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DIGITALIZATION IN AGRICULTURE: DESIGN AND MODELLING OF SMART AGRICULTURE SYSTEMS

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DIGITALIZATION IN AGRICULTURE: DESIGN AND MODELLING OF SMART AGRICULTURE SYSTEMS

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LIST OF SYMBOLS

2TL	2-Tuple Linguistic
2TLFFSs	2-Tuple Fermatean Fuzzy Sets
2TLFFWHM	2TLFF Weighted Hamy Mean
AI	Artificial Intelligence
AO	Aggregation Operators
AR	Augmented Reality
BLE	Bluetooth Low Energy
CC	Cloud Computing
CCUS	Carbon Capture, Utilization, and Storage
CNs	Customer Needs
CPS	Cyber-physical Systems
DA	Data Analytics
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DLT	Distributed Ledger Technology
DM	Decision-maker
DRs	Digital Requirements
DRs	Design Requirements
DSS	Decision Support Systems
EU	European Union
FAO	Food and Agriculture Organization
FFLS	Fermatean Fuzzy Linguistic Set
FFS	Fermatean Fuzzy Set
GAN	Generative Adversarial Networks
GDM	Group Decision-Making
GIS	Geographic Information Systems
GIs	Geographical Indicators
HAPS	High-altitude Platform Systems
HoQ	House of Quality
I4.0	Industry 4.0
IFS	Intuitionistic Fuzzy Set
IIoT	Industrial Internet of Things
IoE	Internet of Everything
IoT	Internet of Things
ISM	Interpretive Structural Modeling
ISPA	International Society of Precision Agriculture
LoRa	Long Range Technologies
MAGDM	Multi-Attribute Group Decision Making
MCDM	Multi-Criteria Decision-Making
ML	Machine Learning

NLP	Natural-language Processing
PA	Precision Agriculture
PESTLE	Political, Economic, Social, Technological, Legal, Environmental
PFS	Pythagorean Fuzzy Set
QFD	Quality Function Deployment
RFID	Radio-Frequency Identification
RQ	Research Question
SA	Smart Agriculture
SARs	Smart Agriculture Requirements
SBC	Single-board Computer
SDG	Sustainable Development Goals
SNs	Sustainability Needs
SWOT	Strengths, Weaknesses, Opportunities, Threats
UAVs	Uncrewed Aerial Vehicles
VR	Virtual Reality
VIKOR	VlseKriterijumska Optimizacija I Kompromisno Resenje
WCRM	Weighted Collective Relation Matrix
WoS	Web of Science
WSNs	Wireless Sensor Networks
ZTA	Zero-trust Architecture

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ABSTRACT

This thesis delves into the multifaceted world of Smart Agriculture (SA), exploring its potential to revolutionize the agricultural sector while addressing critical sustainability concerns. The research adopts a systematic and interconnected approach, weaving together diverse chapters to provide a comprehensive understanding of SA system design.

Chapter 2 conducts a comprehensive systematic literature review, establishing a solid foundation by identifying key technologies shaping the SA landscape, exploring its connections with Industry 4.0, and delving into both the benefits and challenges it presents. A central dilemma emerges, balancing the pursuit of digitalization with the paramount need for sustainability.

In Chapter 3, a comprehensive literature review is undertaken to establish the theoretical underpinnings of the methodologies proposed in this thesis. Emphasizing Fermatean Fuzzy Sets (FFS) as the primary technique, this chapter delves into the intricate details of the suggested methodologies, specifically highlighting the integration of 2-tuple Fermatean Fuzzy Sets (2TLFFS). The literature review not only explores the foundational aspects of FFS but also provides a nuanced understanding of how these methodologies have been previously employed and studied in relevant academic works. This chapter serves as a critical exploration and contextualization of the chosen methodologies, enriching the theoretical framework underpinning the subsequent analyses in the thesis.

Chapter 4 shifts its focus to the specific context of Turkish agriculture, employing a thorough SWOT/PESTLE analysis. This detailed examination exposes the current strengths, weaknesses, opportunities, and threats impacting the sector in its transition towards becoming a sustainable and digitalized smart agriculture system.

The analysis underscores the critical role of sustainability in ensuring the long-term success and resilience of any SA system implemented within the Turkish landscape.

Chapter 5 tackles the design aspect directly, utilizing a two-staged Quality Function Deployment (QFD) application. This rigorous process translates identified customer needs and expectations into actionable technical specifications, serving as a roadmap for the design and development of a SA system that prioritizes both sustainability and digitalization. The resulting 10-step roadmap offers a clear and structured framework for navigating the complexities of SA system design, ensuring its effectiveness and long-term viability.

Chapter 6recognizes the importance of technological underpinnings and focuses on the critical selection of technology providers for key components such as Cloud Computing (CC), Internet of Things (IoT), and sensor technology. These technologies form the backbone of any modern SA system, enabling data collection, connectivity, and automation - vital functions for successful operation. The selection process employs meticulous evaluation criteria, ensuring the chosen providers possess the expertise and capabilities necessary to deliver robust and sustainable technological solutions.

This thesis strategically employs Fermatean Fuzzy Sets (FFS) as a powerful analytical tool to elevate the depth and precision of the research process within the domain of SA. FFS, particularly in the form of 2-tuple FFS, serves as an instrumental framework to navigate the inherent uncertainties and imprecisions embedded in intricate agricultural systems. The integration of FFS into established methodologies such as SWOT/PESTLE, DEMATEL, QFD, and VIKOR introduces a heightened level of sophistication and informativeness to the analysis.

By intricately weaving together these diverse chapters, this thesis presents a compelling narrative that transcends mere summarization. Each chapter builds upon the previous one, progressively delving deeper into the intricacies of SA system design while offering concrete solutions and actionable strategies. This interconnected approach ensures a comprehensive understanding of the multifaceted considerations involved in crafting a successful SA system, providing valuable insights for researchers and practitioners alike.

RÉSUMÉ

Cette thèse explore le monde multiforme de l'Agriculture Intelligente (AI), en examinant son potentiel de révolutionner le secteur agricole tout en répondant aux préoccupations cruciales en matière de durabilité. La recherche adopte une approche systématique et interconnectée, reliant divers chapitres pour offrir une compréhension globale de la conception de systèmes d'AI.

Chapitre 2: Il propose une revue systématique et exhaustive de la littérature, établissant une base solide en identifiant les technologies clés qui façonnent le paysage de l'AI, en explorant ses liens avec l'industrie 4.0 et en approfondissant à la fois les avantages et les défis qu'elle présente. Un dilemme central émerge : équilibrer la poursuite de la numérisation avec le besoin primordial de durabilité.

Chapitre 3 réalise également une revue systématique de la littérature, cette fois-ci pour établir le fondement théorique des méthodologies suggérées dans cette thèse. Les ensembles Fermatean Fuzzy sont recommandés comme la technique principale dans cette thèse, et en conséquence, les détails des méthodologies suggérées avec l'intégration de 2TLFFS et leur littérature pertinente sont détaillés dans ce chapitre. La revue de la littérature explore non seulement les aspects fondamentaux du FFS, mais offre également une compréhension nuancée de la manière dont ces méthodologies ont été précédemment utilisées et étudiées dans des travaux académiques pertinents. Ce chapitre constitue une exploration critique et une contextualisation des méthodologies choisies, enrichissant le cadre théorique sous-tendant les analyses ultérieures de la these.

Chapitre 4: Il déplace son attention sur le contexte spécifique de l'agriculture turque, en utilisant une analyse SWOT/PESTLE approfondie.

Cet examen détaillé expose les forces, les faiblesses, les opportunités et les menaces actuelles qui affectent le secteur dans sa transition vers un système d'agriculture intelligente durable et numérisé. L'analyse souligne le rôle crucial de la durabilité pour garantir le succès à long terme et la résilience de tout système d'AI mis en œuvre sur le territoire turc.

Chapitre 5: Il s'attaque directement à l'aspect conception en utilisant une application en deux étapes de la méthode QFD (Quality Function Deployment). Ce processus rigoureux traduit les besoins et les attentes identifiés des clients en spécifications techniques exploitables, servant de feuille de route pour la conception et le développement d'un système d'AI qui priorise à la fois la durabilité et la numérisation. La feuille de route en 10 étapes qui en résulte offre un cadre clair et structuré pour naviguer dans les complexités de la conception de systèmes d'AI, garantissant son efficacité et sa viabilité à long terme.

Chapitre 6: Il reconnaît l'importance des fondements technologiques et se concentre sur la sélection critique des fournisseurs de technologies pour des composants clés tels que le Cloud Computing (CC), l'Internet des Objets (IoT) et la technologie des capteurs. Ces technologies forment l'épine dorsale de tout système d'AI moderne, permettant la collecte de données, la connectivité et l'automatisation - des fonctions vitales pour une exploitation réussie. Le processus de sélection utilise des critères d'évaluation méticuleux, garantissant que les fournisseurs choisis possèdent l'expertise et les capacités nécessaires pour fournir des solutions technologiques robustes et durables.

Cette thèse utilise stratégiquement les FFS comme un outil analytique puissant pour élever la profondeur et la précision du processus de recherche dans le domaine de l'AI. Les FFS, particulièrement sous la forme de FFS à 2-tuple, servent de cadre instrumental pour naviguer dans les incertitudes inhérentes et les imprécisions intégrées aux systèmes agricoles complexes. L'intégration des FFS dans des méthodologies établies telles que SWOT/PESTLE, DEMATEL, QFD et VIKOR introduit un niveau supérieur de sophistication et d'informativité dans l'analyse.
En reliant étroitement ces divers chapitres, cette thèse présente un récit convaincant qui transcende la simple synthèse. Chaque chapitre s'appuie sur le précédent, approfondissant

progressivement les subtilités de la conception de systèmes d'AI tout en offrant des solutions concrètes et des stratégies actionnables. Cette approche interconnectée garantit une compréhension globale des considérations multiformes impliquées dans la création d'un système d'AI performant, fournissant des informations précieuses aux chercheurs et aux praticiens.

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ÖZET

Bu tez, Akıllı Tarım (AT) dünyasının çok yönlü yapısını inceleyerek, kritik sürdürülebilirlik endişelerini ele alırken, tarım sektöründe devrim yaratma potansiyelini keşfetmektedir. Araştırma, kapsamlı bir anlayış sağlamak için farklı bölümleri bir araya getirerek sistematik ve birbirine bağlı bir yaklaşım benimsemektedir.

2. Bölüm: Kapsamlı bir sistematik literatür taraması gerçekleştirerek, AT ortamını şekillendiren anahtar teknolojileri belirleyerek, Sanayi 4.0 ile bağlantılarını araştırarak ve hem faydalarını hem de zorluklarını derinlemesine inceleyerek sağlam bir temel oluşturmaktadır. Bu bölümde ortaya çıkan merkezi bir ikilem: dijitalleşmenin peşinde koşma ile sürdürülebilirliğin en üst düzeydeki ihtiyacını dengelemektir.

3. Bölüm, bu tezin önerdiği metodolojilerin teorik temelini oluşturmak amacıyla sistemli bir literatür taraması gerçekleştirir. Bu tezde ana teknik olarak Fermatean Bulanık Kümeleri (FBK) önerildiğinden, bu bölümde önerilen metodolojilerin ikili dilsel gösterim (2TL) FFS entegrasyonu ve ilgili literatür detaylı bir şekilde ele alınmaktadır. Literatür taraması, FBK'nin temel yönlerini keşfetmekle kalmayıp aynı zamanda bu metodolojilerin daha önceki akademik çalışmalarda nasıl kullanıldığı ve incelendiği konusunda da derinlemesine bir anlayış sunar. Bu bölüm, tezin sonraki analizlerinin temelini oluşturan seçilen metodolojilerin kapsamlı bir keşfi ve bağlamlandırması niteliğindedir.

4. Bölüm: Odak noktasını Türk tarımının özel bağlamına kaydırarak kapsamlı bir SWOT/PESTLE analizi kullanmaktadır.

Bu ayrıntılı inceleme, sektörün sürdürülebilir ve dijitalleşmiş akıllı tarım sistemine dönüşümünde rol oynayan mevcut güçlü yönleri, zayıf yönleri, fırsatları ve tehditleri ortaya koymaktadır. Analiz, Türk topraklarına uygulanan herhangi bir AT sisteminin uzun vadeli başarısını ve dayanıklılığını garanti altına almak için sürdürülebilirliğin kritik rolünü vurgulamaktadır.

5. Bölüm: Tasarım aşamasını doğrudan ele alarak iki aşamalı Kalite Fonksiyonu Dağılımı (QFD) uygulamasını kullanmaktadır. Bu titiz süreç, belirlenen müşteri ihtiyaçlarını ve beklentilerini uygulanabilir teknik özelliklere dönüştürerek, hem sürdürülebilirliği hem de dijitalleşmeyi önceliklendiren bir AT sistemi tasarımı ve geliştirilmesi için bir yol haritası olarak hizmet vermektedir. Ortaya çıkan 10 adımlı yol haritası, AT sistemi tasarımının karmaşıklıklarında gezinmek için net ve yapılandırılmış bir çerçeve sunarak etkinliğini ve uzun vadeli uygulanabilirliğini garanti altına almaktadır.

6. Bölüm: Teknolojik temellerin önemini kabul ederek, Bulut Bilişim (CC), Nesnelerin İnterneti (IoT) ve sensör teknolojisi gibi temel bileşenler için kritik teknoloji sağlayıcılarının seçimine odaklanmaktadır. Bu teknolojiler, başarılı bir operasyon için hayati fonksiyonlar olan veri toplama, bağlantı ve otomasyonu sağlayan herhangi bir modern AT sisteminin omurgasını oluşturmaktadır. Seçim süreci, titiz değerlendirme kriterleri kullanarak, seçilen sağlayıcıların sağlam ve sürdürülebilir teknolojik çözümler sunmak için gerekli uzmanlığa ve yeteneklere sahip olmalarını garanti altına almaktadır.

Bu tez, AT alanındaki araştırma sürecinin derinliğini ve hassasiyetini artırmak amacıyla FBK adlı güçlü bir analitik aracı stratejik bir şekilde kullanmaktadır. Özellikle 2TLFFK formunda, FBK karmaşık tarım sistemlerine gömülü olan belirsizlikleri ve belirsizlikleri ele almak için enstrümantal bir çerçeve olarak hizmet etmektedir. SWOT/PESTLE, DEMATEL, QFD ve VIKOR gibi kurumsal metodolojilere FFS'nin entegrasyonu, analize daha yüksek bir seviye sofistikelik ve bilgililik katmaktadır.

Bu tezi oluşturan çeşitli bölümleri birbirine karmaşık bir şekilde bağlayarak, sadece özetlemeyi aşan bir anlatım sunmaktadır. Her bölüm, bir önceki bölüm üzerine inşa edilerek, AT sistemi tasarımının inceliklerine giderek daha fazla derinleşirken, aynı zamanda somut çözümler ve uygulanabilir stratejiler sunmaktadır. Bu birbirine bağlı yaklaşım, başarılı bir AT sistemi oluşturmak için gerekli çok yönlü hususların kapsamlı bir anlayışını garanti altına alarak, araştırmacılar ve uygulayıcılar için değerli bilgiler sağlamaktadır.

1 INTRODUCTION

Agriculture, encompassing both an art and a science, involves the cultivation of soil, the growth of crops, and the raising of livestock. Its significance extends beyond sustenance, as it encompasses the preparation of plant and animal products for human consumption, along with their distribution to markets (Deloitte, 2020). The diversity of agricultural products and methods employed manifests distinctively across different regions globally. Over centuries, the evolution of agriculture played a pivotal role in the development of urban centers (Federico, 2010).

