

- To handle uncertainty, fuzzy logic has been widely adopted for flexible demand forecasting, reorder policies, and cost analysis.

- Advancing further, Neutrosophic inventory models incorporate three dimensions of uncertainty—truth, indeterminacy, and falsity—providing superior handling of contradictions and inconsistencies in decision-making.

- The Sngle-Value Neutrosophic Set (SVNS) refines this approach by offering precise uncertainty quantification, improving risk assessment and multi-stage supply chain optimization.

Such are the developments of inventory systems for a sustainable, intelligent and handling uncertainty for the supply chain improvement.

IV. METHODOLOGY:

4.1. Green Supply Chains & Carbon Emission Mitigation:

Several of the articles [5], [14], [20], apply Neutrosophic mathematical programming to manage green supply chain risks and strike an optimal balance between green supply chain sustainability and cost and environmental benefits assuring sustainability.

- The study [5] highlights how the environmental factors and supply chain disruptions can be taken care to make the smartphone CLSC networks in the exemplary networks more sustainable and resilient.

- A multi-objective optimization has been applied for biomass supply chain [20], where logistics, cost and carbon emission randomness has been dealt by fuzzy-Neutrosophic approach. This means that the strategy allows for an eco-efficient supply chain namely an effective supply chain that performs well in environmental aspects without causing high costs.

- Inventory modelling has been also applied together with carbon emission constraints and reworking policies at Neutrosophic setup. This specific study utilizes three different carbon policies and best selects between them with the purpose of achieving an effective management of defective products and at the same time being sustainable.

Both works capture the need for high level decision support systems in the green supply chains, integrating carbon solutions into industrial process, and protecting operational agility.

4.2. Procurement Necessity Rate:

The erudite treatises meticulously dissect an array of inventory and supply chain paradigms, each embedding idiosyncratic demand configurations to navigate the labyrinthine intricacies of real-world economic dynamics.

- The study [1] models demand using a quadratic function, providing a more realistic and adaptive approach compared to traditional linear models. By incorporating nonlinear and dynamic relationships between demand, price, and inventory, this model better reflects market complexities, allowing for more accurate demand forecasting and inventory management.
- The intricacies of seasonal product demand are epitomized through a logistic growth function in [6], which illustrates an initial exponential surge, followed by a gradual slowdown, and ultimately reaching equilibrium.
- The study espouses a quadratic temporal function in **[**10**]**, adeptly encapsulating nonlinear demand oscillations that exhibit variable acceleration and deceleration over time.
- The study augments the domain of inventory prognostication, as seen in **[**12**]**, by assimilating deterioration contingencies and discounted pricing for defective commodities, wherein demand is sculpted by quality metrics and a power-time function. Furthermore, it pioneers the incorporation of generalized triangular Neutrosophic numbers and particle swarm optimization, fortifying the model's robustness against stochastic market aberrations.
- The study ventures into IoT-facilitated supply chain orchestration, with [13] leveraging dynamic aggregation operators to decipher nebulous uncertainties, although it lacks an explicit articulation of its demand framework.
- In a parallel vein, **[**14**]** engineers an inventory schema infused with carbon abatement strategies, though its demand articulation remains indeterminate.
- The Neutrosophic EOQ Model with Price Break, presented in **[**18**]**, harnesses triangular Neutrosophic numbers to encapsulate real-world demand volatility and cost ambiguities, thereby enhancing the adaptability of inventory control mechanisms.
- The logistic growth model effectively captures seasonal demand patterns, reflecting an S-shaped curve with initial low demand, rapid growth, and eventual decline. Its application in [27] enhances forecasting accuracy and decision-making in seasonal inventory systems, enabling businesses to optimize stock levels and minimize costs by anticipating demand fluctuations.

These research works provide a coherent picture of how the demand can be estimated by means of the logistic functions and quadratic functions, and power-time models and Neutrosophic uncertainty. The aforesaid assembled techniques in this framework constitute an ideal model to improve the inefficient inventory system of volatile businesses.

4.3. Flexible Credit Extension policy:

All these research works provide a detailed framework of demand modelling it using logistic functions, quadratic functions and power-time models and Neutrosophic uncertainty. The accured techniques herein reveal an ideal role in revolutionizing the inventory system in organizations operating under conditions of the below: Fuzzy

4.4. Logics & Programming Techniques:

This paper focuses on the fuzzy programming techniques for solving inventory optimization. This is especially useful when it comes to making decision in real world inventories, whereas forecasts and other factors are stochastic in nature.