In the pre-agricultural era, societies relied on hunting and gathering for sustenance. The pivotal transition from this nomadic lifestyle occurred approximately 10,000 to 12,000 years ago when communities gradually acquired the knowledge of cultivating cereal and root crops, leading to a settlement-based existence grounded in farming (Tauger, 2010). The subsequent dependence of a substantial portion of the global population on agriculture remains a historical outcome of this shift. Researchers, although uncertain about the precise triggers for this agricultural revolution, guess that climate change may have played a role in compelling societies to adopt farming practices (Tauger, 2010). In this context, the development of agriculture stands as a multifaceted endeavor shaping human societies, economies, and lifestyles across time and geographical landscape.

1.1 The Evolution of Agricultural Practices: From Manual Labor to Industrial Efficiency

Approximately 12,000 years ago, the advent of agriculture marked a transformative shift in human existence, catalyzing the transition from nomadic hunter-gatherer lifestyles to the establishment of permanent settlements centered around farming (Federico, 2010). Throughout human history, from ancient times until the cusp of the 19th century, agriculture was a fundamental activity that sustained communities. However, the methods employed were vastly different from the technologically advanced practices we witness today. During this era, agriculture was characterized by an overwhelming dependence on human power and the utilization of basic, manual tools. Subsistence farming emerged as the dominant agricultural model, characterized by small-scale cultivation aimed at meeting immediate community needs (Noguchi, 2015). Diversifying crops was a key strategy employed by subsistence farmers, not only to address nutritional requirements but also as a risk-mitigation tactic against potential crop failures or adverse weather conditions affecting specific crops (Noguchi, 2015).

This approach fostered self-sufficiency, as communities relied primarily on their own agricultural output for sustenance (Tauger, 2010). While this autonomy provided a sense of security, it concurrently limited the diversity of available goods and services within these largely self-contained entities. The inherent self-sufficiency of subsistence farming communities, however, was not without constraints. Communities were bound by the resources available within their immediate vicinity, with factors such as soil fertility, water availability, and climatic conditions playing pivotal roles in determining agricultural productivity. This localized and geographically specific approach to cultivation underscored the intimate relationship between the environment and the agricultural practices of these communities.

Despite the self-sufficiency intrinsic to subsistence farming, surplus production was a rarity, with the primary goal being to fulfill immediate needs rather than generating excess for trade or commerce (Tauger, 2010). Any surplus that did emerge was typically small and reserved for times of scarcity or utilized as a form of barter within the confines of local communities.

The agricultural calendar of subsistence farming revolved meticulously around seasonal rhythms. Planting, cultivating, and harvesting were intricately tied to natural cycles, forming a temporal alignment that allowed for the optimization of agricultural practices based on the unique challenges and opportunities presented by each season. This cyclical and knowledge-intensive approach reflected the wisdom passed down through generations, shaping a sustainable and adaptive agricultural system that laid the foundation for subsequent transformations in the 19th century and beyond.

Following the Neolithic Revolution, a pivotal transition from nomadic hunter-gatherer societies to settled agricultural communities, the trajectory of agrarian history experienced a profound transformation with the onset of the First Industrial Revolution (Clegg & Lucas, 2020). The First Industrial Revolution, which emerged in the late 17th century, primarily impacted agriculture through significant changes in labor patterns, production processes, and transportation (Clegg & Lucas, 2020). The transition from agrarian economies to industrialized societies led to the migration of rural populations to urban centers in search of employment opportunities in burgeoning industries. This rural-to-urban shift reduced the agricultural workforce but also increased the demand for food in urban areas. This epoch, characterized by technological innovations and the widespread implementation of machinery, marked a decisive departure from conventional farming practices. The introduction of railroads facilitated the transportation of agricultural products from rural areas to urban markets, expanding the reach of agricultural goods. Despite some disruptions in traditional rural life, the First Industrial Revolution laid the groundwork for subsequent transformations in agriculture, setting the stage for the mechanization and technological advancements seen in later industrial revolutions (Clegg & Lucas, 2020).

The emergence of mechanization during the First Industrial Revolution laid the foundation for the subsequent agricultural transformations, notably recognized as the Second Industrial Revolution in agriculture. This paradigm shift, characterized by key inventions such as the plow, reaper, and later advancements like tractors and harvesters, significantly enhanced operational efficiency and overall output (Moore, 2010). These innovations mechanized diverse stages of the farming process, revolutionizing cultivation, harvesting, and overall farm management. The mechanization initiated during the First Industrial Revolution marked a pivotal departure in agricultural practices, setting the stage for the mechanized advancements that defined subsequent industrial revolutions and their profound impacts on the agricultural sector.

The Second Revolution (18th and 19th Centuries) also witnessed a critical exploration of alternative energy sources (Clegg & Lucas, 2020). The adoption of steam power, subsequently replaced by internal combustion engines, not only powered machinery but also catalyzed a transformative expansion in the scale and scope of agricultural operations. This marked transition from reliance on human and animal power to mechanical power played a pivotal role in reshaping the agricultural landscape. Simultaneously, advancements in the transportation industry played a crucial role in optimizing the agricultural supply chain (Sadowski & Spachos, 2020). The integration of railways and, later, motorized vehicles facilitated the swift and efficient transport of agricultural products, establishing vital connections between distant farms and regional as well as global markets.

A significant consequence of mechanization was the globalization of agrarian markets. As farmers embraced mechanized techniques, production surged, leading to the emergence of diverse agricultural markets. Farmers, once confined to servicing local communities, transitioned to producing for a global clientele. This globalization not only diversified the array of agricultural products available but also profoundly influenced the economic dynamics of farming communities, ushering in an era of interconnected and interdependent global agricultural systems (Clegg & Lucas, 2020).

The Third Industrial Revolution, often associated with the rise of digital technologies, began to take shape in the mid to late 20th century (Moore, 2010). Building upon the mechanization of the Second Industrial Revolution, the Third Industrial Revolution introduced precision agriculture techniques, leveraging tools such as remote sensing technologies (satellite imagery and drones), GPS guidance systems, and automated machinery. These advancements enable farmers to optimize resource utilization, minimize environmental impact, and streamline operations. The result is a more precise, data-driven approach that reduces labor-intensive tasks and improves overall productivity.

The Third Industrial Revolution is often associated with the rise of digital technologies, including the use of computers and automation in manufacturing. However, the concept of the Fourth Industrial Revolution more explicitly focuses on the integration of digital technologies, artificial intelligence, the Internet of Things, and other advanced technologies in a broader societal context, encompassing not only industry but also various aspects of our daily lives (Moore, 2010).

Third Industrial Revolution has revolutionized agricultural practices, ushering in a new era of precision and sustainability. From precision agriculture (PA) techniques to the emergence of smart agriculture (SA), these advancements empower farmers to optimize operations and contribute to a more food-secure and sustainable future (Hussmann, 2018 p.4). Ensuring the accessibility of these technologies to farmers of all scales is crucial for unlocking the full potential of smart agriculture on a global scale.

In summary, the profound impact of the three previous industrial revolutions on agricultural operations is evident in the evolution from labor-intensive practices to the highly mechanized and technologically sophisticated systems seen today (Clegg & Lucas, 2020). The shifts in production lines brought forth by these revolutions are reflected in the transformative nature of agricultural activities. As the agricultural landscape transitions from the Third Industrial Revolution's digital technologies and PA to the Fourth Industrial Revolution, characterized by Industry 4.0's (I4.0) interconnected technologies, the result is a seamless integration of advanced tools such as artificial intelligence (AI), the Internet of Things (IoT), and data analytics (DA). This progression has notably increased the controllability and efficiency of agricultural systems (Arora et al., 2022). Presently, the mass production of food has become industrialized, governing worldwide food production and distribution due to its inherent cost-effectiveness and efficiency, thereby embodying the culmination of historical advancements in agriculture and industrialization.

1.2 From Smart Production to Smart Agriculture (SA)

Currently, we are talking about the new industrial revolution called I4.0. Fluctuating market conditions in a globally connected world challenges companies to adapt and embrace digital transformation across all functions, including procurement, logistics, manufacturing, asset management, and factory operations continuously (Arora et al., 2022). As trade conflicts, pandemic-induced disruption, and skill shortages continue, businesses must change faster and drive more optimized operations to meet customer needs (Oruma et al., 2021). Intelligent technologies and process automation enable alternative ways to solve business problems, generate additional revenue streams, offer digital services, and keep customers engaged – all while achieving supply chain resilience. I4.0, also known as the Industrial Internet of Things (IIoT), provides the mechanisms for connecting industry value chains, and enables companies to understand their businesses better (Touseau & Le Sommer, 2019).

Agricultural digitalization is a critical component of agricultural industrialization, focusing correspondingly on agricultural research, infrastructural improvements, and data services (Masram & Patkar, 2021). The combination of the Internet of Things/Everything (IoT/IoE) with Radio-Frequency Identification (RFID), sensors, and high-tech meters makes up SA. Controlling and monitoring have become more easily applicable thanks to these technological improvements. SA has the power to control water, pesticides, security, the environment, machines, and vehicles. In the short term, it proposes an end-to-end management and monitoring aspect of the entire system (Hassan et al., 2021).

Peer-to-peer digital connectivity provides flexibility and monitoring for all the activities in farming. It empowers the productivity of the farming system (Derus et al., 2019). Generally, end-to-end management systems facilitate the monitoring of daily and hourly work, machine performance, and movement. Some farm productivity systems enable vehicle tracking and automation besides the standard IoT applications in agriculture.

1.3 Features of SA

Simply, I4.0 deals with the digital transformation of all processes via smart networking machines, business processes, and people (Masram & Patkar, 2021). In the interest of this transformation, various technologies are employed in the existing conventional processes. The same situation is binding for agriculture as well. Exploration of the use of elaborated digital technologies enabled network connectivity during agrarian operations such as irrigation and weeding (Albraikan et al., 2022; Kamienski et al., 2019). Agriculture 4.0 is happening with the help of I4.0 (Lezoche et al., 2020). As in I4.0, Agriculture 4.0 covers the combined internal and external interacting farming operations, and it also provides digital information about each farming stage (Bronson, 2018). Like smart factories, smart farms also need to adapt the real-time changes to stabilize their position in the competitive market (Bronson, 2018).

Concerning the on-time data flow, the primary necessity is to have constant communication between the market and production. Therefore, the technologies that fortify this connectivity are the key technologies (McKinsey and Co., 2020). Currently, the scope of the use of these technologies is wider. In the realm of digital transformation and its enabling technologies, a recent McKinsey report, released in July 2023, has redefined key technology trends (McKinsey & Company, 2023). After a volatile year in 2022, characterized by fluctuations in technology investment and talent, the first half of 2023 has witnessed a renewed surge of enthusiasm regarding technology's potential to propel advancements in both business and society. Generative AI is prominently credited with rekindling this optimism, though it represents just one facet of a broader spectrum of upcoming breakthroughs poised to drive sustainable, inclusive growth and offer solutions to complex global challenges (Alreshidi, 2019). This comprehensive report provides valuable insights and considerations spanning all 15 technology trends, making it an essential resource in the context of ongoing digital transformation initiatives. These technologies have the potential to play a vital role in the context of SA. They can be grouped under five categories, and they are given in **Table 1.1** (McKinsey & Company, 2023).

While the technologies discussed in this report are generally applicable to digitalization, their significance extends as key enablers for agriculture (Prabha & Pathak, 2023; Sivakumar et al., 2021). These technological advancements play a pivotal role in enhancing PA, optimizing resource utilization, and fostering sustainable agricultural practices, making them essential components for the realization of SA initiatives.

Table 1.1: Enabler Technologies for SA (McKinsey & Company, 2023).

Technology Categories	**Enabler Technologies**
Transformative AI	Machine Learning (ML) Computer vision Natural-language processing (NLP) Deep reinforcement learning Data Management
Digital Future	Infrastructure as code AI-generated code AI-based testing Automated code review Low- and no-code platforms Digital identity Zero-trust architecture (ZTA) Blockchain Smart Contracts
Innovative Engineering	Augmented Reality (AR) Virtual Reality (VR) Mixed Reality On-body and off-body sensors Autonomous technologies Value chain decarbonization
Computation and Connectivity	Optical fiber Low-power, wide-area networks 5G/6G cellular High-altitude platform systems (HAPS) Direct-to-handset satellite connectivity IoT or device edge
Pursuit of Sustainability	Carbon capture, utilization, and storage (CCUS) Circular technologies Technologies to track net-zero progress Renewable energy technologies

However, agricultural activities still depend on human labor. This situation is still problematic during the health crises, such as the COVID-19 pandemic (Alabi & Ngwenyama, 2022). Such health problems established various kinds of limitations on social and economic activities. In this regard, pandemic will affect indigent countries that profoundly depend on food provided by small farmers, livestock farmers, and artisan fishers the most. According to the Food and Agriculture Organization (FAO), the social confinement enforced by COVID-19 pandemic limit farmers to access input and product markets by deepening the post-harvest costs (FAO, 2020). In wealthier countries, due to the perception of “difficult labor” and unprofitable nature of agricultural tasks, new generations tend to explore new jobs in urban regions. Therefore, farmers search for solutions to compensate losses and minimize future losses.

The leading solution proposed in the literature for transforming and reorienting agricultural systems to support food security under the adaptation of digitalization is then the “Smart/ Intelligent Agriculture” or “Precision Agriculture” context (Zhang, 2023). In 1980’s International Society of Precision Agriculture (ISPA) defined PA as “*a management strategy that gathers, processes and analyzes temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profit- ability and sustainability of agricultural production.”* According to the exposition put forth by Zhang (2023) in his opinion paper, the term PA embodies a farming management construct that optimizes agricultural output through the harnessing of sensed data, consequently curtailing resource consumption. In contrast, the term SA is employed interchangeably with "agriculture 4.0," signifying a paradigm that amalgamates state-of-the-art sensing technologies, data analytics, and AI to bolster farming efficiency, productivity, and sustainability. Correspondingly, the concept of "digital agriculture" aligns with "e-agriculture," encompassing the deployment of digital tools and communication systems to refine various facets of agricultural practices.

Zhang (2023) asserts that these conceptual delineations evince foundational similarities while diverging primarily in their focal domains. While PA accentuates a structured framework, SA directs attention toward the integration of forefront sensing technologies, data analytics, and AI to amplify farming efficiency, productivity, and sustainability. In contrast, "digital agriculture" spotlights the proficient application of digital tools and communication systems to enhance the multifaceted dimensions inherent to agricultural processes.

In concurrence with the viewpoint embraced by Qin Zhang's opinion paper, it is acknowledged that SA serves as a distinctive phase within the overarching framework of PA. PA constitutes the encompassing concept that entails the judicious utilization of technology to optimize various aspects of farming practices. Within this broader concept, SA emerges as a discernible stage characterized by the integration of advanced sensing technologies, DAs, and AI (Zhang, 2023). This phase is designated as "smart" due to its emphasis on leveraging cutting-edge technologies to enhance efficiency, productivity, and sustainability in farming operations. This recognition aligns with Zhang's assertion that while these terms share fundamental commonalities, they also manifest as nuanced stages within the continuum of precision agriculture.

Building upon this comprehension, the present thesis employs the term SA to delineate the evolving era of mechanization in precision agriculture. The essential components of this smart agricultural system, including AI, VR, and Digital Twin technologies, collectively constitute the foundational elements that enable the effective realization of the applications and advancements inherent to SA’s domain.

1.4 Thesis Framework and Objectives

In the domain of SA, farmers should proactively explore opportunities to modernize their traditional farming practices to meet the increasing demands of tech-savvy agriculturalists. It is essential to prepare for serving the growing community of SA practitioners. A thorough analysis of academic literature and industry reports has unveiled significant gaps within the SA research landscape. Notably, there is a scarcity of comprehensive studies that address the full scope of digitalization within agricultural systems. Existing research tends to concentrate on isolated issues, often overlooking the holistic needs of SA.

This thesis seeks to address this gap by focusing on strategic aspects that directly influence the digital transformation of SA. Its objective is to establish an integrated and effective assessment and design framework tailored to the unique requirements and core attributes of SA. The following statements outline the essence of the thesis:

- Considering the numerous challenges posed by traditional agricultural systems and the evolving dynamics of the environment, this thesis endeavors to furnish a comprehensive guideline for the conceptualization of SA systems. This overarching objective is structured into five key chapters. The initial two chapters serve to establish the theoretical foundation, the first elucidating the landscape of SA, and the second expounding upon the analytical techniques relevant to the subsequent chapters. The remaining three chapters collectively delineate a systematic roadmap for the transition towards SA.

- Chapter 3 contains the theoretical background for the applied methodologies in this thesis. At this stage, a systematic review of FFS and 2TLFFS literature is conducted. Plus, the overview of suggested methodologies with their relevant literature are presented as a theoretical foundation for the thesis.

- Chapter 4 initiates with a comprehensive analysis of Turkish agriculture through a strategic examination utilizing SWOT (Strengths, Weaknesses, Opportunities, Threats) and PESTLE (Political, Economic, Social, Technological, Legal, Environmental) methodologies. The study aims to provide an extensive overview of the existing agricultural landscape in Türkiye. Its principal objective is the formulation of strategic insights conducive to the efficient implementation of SA practices and the establishment of sustainable agricultural systems. To attain this objective, the chapter proposes the application of the 2-Tuple Fermatean Fuzzy Sets (2TLFFSs) integrated DEMATEL (Decision-Making Trial and Evaluation Laboratory) methodology, synergistically incorporated with SWOT and PESTLE analyses, to offer a nuanced and multifaceted understanding of the complex dynamics shaping the Turkish agricultural sector.

- Chapter 5 is dedicated to the presentation of a two-stage Quality Function Deployment (QFD) methodology. Within this chapter, the central aim is to design a SA system that precisely balances the imperatives of sustainability and digitalization. The diverged nature of this methodology empowers a comprehensive inquiry into the sustainability aspects inherent to SA systems. It is worth noting that the preceding literature review in the realm of SA serves as the underpinning theoretical basis for this chapter. The review not only furnishes insights into the core technologies employed in SA but also encapsulates the principal expectations that define the SA landscape.

- Chapter 6 subsequently introduces an approach for technology provider selection. This approach systematically aids in the selection of the most efficacious technology provider capable of aligning with criteria assigned for CC (Cloud Computing), IoT (Internet of things) and Sensors. DEMATEL VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) is recommended for this section.

- This thesis employs multi-criteria decision-making (MCDM) techniques as a fundamental methodological approach. SA necessitates intricate choices concerning technology selection, resource allocation, and system design, where multiple criteria and objectives often interplay. MCDM, with its ability to systematically evaluate and prioritize diverse criteria while considering their interdependencies, emerges as an indispensable tool. By facilitating structured and data-driven decision-making, MCDM not only enhances the efficiency of selecting the most suitable technologies for SA but also contributes significantly to optimizing resource utilization and sustainability efforts. Its adaptability to the dynamic and evolving landscape of SA positions MCDM as an invaluable asset in guiding the transformation of traditional farming practices into technologically advanced and sustainable systems.

- To further enhance its efficacy, the integration of MCDM techniques with 2TLFFSs is employed as a strategic methodological choice. The 2TLFFSs represents a potent incorporation of two essential components: the robust 2-Tuple Linguistic (2TL) model and the versatile Fermatean fuzzy set (FFS). Within this framework, the 2TL approach offers decision-makers a robust mechanism for rendering qualitative judgments on various alternatives by employing linguistic labels, thus facilitating a more intuitive and human-compatible decision-making process. Furthermore, it effectively mitigates the challenges of information distortion that often arise during linguistic information processing, while also adeptly addressing the issue of two-sided information in practical applications. Of paramount significance is the inherent structure of the 2TLFFS, characterized by its combination of membership and non-membership grades, presented in the form of 2TL terms, which underpins its adaptability and utility within the context of complex decision-making scenarios.

The proposed thesis study consists of four main stages:

1) Conducting a comprehensive systematic literature review on SA to reveal the highly emphasized I4.0 technologies for SA and their benefits. Plus, conducting FFS-MCDM literature review for the theoretical foundation of the thesis.
2) Assessing Turkish Agriculture landscape for deeper strategy generation for transition to SA under 2TLFFSs GDM environment by using DEMATEL integrated SWOT/PESTLE analysis.
3) Regarding the generated strategies designing a SA structure concerning sustainability and digitalization measures under 2TLFFSs group decision making (GDM) environment by using QFD approach.
4) Assessing the most appropriate technology provider for SA under 2TLFFSs GDM environment by using VIKOR approach.

The following Figure summarized the general flow of this thesis.

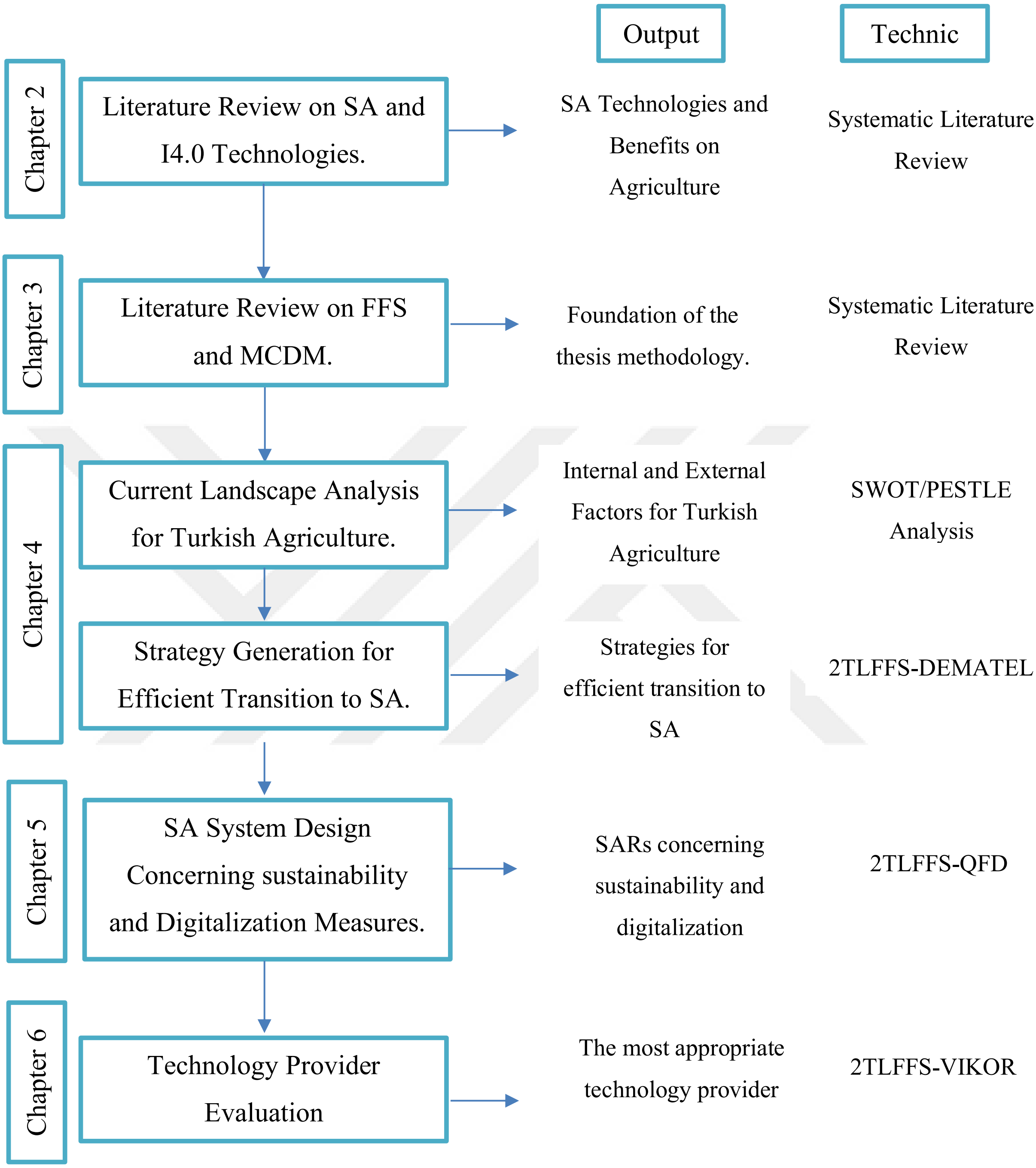

Figure 1.1: Thesis framework and objectives.

2 LITERATURE REVIEW ON SA

Within the framework of this thesis, the forthcoming chapter assumes a meticulous design, strategically poised to delve into the pivotal intersection of I4.0 technologies and their transformative impact on SA. The temporal scope of our inquiry is carefully delineated, encapsulating the dynamic period between 2020 and 2023. This carefully curated exploration is anchored by an overarching objective: to systematically address foundational inquiries that guide our investigation, while simultaneously illuminating critical dimensions that serve as the nexus between the realms of agriculture and I4.0. The chapter unfolds in two distinct yet interconnected parts, with the initial section meticulously examining the intricate relationship between agriculture and I4.0. Subsequently, the narrative takes a deeper plunge into the realms of SA, methodically dissecting the application of I4.0 technologies across the spectrum of the agricultural value chain stages: Production and Processing, Distribution and Retailing, and Consumption and Recycling. This strategic structuring aims to provide a comprehensive and nuanced understanding of the symbiotic relationship between agriculture and I4.0 technologies, laying the foundation for the subsequent analyses and insights to follow.

In configuring the structure of this chapter, the carefully chosen temporal confines extending from 2020 to 2023 assume a pivotal role in facilitating a nuanced exploration of the dynamic interplay between I4.0 and agriculture. This timeframe is strategically positioned to encapsulate the maturation phase of digital technologies in the post-2019 era (LaBaerge et al., 2020; Su et al., 2022), presenting a critical vantage point for analyzing the evolution and intricate interactions within SA. The focal point on this specific timeframe ensures the assimilation of the latest research findings, facilitating a precise evaluation of matured technological trends and strategic shifts. Simultaneously, our analytical endeavor aims to discern changes and advancements relative to the period preceding 2020, providing a comprehensive and holistic panorama.

The selective adoption of this timeframe serves to minimize the inclusion of outdated information, thereby augmenting the accuracy and relevance of the literature review (LaBaerge et al., 2020; Su et al., 2022). This commitment to a defined temporal scope not only aligns with the evolving paradigm of I4.0 in agriculture but also bolsters the credibility of the literature review by affording a comprehensive perspective on the maturity and trajectory of I4.0 technologies within the agricultural sector.

2.1 Review Methodology

The main methodology for the two staged systematic review is presented followingly:

First Stage: Agriculture and I4.0:

1) The review team determined relevant keywords for the subject based on their prior expertise. “Industry 4.0”, “agriculture” is selected as the main keyword for the search for review papers for the first stage.

2) The keywords were structured into search strings. Then the strings are searched in Web of Science and Scopus Database. (TS="industry 4.0" OR "Agriculture") AND (TI="industry 4.0" OR "agriculture") string is used for Web of Science database and TITLE-ABS-KEY ("industry 4.0" OR "agriculture") is used for Scopus database. Only the review studies between 2020-2023 are selected for this review. The studies that were identified underwent a review process based on the inclusion and exclusion criteria outlined in **Table 2.1.** To streamline the selection, a two-stage approach was adopted. The first stage involved assessing the article titles and abstracts against the exclusion criteria, while the second stage involved evaluating the abstracts against the inclusion criteria.

Second Stage: SA and I4.0 Technologies:

3) The review team determined relevant keywords for the subject based on their prior expertise. These keywords were generated through a brainstorming process. “Industry 4.0”, “Smart Agriculture”, “Precision Agriculture”, “Digital

Agriculture", "technology", "agriculture", and "digital" keywords are added to the list.

4) The keywords were structured into search strings. For example, the search string [Agriculture AND technology OR digital* OR industry 4.0].

5) An initial search in Google Scholar data base is conducted using basic research string [(Smart Agriculture OR Precision Agriculture OR Digital Agriculture OR Smart Farming) AND (technology* OR digital*)]. The results are analyzed and used to detect further keywords for search. "Food Logistics", "Food Traceability", "Supply Chain Technology", "Sustainable Agriculture", "Food Safety", "Food Quality", "Food Traceability" keywords are also added to the keyword list to detect different technologies in the different stages of the agricultural value chain.

6) Three stages of the agricultural value chain is derived from [11] such as Production & Planning, Distribution & Retailing and Consumption & Recycling. These stages are used to investigate relevant I4.0 technologies in diverse stages of SA value chain.

7) For Production & Planning stage ("Precision Agriculture" OR "Digital Agriculture" OR "Agricultural Automation") AND ("Crop Management" OR "Farm Equipment" OR "Agricultural Robotics") AND ("IoT in Agriculture" OR "Agricultural Sensors" OR "Crop Monitoring" OR "Soil Management") string is used for search studies between 2020-2023.

8) For Distribution & Retailing stage (("Smart Agriculture" OR "Precision Agriculture" OR "Digital Agriculture" OR "Agricultural Automation") AND ("Food Logistics" OR "Food Traceability" OR "Supply Chain Technology" OR "Transportation Management")) string is used for search studies between 2020-2023.

9) For Consumption & Recycling ("Smart Agriculture" OR "Precision Agriculture" OR "Digital Agriculture" OR "Agricultural Automation") AND ("Food

Consumption" OR "Sustainable Agriculture" OR "Agricultural Recycling" OR "Food Waste Reduction") AND ("Food Safety" OR "Food Quality" OR "Food Traceability") string is used for search studies between 2020-2023.

10) The studies that were identified underwent a review process based on the inclusion and exclusion criteria outlined in **Table 2.1.** To streamline the selection, a two-stage approach was adopted. The first stage involved assessing the article titles and abstracts against the exclusion criteria, while the second stage involved evaluating the full texts against the inclusion criteria. The following **Figure 2.1** presents the general flow of the article selection process.

Table 2.1: Inclusion and exclusion criteria.

Review Stages	Exclusion Criteria	Inclusion Criteria
Both Stages	*Publication Date:* Studies published between 2020 and 2023.	*Publication Date:* Studies published before 2020 or after 2023.
First Stage (I4.0 and Agriculture)	*Irrelevant to I4.0 and Agriculture:* Studies not directly addressing the relationship between I4.0 and agriculture may be excluded if they do not contribute substantially to the review's objectives. *Non-Review Articles:* Non-review articles, such as conference papers, case studies, and technical reports, will be excluded to maintain the depth and synthesis inherent in review articles.	*Focus on I4.0 and Agriculture:* All studies addressing the relationship between I4.0 and agriculture. *Review Articles:* Preference will be given to review articles to ensure a comprehensive synthesis of existing knowledge.
Second Stage (I4.0 Technologies and SA)	*Limited Focus on SA:* Studies with a primary focus on aspects other than SA within the I4.0 context may be excluded if they do not contribute substantially to the review's objectives. *Technologies Unrelated to I4.0:* Studies where the mentioned technologies are not related to I4.0 may be excluded to maintain focus on the central theme.	*Primary Emphasis on SA:* Studies emphasizing the role of I4.0 technologies in SA will be prioritized. *Technology Relevance:* Technologies mentioned in the study should be related to I4.0 technologies.