- The study [1] contributes to the innovation of the inventory management decision-making by alleviating the issue of uncertainty and imprecision of demands by implementing of the Neutrosophic and Pythagorean Hesitant Fuzzy (PHF) logic. This expansion of the existing hesitant fuzzy logic helps decision makers to consider the range of values when the decision-making process is doubtful. Thus, the collection of such complexities has better forecasting and inventory control policies compared to traditional method and so it is especially useful for dynamic and uncertain nature of inventory.
- The Fuzzy logic has been applied to overcome the problem of uncertainty as well as the weakness of criteria for decision.

4.5. Algorithms:

In this paper, a set of new approaches for development of MCDM models is proposed using the Neutrosophos which is generalization of the fuzzy sets [2]. In the paper, metaheuristic DE and PSO techniques are employed to resolve obtained non-linear optimization problem, wherein the usage of DE and PSO algorithms and ANFIS for evaluating production schedule, preservation activity, and green investment are compared [2]. Moreover, there is presented the combination of genetic algorithms and simulated annealing in the solution of complex optimization problems to obtain the near-to-optimal results [5]. An MCDM approach is also developed to assess multiple IoT solutions towards different criteria and achieve organizational goals [13]. In order to overcome the limitations of traditional fuzzy logic for framing ranking alternatives in MCDM under uncertainty, this approach introduces Neutrosophic fuzzy numbers for getting a more reliable picture of ambiguity and partial indeterminacy [19]. Moreover, PSO is applied in enhancing inventory control system through reduction of costs and increase of operating space in areas of deterioration, defective items, and uncertainty demand which makes the problem rather non-linear and complicated [19].

4.6. Single valued Neutrosophic:

Single-Valued Neutrosophic Sets (SVNS) [12][13][16] are used in order to solve the uncertainty, imprecision and indeterminacy more effectively than the fuzzy sets. Cooperating truth with real valued between 0 and 1, SVNS well distinguish truth, indeterminacy and falsity and, therefore, provide a more flexible model of decision making. This is because this mathematical model allows systematic assessment of the critical aspects and relative ranking of the values in realistic case situations.

4.7. Reworking:

The paper [14] makes an attempt at providing a framework for coordination of reprocessing of faulty goods, with specific regard to stock quantities and costs of reprocessing. For instance, [27] develops the economic production quantity model by including production errors, uso of a defective rate to make the model more realistic to the current production systems. This modification also adds to the decision process in the production of defective products in the imperfect products environment. From the analysis, it can be concluded that the integration of rework strategies and the consideration of defects causes an enhancement within the manufacture quantities and inventory levels to minimize the costs within the defective items and the imperfect systems.

4.8. Neutrosophic Methodology:

Multi-criteria decision making (MCDM) model was established through encompassing fuzzy Neutrosophic sets which are an advancement of the mere fuzzy sets [1]. To compare and rank the different risk strategies, Interval-Valued Neutrosophic Fuzzy Evaluation based on Distance from Average Solution (IVN Fuzzy EDAS) method was used [11]. This approach was applied for the first time to the concept of sustainability and sustainability risks in the automotive industry particularly as a more comprehensive way of ranking projects under conditions of uncertainty. To improve the decision analysis frameworks, Neutrosophic logic and sets were used [18], while a new MCDM method which is based on Neutrosophic trapezoidal fuzzy numbers was also presented [21]. consequently, Neutrosophic fuzzy logic was used to overcome inadequacies such as uncertainty that traditional fuzzy logic is unable to measure the grade of unpredictable and contradictions in decision making process [27].

4.9. Other Factors:

Unlike the earlier single-item inventory model described in [1] the authors construct the multi-item inventory model to easily accommodate several products owing to inter-item interaction, inter-item rivalry for resources, joint ordering policies and the overall aim of minimizing the cost. In [2], the Fuzzy Delphi Method (FDM) is implemented since this approach allows achieving the consensus of the experts in the case of dealing with uncertainty and vagueness, especially in the evaluation of factors affecting consumer behavior towards the remanufactured products. Reference [12] integrates deterioration effects and discount strategies for defective items into inventory management, providing solutions for industries dealing with perishable or obsolescent goods. It recognizes that some items degrade over time and proposes optimal stock replenishment policies and pricing strategies to mitigate associated losses while maintaining economic viability. The study in [16] introduces a structured decision support system (DSS) framework incorporating Dombi aggregation operators for flexible and comprehensive criteria aggregation, and Bonferroni mean operators to account for interdependencies among criteria, ensuring accurate reflection of collective impacts in decision-making. In [27], game theory is applied to model strategic interactions between a producer and a retailer, using a non-cooperative game approach to determine optimal production and inventory control strategies while balancing individual interests in both competitive and cooperative contexts.