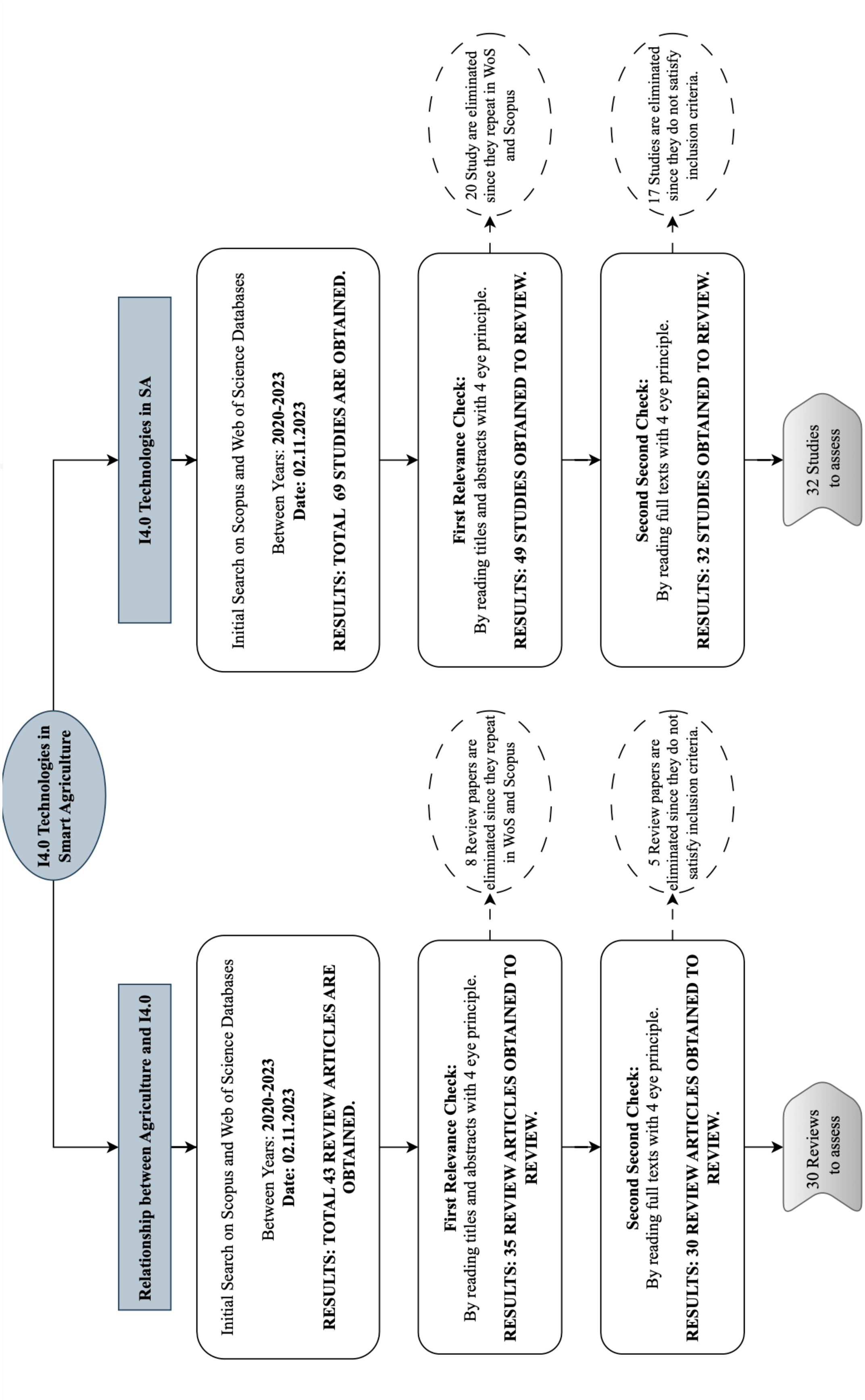

Figure 2.1: General flow of the systematic review.

2.2 Literature Review on SA

This section commences with an exhaustive examination of the relationship between I4.0 and agriculture, a critical analysis achieved through the comprehensive review of relevant review and conceptual studies. Subsequently, our focus shifts to an in-depth review of I4.0 technologies and the overarching concept of SA, where seminal insights from scholarly contributions illuminate the transformative dynamics within the agricultural domain. This dual-phase approach ensures a meticulous and informed exploration of both the theoretical underpinnings and the practical applications of I4.0 in the context of SA.

2.2.1 I4.0 and Agriculture

Critical global challenges, such as climate change, escalating world population, excessive food wastage, and the emergence of potential disease pandemics, imperil both food sustainability and planetary security, demanding immediate attention (Hassoun, Aït-Kaddour, et al., 2023). In an era defined by rapid technological advancements and the relentless pursuit of efficiency and sustainability, the convergence of I4.0 and agriculture has emerged as a transformative force, shaping the future of food production (Djekić et al., 2023).

Undoubtedly, I4.0 stands as the vanguard of digital transformation, orchestrating the integration of intelligent machines, streamlined business processes, and human collaboration (Lemstra & de Mesquita, 2023). This paradigm shift extends its transformative reach to agriculture, encapsulating a realm known as SA. Here, the seamless adoption of advanced digital technologies facilitates network connectivity throughout agrarian operations, reshaping conventional practices such as irrigation and weeding (Abbate et al., 2023). The symbiotic relationship between I4.0 and SA becomes increasingly apparent, portraying agriculture's reliance on I4.0 technologies for enhanced efficiency and productivity. As we delve into the subsequent discussion on specific technologies within this transformative alliance, the intricate synergy between I4.0 and SA becomes more pronounced. Here are the main I4.0 technologies mentioned in the literature in **Table 2.2**.

Table 2.2: List of I4.0 technologies derived from literature.

Technologies	References	Description
Additive Manufacturing Technologies (3D printing)	(Holzmann et al., 2020; Kapetaniou et al., 2018; Tartici et al., 2023; Yeh & Chen, 2018)	Utilizes layer-by-layer material deposition to create three-dimensional objects, offering flexibility in design and customization.
Artificial Intelligence (AI)	(I. Ahmed et al., 2022; Alenizi et al., 2023; Azizi, 2019; Zeba et al., 2021)	Employs algorithms to simulate intelligent behavior, enabling machines to learn, reason, and make decisions independently.
Augmented Reality (AR)	(Fraga-Lamas et al., 2018; Reljic et al., 2021; Voinea et al., 2023)	Integrates digital information into the user's real-world environment, enhancing perception and interaction with the surroundings.
Big Data	(Alfred et al., 2021; Barzizza et al., 2023; Cravero et al., 2022)	Involves the processing and analysis of vast datasets to extract valuable insights, patterns, and trends.
Blockchain	(Bovenzi et al., 2023; Ellahi et al., 2023; Guo et al., 2023)	Utilizes a decentralized and secure ledger system to record and verify transactions, enhancing transparency and trust.
Cobotic Systems (Collaborative Robotic Systems)	(Prati et al., 2022)	Involves the collaboration between robots and human workers, enhancing efficiency and safety in shared workspaces.
Deep Learning (DL)	(Diaz-Martinez et al., 2023; Serey et al., 2023)	A subset of ML that involves neural networks (NNs) to mimic human-like decision-making and problem-solving.
Global Positioning System (GPS)	(Venanzi et al., 2023)	Provides precise location information using satellite signals.

Technologies	References	Description
IoT	(Chataut et al., 2023; Chiarini et al., 2020; Goknil et al., 2023)	Connects physical devices to the internet, enabling data exchange and communication for smart applications.
Machine Learning (ML)	(Carnagie et al., 2023; Shahbazian et al., 2023)	Enables systems to automatically learn and improve from experience without explicit programming.
Robotics (Drones, Autonomous robots)	(Norhashim et al., 2023)	Involves the use of mechanical devices and autonomous systems to perform tasks, often in challenging or hazardous environments.
Radio-Frequency Identification (RFID)	(Dastres et al., 2022; Mostaccio et al., 2023)	Uses electromagnetic fields to identify and track objects.
Remote Sensing Technologies (Sensors)	(Kalsoom et al., 2020; Korkmaz et al., 2022)	Devices that detect and measure physical properties, converting them into signals for monitoring and control.
Simulation	(Nasirahmadi & Hensel, 2022; Peladarinos et al., 2023)	Utilizes computer models to replicate real-world processes, facilitating analysis, testing, and optimization.
Cloud Computing	(Alshahrani, 2023)	Provides on-demand access to a shared pool of computing resources, offering scalability and flexibility for various applications.

The detailed overview of reviews conducted between 2020 and 2023 is presented **Table 2.3**. The assessment criteria encompass the publication year, methodological approach employed, articulated benefits of I4.0 in agriculture, identified challenges and risks associated with I4.0 in the agricultural domain, and the specific focal areas of investigation.

Table 2.3: Reviews on agriculture and I4.0

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Hassoun, Aït-Kaddour, et al., 2023)	Critical Reviews in food Science and Nutrition	General Overview	• Improved efficiency and productivity • Sustainable, intelligent, and innovative food production systems, • Climate resilience and food sustainability, • Contribution to the green transition, • Potential to achieve valuable outcomes for public health, environmental and economic development.	• Security and privacy issues, • Vulnerability to confidentiality attacks • Lack of common standards and legal frameworks, • Disruptions in the food supply chain, • Negative impacts on environment, • Gap between laboratory-scale research and real-time applications.	Sustainable and resilient food systems
(Chataut et al., 2023)	Sensors	Systematic Literature Search	• Precision farming and resource optimization, • Improved crop yields and quality, • Reduced environmental impact.	• Lack of standardization and interoperability among IoT devices and platforms, • Limited availability of reliable and affordable IoT sensors and devices, • Data privacy and security concerns, • Limited technical expertise and knowledge	Data analytics Precision agriculture practices Decision-making

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Chataut et al., 2023)	Sensors	Systematic Literature Search	• Precision farming and resource optimization, • Improved crop yields and quality, • Reduced environmental impact.	• Lack of standardization and interoperability among IoT devices and platforms, • Limited availability of reliable and affordable IoT sensors and devices, • Data privacy and security concerns, • Limited technical expertise and knowledge.	Data analytics Precision agriculture practices Decision-making
(Derakhti et al., 2023)	Sustainability	Systematic Literature Review (SLR)	• Enhanced security, transparency, and traceability aligned with SDGs • Improved efficiency and productivity, • Augmented supply chain visibility and real-time KPI monitoring, • Informed decision-making through data analytics and predictive modeling, • Minimized waste and environmental impact.	• Lack of clear understanding and consensus on what I4.0 is and its extensions. • Complexity of integrating new technologies with existing systems, • High implementation and maintenance costs, • Shortage of skilled labor and expertise, • Need for data standardization and interoperability.	Agri-food supply chain

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Senturk et al., 2023)	Journal of Cleaner Production	General Overview	• Increased productivity and efficiency, • Improved resource management, • Enhanced quality control and traceability, • Reduced waste and environmental impact, • Better decision-making through data, analytics.	• High initial investment costs, • Limited availability of skilled labor, • Data privacy and security concerns, • Interoperability issues, • Dependence on technology and potential loss of traditional knowledge and skills, • Ethical concerns related to the use of automation and artificial intelligence in agriculture.	Agriculture and Food Chains
(D. Garg & Alam, 2023)	Journal of Management Analytics	Literature Collection, Descriptive Analysis, Category Selection, and Literature Analysis	• Solving issues related to irrigation, pest control, crop development, and weather prediction, • Utilizing transparent AI for monitoring crop growth, evaluating crop health, and managing pests and diseases.	• Challenges related to data quality, • Expenses associated with smart systems, • Limited comprehension of digital technology and its application in agricultural digitization, • Potential complications when employing ICT technologies in farming, including issues like inadequate irrigation, weed management, and crop yields.	Not specified

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Peladarinos et al., 2023)	Sensors	Systematic Process of Narrowing Down References Based on Specific Criteria and Keywords	• Informed decision-making, • Boosted productivity and profits, • Improved sustainability, • Innovation and expansion.	• Skill Gaps, • Costly Implementation, • Complexity Challenges, • Security Measures, • Connectivity Issues, • Connectivity and mobility, • Ethical Considerations.	Precision agriculture Precision irrigation Precision livestock farming
(Hassoun, Marvin, et al., 2023)	Frontiers in Sustainable Food Systems	Comprehensive Overview	• Fosters precision farming and smart factories, • Strengthens resilient and sustainable food supply chains, • Offers enhanced precision in automated systems, • Robots and drones address labor shortages due to events like the COVID-19 pandemic and global conflicts.	• Substantial costs and investments required, • Inadequate infrastructure poses challenges, • Integrating systems into decision-makers' routines, • Regional socio-economic and political factors affect tech adoption, • Conservative food industry culture and silo mentalities can hinder tech acceptance and collaboration.	Not specified

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Hassoun, Marvin, et al., 2023)	Frontiers in Sustainable Food Systems	Comprehensive Overview	• Fosters precision farming and smart factories, • Strengthens resilient and sustainable food supply chains, • Offers enhanced precision in automated systems, • Robots and drones address labor shortages due to events like the COVID-19 pandemic and global conflicts.	• Substantial costs and investments required, • Inadequate infrastructure poses challenges, • Integrating systems into decision-makers' routines, • Regional socio-economic and political factors affect tech adoption, • Conservative food industry culture and silo mentalities can hinder tech acceptance and collaboration.	Not specified
(Dionisio et al., 2023)	Environment, Development and Sustainability	Systematic Review	• Improved efficiency and productivity, • Optimized irrigation and fertilization, • Reduced waste, • Customized tools and equipment, • Reduced costs, • Increased yields, • Improved sustainability of agricultural practices.	• Significant investment in infrastructure, training, and data management may be required, • Concerns around data privacy and security, • Potential job displacement due to increased automation.	Not specified

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Iñiguez-Moreno et al., 2023)	Biomass, Biofuels, Biochemicals	Comprehensive Overview	• Enhanced efficiency, precision, and sustainability, • Real-time decision-making, • Improved productivity, flexibility, and agility, • Analyzing complex relationships in extraction processes, • Identifying optimal extraction conditions.	• Limited awareness among consumers and industry stakeholders, • Technical challenges in optimizing extraction and processing methods, • The need for standardized quality control and regulatory frameworks, • High cost of manufacturing, • Lack of thorough research on nanofibers.	Agro-waste biopolymer production for food industry applications
(Djekić et al., 2023)	Food Engineering Reviews	Comprehensive Overview	• Enhanced food quality and safety, • Minimized waste and pollution, • Optimized supply chain management and logistics, • Augmented transparency and accountability in the food supply chain, • Boosted consumer trust, • Informed decision-making through data analysis and new insights.	• Small and medium-sized food companies face knowledge and resource limitations, • Issues include dataset interoperability, trust, and innovation value, • A skills gap and lack of knowledge, • Cyber threats and data breaches are potential risks, • Change resistance and limited awareness of I4.0 benefits persist.	Not specified

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Boz & Martin-Ryals, 2023)	Journal of the ASABE	Scoping Literature Review	• Enhanced efficiency and reduced resource consumption, waste, and emissions, • Improved traceability and carbon footprint analysis, • Minimized lead times and costs, • Increased customization, productivity, and flexibility in operations.	• Technological barriers, • Policy-related challenges, • Economic challenges, • Cultural acceptance challenges, • Workforce training challenges.	Circular economy in the agri-food industry
(Y. Chen et al., 2022)	Information Systems Frontiers	General Overview	• Enhanced agri-food supply chain efficiency and quality management, • Improved food traceability and waste reduction, • Increased productivity and cost savings via precision agriculture, • Enhanced transparency and trust in the supply chain, • Strengthened data security and privacy in agricultural transactions, • Improved collaboration among agricultural stakeholders.	• Limited awareness of Blockchain among agricultural stakeholders, • High implementation costs and tech expertise gaps, • Issues with Blockchain platform interoperability, • Data privacy and security concerns, especially with sensitive agricultural data, • Legal and regulatory challenges in Blockchain adoption, • Stakeholder resistance to change and technology adoption.	Blockchain technology

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Slob & Hurst, 2022)	Smart Cities	SLR	• Improved efficiency and productivity, • Reduced costs, • Increased sustainability, • Improved decision-making through real-time data analysis, • Enhanced crop quality and yield, • Better resource management.	• High initial investment costs, • Limited availability of skilled, • Data privacy and security concerns, • Dependence on reliable internet connectivity, • Integration challenges with existing systems, • Potential for increased complexity and reduced transparency.	Digital Twins Agricultural Greenhouse
(Bersani et al., 2022)	Energies	SLR	• Enhanced production efficiency and crop resilience, • Real-time monitoring and data collection, • Efficient control of indoor parameters, • Improved energy efficiency, production, throughput, and productivity, • Predictive maintenance and anomaly detection.	• Data privacy and security concerns, • Lack of standardization in IoT devices and protocols, • Integration of different IoT systems and platforms, • Limited availability of a skilled workforce for IoT implementation, • Compatibility issues between different IoT devices and systems.	IoT approaches Monitoring and Control of Smart Greenhouses

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(R. Singh et al., 2022)	Applied Sciences	General Overview	• Sustainable, real-time intelligent farming, • Increased yields with resource efficiency for a sustainable food supply, • Enhanced process automation and accuracy, • Integration of IoT, AI, blockchain, robotics, digital twins, and big data, • Advancing industrial agriculture into Horticulture 4.0.	• The short shelf-life of fruits and vegetables post-harvest, • Environmental challenges such as soil decline, global warming, land prices, water scarcity, and labor shortages, • Land and irrigation-water salinity concerns, • The need for sustainable pest management and marketing challenges, including market transparency.	Horticulture for Meeting Sustainable Farming
(Hassoun, Prieto, et al., 2022)	Food Research International	General Overview Expert analysis	• Enhancing agricultural waste utilization, • Elevating food quality, safety, and traceability, • Minimizing and repurposing food waste, • Innovating healthier food products, • Advancing smart food systems, • Promoting sustainable development and lean manufacturing.	• Insufficient digital infrastructure, skills, and investment, • Privacy and security concerns about data, • Limited tech access and knowledge in developing nations, • Possible adverse environmental effects of technology, • Ethical issues in technology use in food production.	Achieving sustainable development goals in food sector

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Yadav et al., 2022)	Computers & Industrial Engineering	SLR	• Improved agro-practice control and productivity with smart farming, • Elevated food safety and traceability via blockchain, • Meeting rising food demand through industrialization and supply chain enhancements, • Advancing sustainability and resilience through collaboration, • Reducing waste and enhancing resource efficiency.	• Unexplored technical feasibility, legal, privacy, and standardization challenges for blockchain, • Security concerns and interoperability issues in IoT systems, • Cost barriers, particularly for small-scale farmers, • Limited integration due to technological gaps, • Infrastructure development needed at a lower cost, • Low tech awareness and education among stakeholders.	Agricultural food supply chain
(Wójcicki et al., 2022)	Energies	Comprehensive Analysis	• Precise field control with satellite data, • Greenhouse process optimization, • Sensor-equipped digitized farms for decision support, • Enhanced traceability of agri-products.	• Budget and staff constraints for IoT adoption, • Challenges in talent acquisition, • Information security and privacy concerns, • Barriers to faster IoT diffusion, • Potential implementation and operational errors.	Not specified

Author(s)	**Publication**	**Methodology**	**Benefits**	**Challenges/Risks**	**Focused Area**
(Hassoun, Boukid, et al., 2022)	Current Research in Food Science	Comprehensive Overview	• IoT boosts crop productivity and precision in agri-operations, • Smart food factories cut costs and enhance efficiency, • Smart sensors elevate food safety and quality, • IoT supports a shift toward sustainable diets, • Blockchain improves supply chain management and traceability.	• High investment and skills needed for tech implementation, • Stakeholder resistance to change, • Lack of tech standardization and interoperability, • Cybersecurity risks with digital tech use, • Automation leading to job displacement and inequality.	Agri-food sector
(M. Singh et al., 2022)	Applied Sciences	Comprehensive Review	• Enhanced farming productivity and efficiency, • Informed decisions through intelligent data analysis, • Sustainability promotion through environmental tracking, • Reduced resource consumption. • Improved crop quality and yields, • Enhanced livestock and farm management.	• High upfront costs, • Limited tech awareness among stakeholders, • Skill shortage for tech operation, • Data privacy and security worries, • Integration hurdles with existing systems.	Digital Twin Agriculture Sector

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Sott et al., 2021)	Sensors	Bibliometric Network Analysis	• Enhanced agricultural efficiency, • Improved data traceability, • Strengthened sustainability and integration, • Addressed global productivity and cost concerns, • Ensured food safety and environmental protection.	• Technical adaptation challenges, • Diversity in agricultural factors, • Economic growth vs. sustainability dilemma, • Infrastructure and training investments required, • Risk of agricultural monopolies favoring large farms.	Digital Agriculture
(Javaid et al., 2021)	Sensors International	Comprehensive Overview	• Enhanced Resource Management, • Early Problem Detection, • Real-time Efficiency, • Data-Driven Decision-Making, • Safety and Competitiveness.	• Resistance to change or lack of awareness of the potential benefits of sensor technology among farmers, • Concerns about data privacy and security, • High cost of sensors and associated infrastructure, • Need for specialized technical expertise to install and maintain sensors.	Sensors in agriculture

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Shu et al., 2021)	IEEE Transactions on Industrial Informatics	Comprehensive Overview	• Enhanced Agricultural Efficiency • Informed Decision-Making with Data Analytics, • Elevated Food Safety and Traceability via Blockchain, • Sustainable Farming for Reduced Environmental Footprint, • Augmented Farmer Profitability through Efficiency and Yield Gains.	• High initial investment costs, • Limited skilled labor and expertise, • Data privacy and security concerns, • Lack of technology standardization, • Resistance to technological change.	Precision agriculture
(Bongomin et al., 2020)	Journal of Engineering	Literature Search	• Increased efficiency and productivity, • Improved decision-making through real-time data analysis and predictive analytics, • Enhanced food safety and traceability, • Reduced environmental impact through precision farming and resource management, • Addressing challenges facing the agriculture sector, such as labor shortages, climate change, and food security.	• High initial investment costs and ongoing maintenance expenses, • Lack of digital infrastructure and connectivity in rural areas, • Limited availability of skilled labor and expertise in digital technologies, • Concerns around data privacy and security, • Ethical considerations around the use of AI and automation in agriculture.	I4.0 in industrial sectors

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Lezoche et al., 2020)	Computers in Industry	Literature Review	• Improved supply chain management with real-time data processing, • Enhanced efficiency, productivity, and sustainability, • Advanced data collection using sensors and drones, • Informed decision-making for farmers, • Sustainable, competitive products through supply chain co-innovation.	• Limited capital for IoT investment, • Shortage of technical skills among farmers, • Resistance to new technologies, • Unclear data governance, • Challenges related to blockchain decentralization, • Complex big data analytics, • Rural connectivity limitations.	Agricultural food supply chain
(Klerkx & Rose, 2020)	Global Food Security	Critical Analysis	• Diagnostic technology for data analysis, • Decision support tools, • Precision agriculture.	• Ingrained habits and lack of operating skills among farmers, • High implementation costs, • Diverging expectations between experts and farmers, • Difficulty in foreseeing the consequences of large-scale technology adoption, • The need for responsible, inclusive transitions in technology adoption.	Agriculture Food systems

Author(s)	Publication	Methodology	Benefits	Challenges/Risks	Focused Area
(Romeo et al., 2020)	Sensors	Comprehensive Overview	• Increased productivity, quality, and profitability, • Sustainability benefits such as wildlife conservation, carbon storage, and flood protection enabled by data analysis from IoT systems and mobile robots combined with cloud computing, • Enhanced product quality and quantity by leveraging the expertise of robotic systems in agriculture.	• Incomplete development of IoRT applications for real-world industrial use, • Need for effective cooperation between robots and humans in smart environments. • Significant investment required for workforce training and education to adapt to new technologies, • Infrastructure investment challenges, • Ethical concerns regarding the impact on employment, privacy, and security when implementing IoRT systems in agriculture.	Internet of Robotic Things Agriculture
(Kodan et al., 2020)	Food Reviews International	Comprehensive Overview	• Increased production and crop yields, • Real-time data and production insights, • Lowered operation costs, • Improved quality of production, • Accurate farm and field evaluation.	• High initial investment costs, • Limited access to technology and infrastructure in rural areas,Data privacy and security concerns, • Lack of standardization and interoperability among different systems and devices, • Resistance to change and lack of awareness or understanding of the benefits of new technology.	IoT Food sector

2.2.2 Analysis of I4.0 and Agriculture Review

In this section, the thesis conducts an analysis of the review and conceptual papers included in our study. The highly emphasized benefits and challenges are extracted from the previously created **Table 2.3**, transforming the list into a text file. Subsequently, the MonkeyLearn WordCloud Generator[1] is employed to construct word clouds based on the relevance and frequency of words within the text. The resulting figures illustrate the prominent benefits and challenges outlined in the literature pertaining to agriculture and I4.0 (**Figure 2.2**)

Figure 2.2: Word cloud for benefits of using I4.0 technologies in agriculture.

The period from 2020 to 2023 witnessed a visible emphasis in the literature on the intersection of I4.0 and agriculture, with particular attention given to key concepts shaping this dynamic relationship. Notably, the recurring themes of productivity, efficiency, sustainability, traceability, and decision-making emerged as focal points in conceptual and review studies during this timeframe. This thematic prevalence underscores the strategic priorities and overarching goals within the incorporation of I4.0 technologies and agriculture.

[1] https://monkeylearn.com/word-cloud/

Productivity: In the period spanning 2020 to 2023, the nexus between I4.0 and agriculture prominently accentuated the dimension of *productivity*. Technological advancements during this era have been strategically leveraged to augment agricultural output and efficiency (Bongomin et al., 2020; Lezoche et al., 2020). Innovations such as PA and smart farming practices, enabled by sensors, IoT, and ML algorithms, have played pivotal roles in optimizing resource utilization and fostering higher yields (Jawad et al., 2017; Peladarinos et al., 2023; Shu et al., 2021; Q. Zhang, 2023). This emphasis on productivity underscores a collective pursuit to meet the escalating demands of a growing global population while ensuring sustainable agricultural practices (Shu et al., 2021).

Efficiency: Automation, data analytics, and robotics have emerged as key enablers, streamlining various agricultural processes (Derakhti et al., 2023; Hassoun, Aït-Kaddour, et al., 2023; R. Singh et al., 2022). From automated harvesting techniques (Hassoun, Marvin, et al., 2023) to precision irrigation systems (Peladarinos et al., 2023), these advancements seek to minimize resource wastage and operational inefficiencies. The collective goal has been to forge a more resource-efficient and economically viable agricultural sector, aligning with the principles of I4.0 (Shu et al., 2021).

Sustainability: A heightened awareness of environmental impact and climate concerns has propelled the integration of sustainable practices in agriculture (Hassoun, Marvin, et al., 2023; Hassoun, Prieto, et al., 2022; Shu et al., 2021). Technologies such as IoT-driven soil monitoring, renewable energy applications, and eco-friendly precision farming have emerged as catalysts in fostering agricultural sustainability (Bersani et al., 2022). This alignment underscores a conscientious effort to balance agricultural productivity with ecological responsibility, ensuring the resilience of farming practices for future generations.

Traceability: Blockchain technology, RFID systems, and advanced sensors have been instrumental in establishing transparent and traceable supply chains in agriculture (Ellahi et al., 2023). From farm to fork, these technologies enable precise tracking of agricultural products, ensuring authenticity, quality, and safety (Djekić et al., 2023). The heightened focus on traceability reflects a commitment to meet consumer demands for transparency while addressing concerns related to food safety and authenticity.

Decision-making: Advanced DAs, ML, and AI have empowered farmers and stakeholders with real-time insights for informed decision-making (Bongomin et al., 2020; Klerkx & Rose, 2020). From predicting optimal planting times to disease outbreak forecasts, these technologies have become indispensable tools in enhancing the agility and responsiveness of agricultural operations (Sott et al., 2021). The era underscores a shift toward data-driven decision-making (Alfred et al., 2021), fostering a more resilient and adaptive agricultural ecosystem.

The integration of I4.0 technologies into agriculture brings numerous benefits, but the review highlights key challenges: data privacy, security concerns, and a shortage of skilled labor, restricted technology access and elevated investment cost ranked by their frequency in the literature **(Figure 2.3)**.

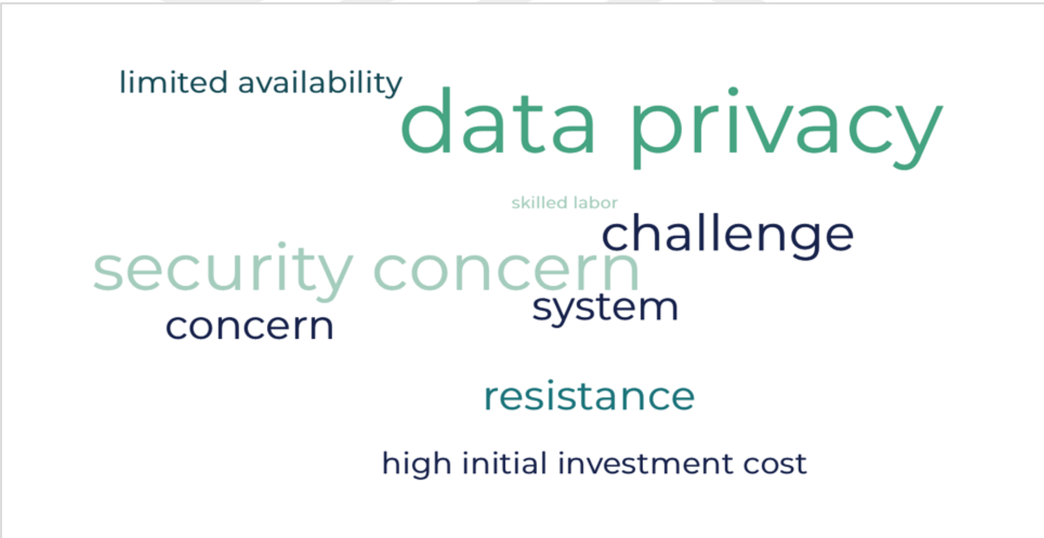

Figure 2.3: Word cloud for challenges of using I4.0 technologies in agriculture.

Data Privacy: The extensive utilization of IoT devices, sensors, and DAs in agriculture generates vast amounts of sensitive information (Javaid et al., 2021; Kodan et al., 2020; Shu et al., 2021). Safeguarding this data from unauthorized access and ensuring compliance with privacy regulations emerge as critical considerations (Slob & Hurst, 2022).

Security Concerns: The interconnected nature of SA systems and the reliance on digital platforms expose agricultural operations to potential cybersecurity threats (Hassoun, Boukid, et al., 2022). Safeguarding against data breaches, system vulnerabilities, and malicious attacks becomes imperative.

Shortage of Skilled Labor: The adoption of advanced technologies such as robotics, automation, and data analytics demands a workforce proficient in managing and leveraging these tools (Derakhti et al., 2023; Senturk et al., 2023). Addressing the gap in skill sets becomes crucial to realizing the full potential of Industry 4.0 in agriculture.

Restricted Technology Access: Access to cutting-edge technologies can be constrained by factors such as geographic location, economic disparities, and infrastructure limitations (Derakhti et al., 2023; Kodan et al., 2020). Ensuring equitable access to I4.0 innovations across diverse agricultural settings becomes a challenge.

Elevated Investment Cost: Acquiring and implementing technologies such as precision farming equipment, robotics, and advanced sensing systems can pose financial challenges for agricultural stakeholders (Yadav et al., 2022). Striking a balance between the potential long-term benefits and the immediate investment costs becomes pivotal in ensuring widespread adoption and sustainability in the agricultural sector (Klerkx & Rose, 2020).