The reviewed studies highlight the growing role of Neutrosophic and fuzzy-based approaches in optimizing inventory management, supply chain efficiency, and decision-making under uncertainty. These methodologies provide robust solutions for addressing sustainability challenges, enhancing computational efficiency, and improving real-world applications across multiple industries.

V. RESEARCH GAP & SCIENTIFIC CONTRIBUTION:

Addressing the existing gaps in the literature, this study seeks to advance the field of Neutrosophic inventory modelling by making the following key contributions:

1. **Development of a Comprehensive Taxonomy and Classification Framework:** This research systematically categorizes and classifies studies on sustainable inventory modelling under Neutrosophic sets and logic, covering the period from 2013 to 2025. It will give the framework for analyzing the development of research in this area, which would ensure that the current research work is comprehensive and systematic in terms of theoretical contributions and real-world implications.

2. **Formulation of a Research Agenda and Future Directions:** Based on the literature review, this work recognizes some research lacuna and new trends in Neutrosophic inventory modelling. From these directions, a research agenda is then provided out for further studies to advance the inventory management systems based on the Neutrosophic theory with more solidity and extended approaches. This study does not only supplement and synthesize the existing literature but also points out the direction for further enhancement of Neutrosophic inventory modelling to fit into the current and future sophisticated supply chain and the ever increasing importance of sustainability.

VI. DISCUSSIONS & MATERIAL INSIGHTS:

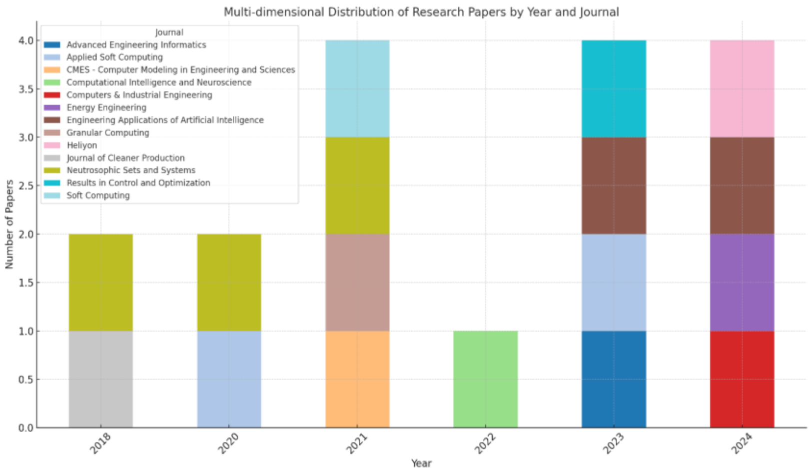

Figure 1: Multi-Dimensional Distribution of Research Papers by years and journals

Figure 1 also shows that research papers have been published from 2018 to 2024 by the year and type of journal. The part of the figure divided by a colour means the number of papers published in a year and in different journals. The multi-colour stacked bar chart will help to compare the number of publications over the years and the type of source, where one can be able to see how much concentration was put on certain sources as opposed to others over a given period of time.

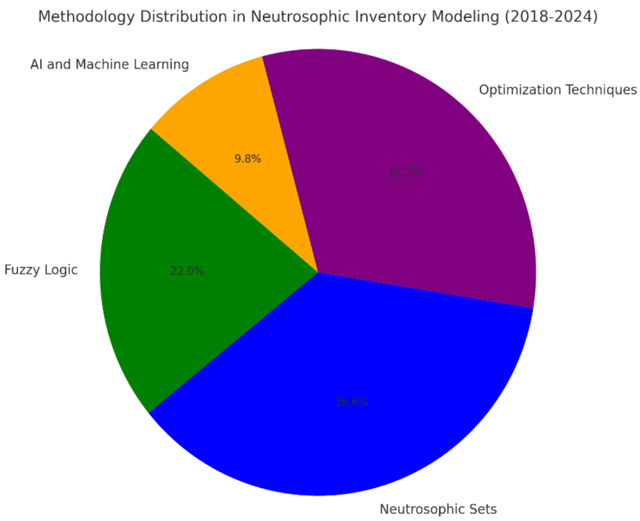

Figure 2: Methodology Distribution in Neutrosophic Inventory Modelling (2018-2024)