In the dynamic landscape between 2020 and 2023, the intertwining of I4.0 technologies and agriculture unfolded a dual narrative. On one hand, the synergy yielded tangible benefits, elevating productivity, efficiency, sustainability, traceability, and decision-making. On the other, inherent challenges emerged, ranging from data privacy and security concerns to restricted technology access, elevated investment costs, and the persistent shortage of skilled labor. This symbiotic relationship underscores the imperative for a nuanced and balanced approach, recognizing that addressing challenges is essential to fully unlock the transformative potential and reap the benefits of I4.0 in the agricultural domain (Masram & Patkar, 2021).

In the forthcoming section, thesis will delve into studies centered around SA, with a particular focus on the pivotal I4.0 technologies that have garnered prominence and emphasis in the contemporary era.

2.2.3 SA and I4.0 Technologies Review

As previously defined, SA signifies the progressive phase of mechanization within PA, where I4.0 technologies play a pivotal role (Q. Zhang, 2023). In this section of the review, we will systematically assess the current status of I4.0 technologies in the context of SA studies, with particular emphasis on the years between 2020 and 2023 (November). To ensure a comprehensive analysis, we have organized the studies into distinct groups based on the stages of the agricultural value chain: Production & Processing, Distribution & Retailing, and Consumption & Recycling (Deloitte, 2020).

This categorization serves a dual purpose. First, it aligns with the natural progression of agricultural activities, offering a structured lens through which to examine the impact of I4.0 technologies across the various phases of the value chain (Djanian & Ferreira, 2020). Plus, it allows for an in-depth understanding of the dynamic role of I4.0 technologies in shaping the trajectory of agricultural products.

The following tables (**Table 2.4**, **Table 2.5** and **Table 2.6**) provide a detailed overview of the studies related to the Production & Processing, Distribution & Retailing, and Consumption & Recycling stages of the agricultural value chain. These tables categorize the studies according to their type (review, analytical study, conceptual study or proceeding), their primary objectives, the specific I4.0 technologies emphasized, and the intended purpose of using these technologies and opportunities.

Table 2.4: Studies related to Production & Processing stages in SA.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Prabha & Pathak, 2023)	Proceedings Paper	Assessing target information recognition systems and IoT's role in precision agriculture, with a focus on enhancing farming efficiency, attracting tech-savvy individuals to agriculture, and meeting future agricultural expectations.	IoT, sensors, drones (UAVs), robotics, AI, ML, blockchain, and automation.	Optimizing crop yields, reducing costs, and addressing ethical, social, and environmental concerns.	Precision agriculture for resource efficiency and sustainability, data-driven crop management and automation, enhancing food supply chain traceability and farmer business growth.
(Yépez-Ponce et al., 2023)	Conceptual	Providing an overview of mobile robotics in agriculture, including current applications, challenges, future trends, and conclusions.	Blockchain, Digital Twin, Robotics, WSNs (wireless sensor networks)	Gathering data, improve decision-making, optimizing resource usage, and reducing environmental impact in PA.	Digital twins and simulation for optimized robot-based production, blockchain for supply chain traceability, transparency, IoT, sensor networks, and multi-objective planning for PA and data integration.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Pokhariyal et al., 2023)	Review	Systematically reviewing the utilization of machine learning and remote sensing in Indian agriculture, specifically focusing on crop, water, and soil management.	ML, Sensors, automatic data recording, satellite datasets, UAVs, and decision support systems (DSSs)	Monitoring crop production to feed a growing population, choosing economically viable activities, reducing negative environmental impacts, establishing smart, sustainable, and lucrative farming systems.	Non-destructive data acquisition, offering valuable insights for agricultural management, processing vast data beyond manual capacity. Increasing accessibility and understanding among farmers. Smartly managing Indian agriculture for sustainability.
(Atalla et al., 2023)	Analytical	Proposing a framework for integrating IoT systems in precision agriculture applications.	IoT, Sensors, Satellite imaginary, ML algorithms	Improve production yield, quality, and efficiency, as well as to optimize the entire farming process chain.	Offering comprehensive crop and environmental insights with greater detail and accuracy, advancing PA with efficient monitoring and management.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Revathi et al., 2022)	Analytical	Creating a drone that regularly monitors a designated area for field conditions, crop growth, and weather conditions.	IoT, Sensors, UAVs	Smart irrigation, crop monitoring, weather forecasting.	Increased productivity. reduced costs, improved crop quality, better decision-making, and sustainable agriculture.
(W. Zhu et al., 2022)	Analytical	Identifying the most informative UAV-based indicators for monitoring crop growth variables and assess their appropriateness.	UAVs, Sensors	Field-scale crop monitoring and PA	Improved crop yield and resource use efficiency, reduced costs and increased efficiency.
(Goh et al., 2022)	Analytical	Establishing a theoretical foundation for a winter wheat agronomy service's crop growth monitoring system.	Remote sensing, DAs	Crop monitoring, provide reliable information for timely crop management to achieve optimum crop production.	Efficient non-destructive method to retrieve crop properties, thorough monitoring of crop growth conditions, reliable information for timely crop management.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Goh et al., 2022)	Analytical	Establishing a theoretical foundation for a winter wheat agronomy service's crop growth monitoring system.	Remote sensing, DAs	Crop monitoring, provide reliable information for timely crop management to achieve optimum crop production.	Efficient non-destructive method to retrieve crop biophysical properties, thorough monitoring of crop growth conditions, objective, and reproducible reflection of changes in crop biophysical properties, reliable information for timely crop management.
(Banerjee et al., 2022)	Analytical	Developing and using an integrated ground-based sensor for non-destructive estimation of plant biomass and height in wheat crops.	Sensors, IoT, single-board computer (SBC) technology.	In-field crop height and biomass measurements, real-time decision-making with a high level of automation.	plant phenotyping and agriculture research, high levels of automation in agriculture for efficiency and productivity.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Vulpi et al., 2022)	Analytical	Developing and test a cost-effective multi-view RGB-D sensing device for in-field proximal monitoring of high-value crops.	Sensors, ML algorithms	Supplying precise, enabling PA practices, supporting autonomous driving, identifying, and mapping anomalies.	Improved crop yields, reduced costs, and increased efficiency.
(Cravero et al., 2022)	Review	Analyzing the challenges of using ML for data analysis in agricultural big data and proposing a framework that summarizes these challenges.	Big Data analytics, ML, Cloud computing, IoT, Cyber-physical systems (CPS), AI	Crop monitoring for health, enhance the quality of agricultural products, optimize resource use, improve supply chain management.	Increased yields and profits, reduced waste and environmental impact, improved decision-making based on data-driven insights, enhanced food safety and quality, improved access to information and resources for farmers.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Montilla et al., 2021)	Analytical	Assessing the effectiveness of PA techniques to provide farmers with relevant information to improve crop management and increase yields in rice crops.	NDVI-health maps, 2D, DEM, and 3D maps, UAVs, Satellite image technology	Monitor crop health and detect problematic areas in rice crops.	Ability to acquire and process a large amount of crop data in a short time, informed decisions about crop management, help farmers to optimize their use of resources.
(Dutta & Mitra, 2021)	Book Chapter	Investigating how smart farming enhances crop management through data-driven approaches and IoT technology.	IoT, WSN, AI	Enhance productive crop management, efficiency, Nutrients management, and automation.	Improving crop management, enhancing data management for efficiency, surveillance, and monitoring.
(Pandya et al., 2021)	Proceedings Paper	Seeking to discover research gaps, analyze current technology-driven PA methods.	IoT, AI-based agricultural analytics, cloud computing, and WSN	Automation, enhanced decision-making, PA, efficiency, data management, security.	Automation, Enhanced crop and irrigation efficiency, Real-time Environmental Data.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Benos et al., 2021)	Review	Aiming to guide stakeholders in recognizing the benefits of machine learning in agriculture and fostering systematic research in this area.	Remote sensing technologies, IoT, AI and ML algorithms, Robotics, and automation	Monitor crop growth and health, detect pests and diseases, optimize irrigation and fertilization, real-time data on soil, identify patterns and trends in large datasets.	Improved sustainability, better decision-making, enhanced food safety and quality.
(Gsangaya et al., 2020)	Analytical	Creating an advanced system for remote environmental parameter monitoring in agriculture fields, offering real-time alerts and data storage for future reference.	Sensors, IoT, Cloud Computing (CC)	Enhance remote environmental parameter monitoring in agriculture fields, offering real-time alerts, information, and data storage for future use.	Reduced running cost and workload, Automated irrigation systems in the field, Improved crop productivity.

Author(s)	Type	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(L. García et al., 2020)	Analytical	Suggesting employing remote sensing drones as a mobile gateway for Wireless Sensor Networks (WSN) in precision agriculture.	WSN, UAVs, IoT, Big data analytics	Improve crop management and increase agricultural productivity through the collection and analysis of data.	Improved crop monitoring, Increased efficiency, Cost savings, Sustainability, New business opportunities.
(Segarra et al., 2020)	Review	Outlining Sentinel-2's enhanced features and applications in agriculture	Geospatial Technologies	Land monitoring, crop stress detection, yield forecasting, optimization of fertilization, irrigation, and soil tilling activities.	Optimizing agricultural practices, a short revisit time for frequent land cover monitoring, support economic and ecological sustainability.
(de Queiroz et al., 2020)	Conceptual	Offering a comprehensive view of agricultural sensors for soil, plant, and crop yield monitoring and investigate remote sensing applications in crop management.	Sensors	monitoring soil attributes, detecting the presence of weeds, mapping crop yields.	Improving crop yields, reducing resource waste, increasing efficiency in farming practices.

Table 2.5: Studies related to Distribution & Retailing stages in SA.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Lv et al., 2023)	Conceptual	Providing a comprehensive overview of the application research work of agricultural product traceability based on blockchain technology in recent years.	Blockchain, deep neural network-based models, IoT sensor devices, LoRa (Long Range) technologies	Ensure end-to-end product traceability, enable direct farmer-distributor communication, reducing reliance on intermediaries and fostering trust, enhance efficiency, minimize risks, and lower costs related to recalls, fraud, and losses in the food supply chain.	Blockchain for food traceability and brand trust, IoT and machine learning for precise crop management, LoRa and edge computing for enhanced security and sustainability, blockchain for end-to-end traceability, product protection, and transparency.
(Jiao et al., 2022)	Proceedings Paper	Enhancing the safety and quality of green agricultural products using item coding technology and blockchain.	Blockchain, Item coding, information technologies	Enhance product traceability, ensure product safety and quality, increase market visibility and recognition.	Improved product safety, enhanced product quality, market credibility and SA Big Data projects.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(V. Sharma et al., 2022)	Review	Systematically reviewing the technologies and applications in smart farming, explore their potential benefits, and analyze research on emerging technologies, classifications, challenges, and future research directions within this field.	ML, DL, swarm intelligence, IoT, blockchain, generative adversarial networks (GAN), robotics and autonomous systems.	Enhancing agricultural productivity and efficiency, improving decision-making processes in farming operations, facilitating automation and autonomous operations in farming.	Supply chain traceability and transparency through blockchain technology, automation of repetitive tasks through robotics and autonomous systems, real-time monitoring, and control of agricultural processes.
(Akella et al., 2021)	Proceedings Paper	Creating a decentralized blockchain architecture for smart and sustainable agriculture, aiming to minimize intermediaries and enhance supply value chains.	Blockchain technology, Smart contracts, IoT	information asymmetry, traceability, and provenance, support PA and enable secure and automated transactions, enable the integration of physical devices and sensors with blockchain technology.	Robust processing of transactions, reducing intermediaries and payment delays, increasing secured transactions, enhancing finance and insurance services, improving traceability and authenticity in agricultural products.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Visconti et al., 2020)	Analytical	Presenting the development of a Sensors-Based Agri-Food Traceability System Remotely Managed by a Software Platform for Optimized Farm Management.	IoT technologies, WSNs, ESP8266 NodeMCU module, Bluetooth Low Energy (BLE) technology	Optimize farm management, improve crop monitoring, and provide traceability of agri-food products.	Product traceability throughout the supply chain, improved product quality certification for consumers, economic benefits for farmers through efficient distribution and customer satisfaction.
(Corallo et al., 2020)	Proceedings Paper	Discussing the application of the logical model to all phases of the supply chain in the agri-food sector, specifically focusing on the efficiency of the organizational distribution at a local scale.	Big Data, Analytics, IoT, Computing technologies, and Sensors	Increase efficiency, improve accuracy, enhance traceability, and provide real-time monitoring and guidance in the production system.	Need for low-cost and pervasive connectivity, improvement in storage and data exchange, innovative business models and partnerships, application for agricultural information services.

Table 2.6: Studies related to Consumption and Recycling stages in SA.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(A. Singh et al., 2022)	Review	Investigating how deep learning and machine learning can more efficiently reduce postharvest losses for different fruits and vegetables.	DL algorithms, ML models and frameworks, Modified algorithms, RFID technology, IoT sensors	Improving the quality management of fruits and vegetables, tracing the condition of materials during transportation, identifying diseases and rotten fruits, monitoring humidity and temperature during the food supply chain process.	Enhancing food quality management and safety, improving supply chain efficiency, and reducing waste, enabling real-time monitoring, and tracking of perishable goods during transportation, optimizing resource allocation and inventory management in the food supply chain.
(Peng et al., 2022)	Analytical	Developing and test a refined supervision model for the rice supply chain using multi-blockchain technology.	Blockchain, Neural network algorithms, big data technology.	Promote the refined management of products and food, ensure the quality and safety, and enhance the transparency and traceability.	Improving the supervision and management of agricultural products information, ensuring the quality and safety, building trust.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Martos et al., 2021)	Review	Discussing the role of remote sensing technology in ensuring agricultural sustainability in the era of Agriculture 5.0.	Remote sensing technology, WSNs, Wi-Fi, RFID, Satellites, Sensors, AI	Monitoring and analyzing agricultural landscapes, collecting data, providing wide-area coverage and high-resolution imagery for monitoring crop growth, land use, and environmental changes.	Environmental monitoring for environmental impacts, data-driven decision-making, sustainable resource management.
(Sivakumar et al., 2021)	Proceedings Paper	Implementation of I4.0 technologies in agriculture, specifically focusing on Climate Smart Agriculture and Food Security.	IoT, CPSs, Distributed Ledger Technology (DLT), Optical sensors	Enable data collection, integrate computational and physical processes to enhance agricultural operations, enhance transparency and traceability in the food supply chain.	Water conservation, protection of farmer's health, increased productivity, food safety, supply chain transparency, strengthening the connection between urban and rural areas.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(Agrimonti et al., 2021)	Conceptual	Discussing the impact of climate change on crop plants and the food industry, and to explore how SA can help maintain food quality in the face of these challenges.	PA techniques, automated optical sensing, and intelligent planning options	Automated optical sensing, and intelligent planning options is to address the impact of climate change on agriculture and food quality.	Maximize crop yields and address field variability through PA and real-time data integration, prevent diseases, ensure plant health, and enhance food safety, improve fertilizer efficiency, ensure food quality and safety, and adapt to climate change impacts with traceability and data-driven insights.

Author(s)	Types	Objectives	I4.0 Technologies	Technologies' Purpose of use	Opportunities
(R. García et al., 2020)	Review	Presenting a SLR on the applications of ML algorithms in the context of sustainable agriculture supply chain (ASC) performance.	ML, Big data analytics, CC, blockchain	Monitoring and analyzing agricultural landscapes, enabling wireless communication and data transfer for real-time monitoring and control of agricultural processes.	PA, Environmental Monitoring, Data-Driven Decision Making: Integrating remote sensing and AI for predictive analytics, risk assessment, and sustainable resource management in agriculture.

The review results highlight the distinct roles and impacts of I4.0 technologies across the stages of the agricultural value chain. In the *Production & Processing* stage, the focus on crop monitoring using technologies like IoT, UAVs, and ML algorithms underscores the potential for real-time insights and predictive analytics to enhance yield, resource efficiency, and overall sustainability (Atalla et al., 2023; L. García et al., 2020; Goh et al., 2022). This aligns with the common understanding that precision monitoring and data-driven decision-making are crucial for optimizing agricultural production (Kamble et al., 2020).

Moving to the *Distribution & Retailing* stage, the emphasis on Blockchain and IoT reflects the critical need for trust, transparency, and traceability in the agricultural supply chain (Akella et al., 2021; Lv et al., 2023; Peng et al., 2022). These technologies play a central role in ensuring product quality and safety, addressing key concerns in distribution and retailing [94]. This aligns with the well-established importance of supply chain visibility (Jiao et al., 2022) and consumer confidence (Corallo et al., 2020) in the agri-food sector.

In the *Consumption & Recycling* stage, the recurrent features of remote sensing, IoT, and blockchain point to a shift towards overarching sustainable agriculture approaches (Martos et al., 2021). This aligns with the broader trend in agriculture towards more holistic and environmentally conscious practices (Alreshidi, 2019), addressing considerations beyond production and distribution to encompass the entire agricultural lifecycle.

In the subsequent stage, an exploration beyond academic databases involves the inclusion of grey literature to enrich the understanding of SA and I4.0 technologies (**Table 2.7**). The incorporation of grey literature aims to establish a bridge between academic perspectives and real-world applications or trends. This phase entails a meticulous review of non-peer-reviewed sources, with a specific focus on reports retrieved from the Google Search engine. The search criteria employed involve querying major industry players, commonly referred to as the Big 4 companies (Deloitte, PricewaterhouseCoopers (PwC), Ernst & Young (EY), KPMG) and others (McKinsey & Company, The Boston Consulting Group (BCG)) using the terms "smart agriculture" AND "industry 4.0 technologies." This process, conducted with a temporal focus on reports spanning from 2020 to 2023 (November), provides a broader contextualization by incorporating insights from industry reports and trends alongside academic discourse.

Table 2.7: Industrial reports about SA and its technologies.

Source	Objective	Focused Area and I4.0 Technologies
(Vezbergien et al., 2023)	Providing insights into the innovative changes happening in the food industry and practical solutions for food supply chains.	Advanced analytics for predicting harvesting, Smart harvesting using drones and sensors, IoT for predicting the size and quality of the harvest, Blockchain technology for traceability and transparency in the food supply chain
(Saran et al., 2023)	Exploring how digital technologies are transforming traditional manufacturing processes and creating new business models in various industries, including SA.	PA, Cloud-based farm management systems, AI and vision technology, Electric and self-driving farm equipment
(Bengston et al., 2023)	Highlighting the importance of sustainable farming for decarbonization and to provide guidance for food and agriculture organizations as they transition to increased sustainability	Remote sensing, robotics, autonomous vehicles, PA
(Ernst & Young, 2022)	Providing insights and analysis on the food and agriculture	IoT, Spatial geographic information systems (GIS), AI and

	industry, including trends, challenges, and opportunities.	data science, Blockchain, Automation
(Ruan et al., 2022)	Exploring how technology can help cut emissions and deliver carbon-neutral agriculture.	SA platforms, Data analytics, Connectivity, Automation, Farm management software, Farm robots and drones
(Deloitte, 2020)	Reviewing the importance of agriculture by defining its bounds with mega trends.	Robotics/Drones, Sensors, Cloud Computing, Blockchain AI catalyst
(McKinsey and Co., 2020)	Overview of the digital transformation in the agriculture sector.	IoT, Sensors, Automation, Connectivity

This synthesis encapsulates a nuanced analysis derived from industrial reports, a subset of the grey literature, providing a distinctive real-world perspective on the post-2019 era. The exploration of the food and agriculture industry's landscape, characterized by substantial technological maturation, delves into emergent trends, digital transformations, and sustainable farming practices. The regional focus on the European Union offers practical insights into policy-making and sustainable practices within this context (*Transforming Food Systems with Farmers: A Pathway for the EU*, 2022). The regional focus on the European Union provides practical insights into policy-making and sustainable practices, revealing a nexus between technological advancements and regulatory frameworks.

The emphasis on technology for carbon-neutral agriculture aligns with broader sustainability objectives, attesting to the pivotal role of technological solutions in addressing environmental concerns (Bengston et al., 2023). The dimension of defining agriculture's bounds with mega trends suggests an examination of how broader societal and environmental shifts shape the sector, emphasizing the interconnectedness of SA with larger contextual factors (Vezbergien et al., 2023). Addressing future food demand anticipates the challenges posed by population growth, accentuating the importance of advanced technologies and sustainable approaches.

In summation, although the synthesis offers valuable perspectives derived from industrial reports and grey literature, the inclusion of academic studies is imperative to enhance the depth and methodological rigor of the analysis pertaining to the intricate interplay between SA, I4.0 technologies, and their overarching implications within societal and environmental frameworks. In presenting the grey literature, we aim to bridge the gap between theoretical frameworks and real-world applications, thereby facilitating a holistic examination of the tangible outcomes and challenges associated with the integration of I4.0 technologies in agricultural contexts.

2.2.4 Analysis of SA and I4.0 Technologies Review

When it comes to reviewing SA and I4.0 technologies, certain technologies stand out in terms of frequency of appearance in research papers. We extract the highly emphasized technologies from the previously created **Tables 2.4- 2.6** transforming the list into a text file. Subsequently, we employ the MonkeyLearn WordCloud Generator[2] to construct word clouds based on the relevance and frequency of words within the text. The following **Figure 2.4**gives the list of technologies highly emphasized in the reviewed studies.

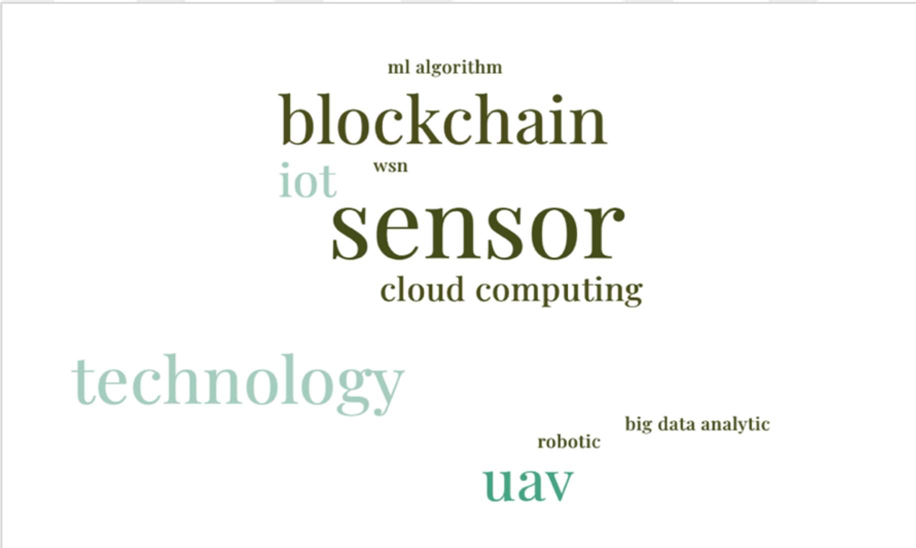

Figure 2.4: Word cloud for I4.0 technologies in SA.

SA and I4.0 technologies have gained increasing prominence, particularly in the post-2020. Research indicates that the utilization of technologies like sensors, blockchain,

[2] https://monkeylearn.com/word-cloud/

UAVs, IoT, cloud computing, big data analytics, ML algorithms, robotics, and WSN in agriculture holds the potential to address pressing challenges related to food security, safety, and traceability.

Sensors: The widespread use of sensors in agriculture during the 2020-2023 period reflects a concerted effort to gather real-time data on various parameters, enhancing precision farming practices (Banerjee et al., 2022; Pokhariyal et al., 2023). Sensors contribute to data-driven decision-making and enable proactive management by providing insights into crop conditions, soil health, and environmental factors (de Queiroz et al., 2020; Gsangaya et al., 2020).

Blockchain: The adoption of blockchain technology signifies a growing emphasis on trust, transparency, and traceability within the agricultural value chain (Corallo et al., 2020; Visconti et al., 2020). Blockchain applications in agriculture, particularly during 2020-2023, aim to ensure the integrity and authenticity of data related to product origin, quality, and distribution, bolstering consumer confidence (Akella et al., 2021).

UAVs (Drones): The increased utilization of UAVs or drones in agriculture points to advancements in remote sensing and crop monitoring (Revathi et al., 2022). Drones provide a bird's eye view, facilitating efficient and timely surveillance of large agricultural fields (W. Zhu et al., 2022). This technology aids farmers in making informed decisions related to crop health, pest control, and irrigation management (L. García et al., 2020; Yépez-Ponce et al., 2023).

IoT: The integration of IoT devices in agriculture during the specified timeframe underscores a networked approach to farm management (Prabha & Pathak, 2023). IoT enables the seamless connectivity (McKinsey and Co., 2020) of various devices, allowing for comprehensive data collection and analysis. This interconnectedness enhances automation, resource optimization, and overall operational efficiency in SA (Atalla et al., 2023).

Cloud Computing: The prominence of cloud computing technologies in agriculture aligns with the need for scalable and accessible data storage and processing solutions (Gsangaya et al., 2020; Pandya et al., 2021). Cloud platforms facilitate the aggregation of data from diverse sources, supporting analytics, and enabling collaborative decision-making in the agricultural domain (R. García et al., 2020).

Big Data Analytics: The emphasis on big data analytics signifies a focus on deriving meaningful insights from the vast datasets generated in agriculture (Cravero et al., 2022). During 2020-2023, the agricultural sector recognizes the value of data analytics in uncovering patterns, predicting trends, and optimizing farming practices for increased productivity and sustainability (Corallo et al., 2020; Jiao et al., 2022).

ML Algorithms: The integration of ML algorithms in agriculture suggests a move towards predictive analytics and autonomous decision-making (A. Singh et al., 2022). During the specified period, ML contributes to the development of intelligent systems capable of adapting to changing environmental conditions and optimizing agricultural processes (Cravero et al., 2022; Pokhariyal et al., 2023).

Robotics: Robotics in agriculture, as reflected in the 2020-2023 timeframe, points to advancements in automation and precision farming (Prabha & Pathak, 2023). Agricultural robots contribute to tasks such as planting, harvesting, and weed control, enhancing operational efficiency, and reducing manual labor requirements (Benos et al., 2021; Yépez-Ponce et al., 2023).

WSNs: The deployment of WSNs in agriculture indicates a focus on creating interconnected systems for data collection and communication (L. García et al., 2020). WSNs enhance the scalability of sensor networks, enabling efficient monitoring of large agricultural areas and facilitating real-time data transmission for improved decision support.

In conclusion, the analysis of emphasized technologies in SA during the 2020-2023 period reveals a concerted effort to integrate cutting-edge solutions for PA and sustainable practices (Abioye et al., 2020; Norhashim et al., 2023). The widespread adoption of sensors underscores a commitment to real-time data collection for informed decision-making. Blockchain technology emerges as a pivotal tool to ensure trust and transparency in the agricultural value chain (Lv et al., 2023). UAVs play a crucial role in advancing remote sensing and crop monitoring capabilities (W. Zhu et al., 2022). The integration of IoT devices fosters a networked approach to farm management, promoting connectivity and data-driven insights (McKinsey and Co., 2020). Cloud computing technologies and big data analytics reflect the industry's recognition of the need for scalable, accessible, and analytical solutions (R. García et al., 2020). ML algorithms contribute to the development of intelligent, adaptive systems, while robotics and wireless sensor networks enhance automation and efficient monitoring (A. Singh et al., 2022). Collectively, these technological trends in SA demonstrate a transformative shift towards more *sustainable, data-driven, and efficient* farming practices during the specified timeframe.

2.3 Discussions on SA and I4.0 Technologies

This section will offer an in-depth discussion on I4.0 technologies and their applications across distinct stages of the agricultural value chain. The exploration will provide detailed insights into how these technologies are strategically employed at each stage, shedding light on their specific roles and contributions to the overall agricultural process. Thematic maps, generated through bibliometric analysis based on abstracts, by using Bibliometrix[3], will serve as a valuable tool for unraveling emerging themes, trends, and potential areas of focus within the SA literature, providing a forward-looking perspective grounded in the existing scholarly discourse (Aria & Cuccurullo, 2017).

Production and Planning:

As highlighted earlier, technologies pertaining to crop monitoring and management take center stage in the Production & Processing phase of the agricultural value chain. To delve deeper into the nuances, we extract key technologies from Table 4 and convert the list into a structured text file. Using the MonkeyLearn WordCloud Generator, we visually represent the relevance and frequency of words within the text through word clouds. The ensuing figure provides a comprehensive illustration of the technologies accentuated in the Production & Processing stage of the agricultural value chain.

[3] https://www.bibliometrix.org/home/index.php/layout/biblioshiny

This list diverges from the findings presented in **Figure 2.4**, derived from the amalgamation of **Tables 2.4 to 2.6**. Notably, the Production & Planning phase deviates from the general trend of SA technologies, emphasizing the pivotal roles of sensors, WSNs, cloud computing, and the IoT. This discrepancy is understandable, given that these technologies serve as the primary enablers for connectivity, a prerequisite for effective SA implementation.

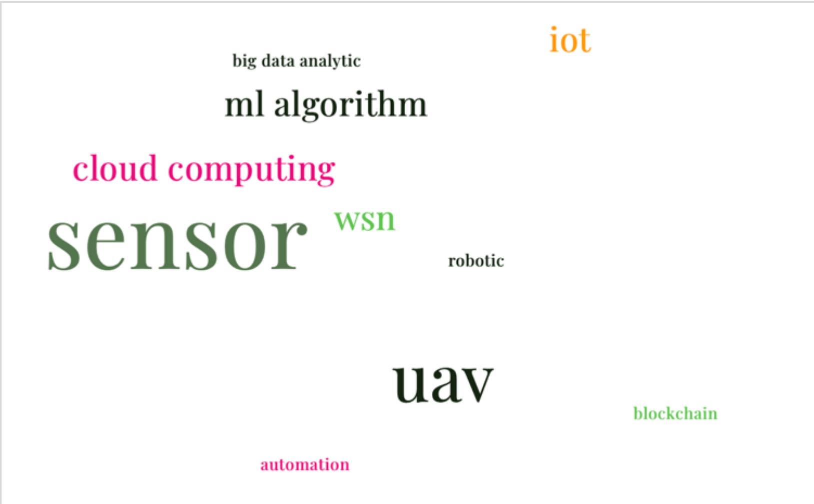

Figure 2.5: Emphasized technologies in Production & Planning stage of the agrarian value chain.

The technologies involved in information gathering, such as sensors, UAVs, WSNs, and IoT, take precedence in this stage, reflecting their significance in crop monitoring (Atalla et al., 2023). Moreover, decision-making emerges as a crucial aspect of crop management, leading to a focused exploration of ML algorithms and big data analytics in this specific segment of the agricultural value chain (Shukla et al., 2021). To provide a deeper insight into the thematic areas of I4.0 technologies in the Production & Planning stage, the ensuing **Figure 2.6** presents thematic maps derived from the studies outlined in **Table 2.4.**

The nuanced patterns revealed by the second thematic map for the Production & Processing stage offer valuable insights into the emphasis and development of key themes within this agricultural value chain phase.