The research methodologies of Neutrosophic inventory modelling for the period of 2018 to 2024 is depicted in pie chart as shown in Figure 2. It also indicates the percentage of papers featuring applications of fuzzy logic, Neutrosophic sets, clustering and optimization algorithms, and AI/ML for all the years examined. Key Material Insights:

- **From Rigid to Resilient**: Inventory models have evolved from deterministic EOQ models to intelligent, uncertainty-aware systems powered by fuzzy and Neutrosophic logic.
- **Smarter Decision-Making**: Fuzzy, intuitionistic fuzzy, and Neutrosophic sets help handle ambiguity, hesitation, and contradiction in supply chain decisions.
- **Sustainability Built-In**: New models embed carbon constraints, green logistics, and rework strategies for environmentally responsible supply chains.
- **Demand Gets Real**: Shift from simple demand assumptions to logistic, quadratic, and dynamic demand models—more aligned with market behaviour.
- **Finance Meets Inventory**: Credit delays and cash flow considerations now influence inventory policies—bridging financial strategy with operations.
- **Algorithm-Driven Optimization**: Metaheuristics (PSO, DE, GA) and ANFIS models drive real-time, adaptive inventory control.
- **Defects & Rework Included**: Models now consider imperfect production, defective rates, and reworking costs—real-world ready.
- **SVNS Power**: Single-valued Neutrosophic sets allow sharper modelling of truth, falsity, and indeterminacy—great for complex decisions.
- **Multi-Criteria Tools**: Advanced decision-making uses fuzzy Delphi, EDAS, and aggregation operators for evaluating options under uncertainty.
- **Gaps & Future Focus**: Push for more scalable, AI-integrated, Neutrosophic models across domains like healthcare, energy, and logistics.

VII. CONCLUSION:

This review indicates that the fundamental development of inventory and supply chain from the traditional deterministic models to robust and complex uncertain environment is supported by fuzzy logic, intuitionistic fuzzy sets and Neutrosophic approaches. The current paper aims to review and summarise the literature review over a decade, pointing out to the growing sophistication of today's supply chains and, consequently, the demand for intelligent decision support systems to manage uncertainty. It has been established that the combination of Neutrosophic logic and fuzzy-based techniques holds immense applicability in solving realistic problems such as internal and external fluctuations in demand, leadership in sustainable practices, unpredicted production issues, and limited budgets. The most significant strategies that have been identified from the literature include the varied demand forecasting along with the creation of refined demand models, the use of heuristic solutions and metaheuristic methods, and the management of multiple-criteria decision-making methodologies. Incidentally, credit extension policy, modification of the product, and the green supply chain management profiles for improved supply chain analytics through AI models are emerging as effective strategies for sustainable inventory systems. The concept of SVNS, integration of IoT and the use of hybrid optimization also sign the practicality of such paradigms. This research benefits the academia by presenting a comprehensive classification system and also mapping out research trends and deficits thus creating a foundation for future research. As businesses increasingly grapple with complexity and ambiguity, Neutrosophic and fuzzy-based models will play a pivotal role in shaping intelligent, resilient, and sustainable inventory and supply chain systems. Future research should focus on real-time implementation, hybridization with machine learning, and cross-industry applications to ensure continued relevance and efficacy.

7.1. Future works:

Future research should explore real-time inventory models integrated with IoT and AI for dynamic decision-making. Hybrid approaches combining Neutrosophic logic with machine learning can enhance predictive capabilities. Blockchain integration offers potential for transparent and sustainable supply chains. Expanding models to multi-echelon and global networks remains essential. Applications in healthcare, energy, and circular economies also present promising directions.

Declaration of Interests:

The authors affirm that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability:

This literature study in the manuscript does not utilize any data.

CRediT authorship contribution statement:

K.P. Vilaasini: Investigation, Conceptualization, Methodology, Visualization, Writing – original draft.

K. Rangarajan: Formal analysis, Project administration, Supervision.

Declaration of competing interest:

The authors declare that there is no conflict of interest about this paper.

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