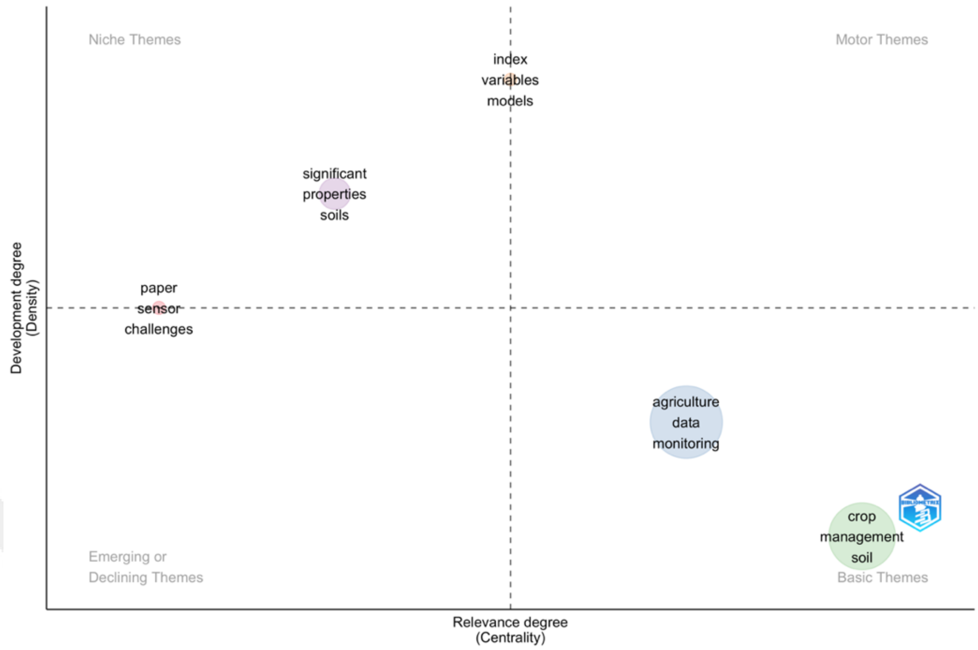

Figure 2.6: Thematic map for Production & Planning stage related studies in agrarian value chain.

Thematic map for Production & Planning stage related studies in agrarian value chain. Themes such as *Agriculture, Data, Monitoring* and *Crop, Management, and Soil* occupying the fourth quadrant signify not only their high relevance but also extensive development in the literature, indicating their pivotal roles in the Production & Processing stage.

In contrast, the second group, featuring *Sensor and Challenges*, holds a position with moderate density and lower relevance, suggesting an area of ongoing development that may benefit from increased scholarly attention. The dominance of *Index, Variables, and Models* in the top-middle area between the first and second quadrants signifies their medium relevance and robust development, underscoring their importance in the evolving landscape of Production & Processing. Meanwhile, the fourth theme, *Significant Properties and Soil*, positioned in the third quadrant, highlights a focus area with lower centrality but heightened density, suggesting a potential avenue for further exploration and research refinement within the Production & Processing stage. This nuanced analysis enhances our understanding of the current thematic landscape and directs attention to strategic areas for future research endeavors in this crucial stage of the agricultural value chain. The subsequent subsection will expound upon significant propositions pertaining to gaps and potential future trajectories based on the thematic maps presented in the various components.

Distribution and Retailing:

The word cloud generated from **Table 2.5** highlights the salience of specific technologies within the Distribution & Retailing stage of the agricultural value chain. Notably, blockchain technology takes a prominent position, underscoring its significance in ensuring trust, transparency, and traceability throughout the distribution and retailing processes (Lv et al., 2023). Unlike the comprehensive figure presented in **Figure 2.4**, the word cloud from **Table 2.5** places a distinct emphasis on blockchain. This nuanced view aligns with the challenges and opportunities present in the Distribution & Retailing phase, where trust and transparency are pivotal for consumer confidence (Y. Chen et al., 2022). Additionally, the persistent presence of DL in this context, as revealed by the word cloud, suggests its relevance in optimizing various aspects of the Distribution & Retailing processes (P. W. Khan et al., 2020; Punia et al., 2020).

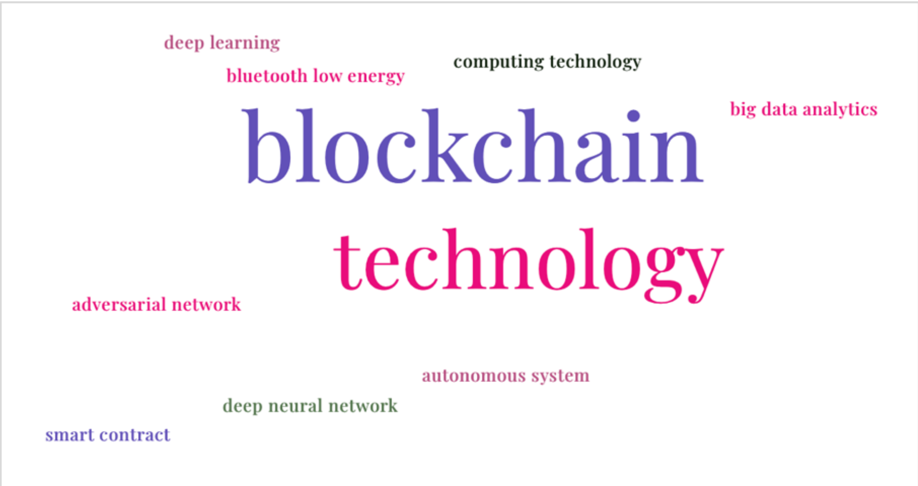

Figure 2.7: World cloud for Distribution & Retailing stage related studies for agrarian value chain.

The detailed analysis of the thematic map for the Distribution & Retailing stage offers valuable insights into the intricate relationship between I4.0 technologies and this particular phase of the agricultural value chain (**Figure 2.8**). The core quadrant's concentration of motor themes, such as *Technology, Chain*, and *Traceability*, underscores their pivotal and extensively explored role in the Distribution & Retailing context. These themes are not only centrally positioned but also exhibit high relevance and density, indicating their crucial significance and well-established presence in the literature. This dominance emphasizes the industry's acknowledgment of the transformative impact of these technologies on distribution and retail operations within agriculture (Büyüközkan & Göçer, 2018).

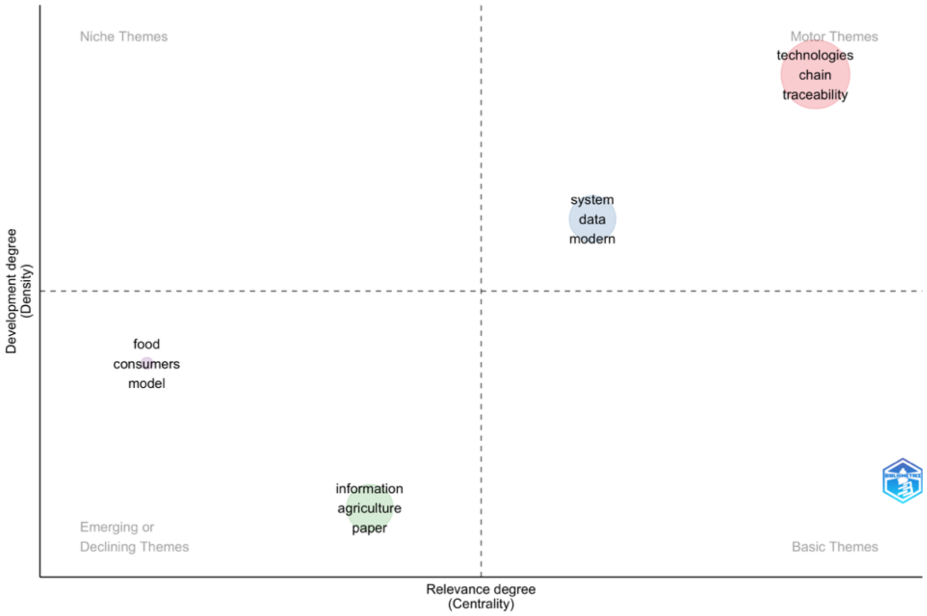

Figure 2.8: Thematic map for Distribution & Retailing stage related studies in agrarian value chain.

Themes like *System*, *Data*, and *Modern*, while centrally located, demonstrate a nuanced pattern with slightly lower relevance and density. This suggests a significant focus on these areas, but they may not be as extensively developed as the motor themes. The third quadrant, housing the cluster associated with *Information* and *Agriculture*, reflects a less central and less developed position. This indicates that certain themes related to information and its role in agriculture, within the context of Distribution and Retailing, might require more exploration and development.

Furthermore, the themes of *Food*, *Consumers*, and *Model*, positioned in the third area with very low relevance and almost medium density, point to areas that are less central and less developed in the literature. This suggests that while these themes are present, they may not have received the same level of attention or comprehensive exploration compared to the motor themes.

In summary, the thematic map not only illuminates the present landscape, emphasizing key themes and their developmental status in Distribution & Retailing, but it also serves as a compass, guiding future research directions. A more detailed synthesis of these findings will be expounded upon in the subsequent section.

Consumption and Recycling:

The word cloud derived from **Table 2.6** sheds light on the key technologies emphasized in the Consumption & Recycling stage of the agricultural value chain (**Figure 2.9**). Notably, sensor technology and blockchain take center stage, emerging as recurrent themes within the literature.

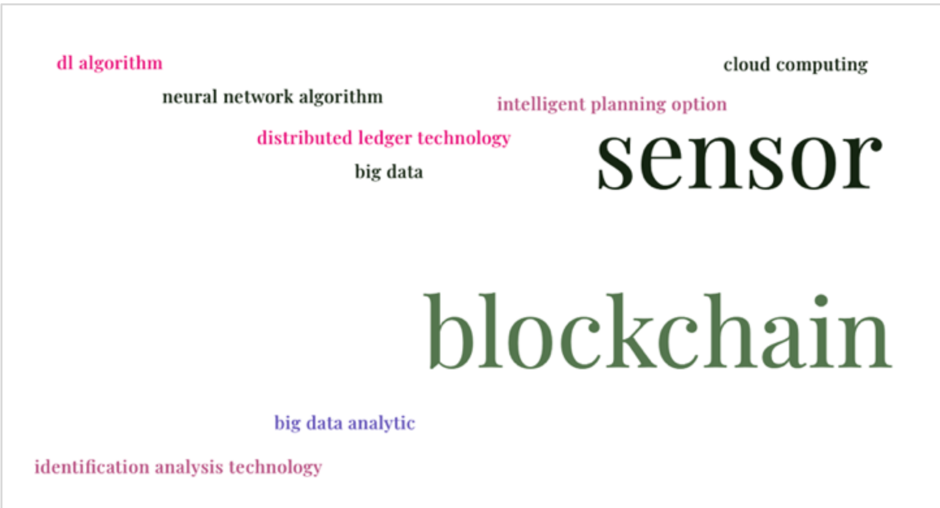

Figure 2.9: World cloud for Consumption & Recycling stage related studies for agrarian value chain.

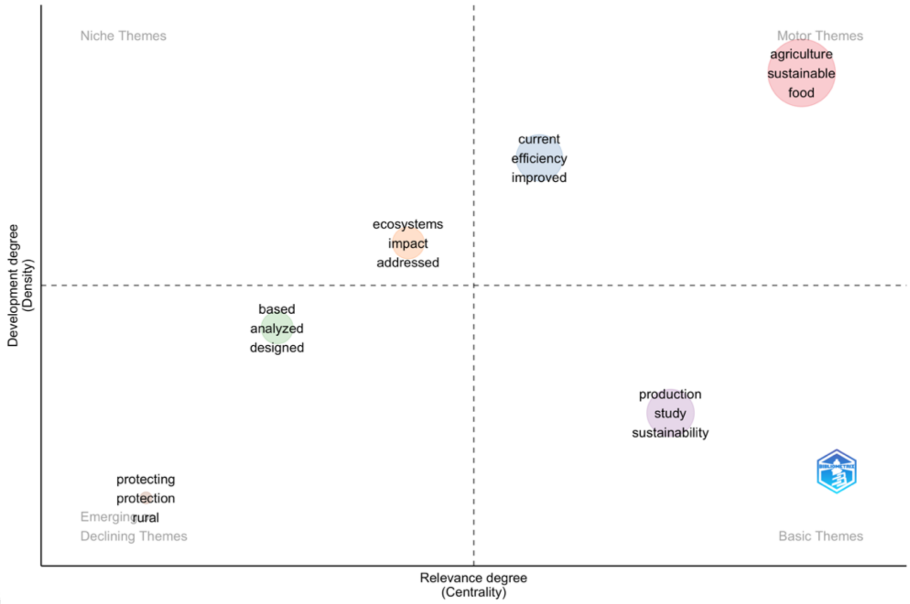

Figure 2.10: Thematic map for Distribution & Retailing stage related studies in agrarian value chain.

Thematic map for Distribution & Retailing stage related studies in agrarian value chain. The third thematic map, dedicated to the Consumption & Recycling stage of the agricultural value chain, unravels a comprehensive landscape characterized by six distinct themes, indicating a richer thematic exploration compared to other stages. Two prominent theme clusters, namely *Agriculture, Sustainable, Food* and *Efficiency* dominate the first quadrant, symbolizing both high relevance and density. The former exhibits a higher density than the latter, underscoring its greater significance and development in the literature. Notably, the theme cluster *Production and Sustainability* emerges in the fourth quadrant, demonstrating high centrality but lower density. This suggests that while the theme is centrally positioned, there is room for further development and exploration within the realm of *Production and Sustainability* in the Consumption & Recycling stage. *Ecosystem, Impact, and Addressed* is strategically located in the second quadrant, closer to the middle of the map, with lower centrality but moderate density. This positioning implies a thematic area that is not as central but is gradually developing and may gain prominence with more scholarly attention. Lastly, the theme group *Protecting, Rural, Protection* resides at the bottom of the map, indicating low centrality and density. This thematic positioning suggests a less explored area in the literature, potentially serving as a niche for future research endeavors.

2.4 Gaps and Future Directions

The observations made by the author in this preliminary exploration form the foundation for delineating specific future research areas tailored to each stage of the agricultural value chain. Subsequently, we will present a thematic evaluation map that facilitates a more in-depth exploration of the evolving trends within SA literature over the years. This structured approach aims to provide a nuanced understanding of the changing landscape in SA and offer valuable directions for prospective research inquiries.

2.4.1 Production & Processing

In the context of the Production & Processing stage within the agricultural value chain, where the predominant theme revolves around crop monitoring and management, our thematic map analysis has illuminated areas that warrant future research attention. Three key dimensions emerge from our examination:

1. **Monitoring:** The critical role of monitoring in the production and processing stage necessitates advanced sensors or WSNs to enhance the analysis of crop growth (McKinsey and Co., 2020). This dimension demands further exploration to develop and refine monitoring technologies and their integration with Decision Support Systems (DSS) for better decision-making.

2. **Crop Growth Indexes and Key Properties:** The thematic map underscores the importance of crop growth indexes and key properties for effective monitoring. This dimension suggests that cognitive computing technologies serve as crucial enablers in this stage, indicating a potential area for research exploration (Gupta et al., 2022).

3. **Soil Properties:** In line with the emphasis on detailed soil examination, optimizing resources such as water and pesticides emerges as a priority. Novel approaches for analyzing soil properties present a promising avenue for future research in SA (Gupta et al., 2022).

2.4.2 Distribution and Retailing

In the Distribution & Retailing stage of the agricultural value chain, where traceability emerges as a central theme, our analysis highlights critical areas that demand attention in future research endeavors. Three distinct dimensions arise from our thematic map examination:

1. **Traceability:** Despite being a highly studied theme, traceability presents significant challenges in agricultural value chains due to limited information sharing and data collection. Future research should focus on developing novel, energy-efficient, and interoperable trace systems to address these challenges (Corallo et al., 2020).

2. **Data Collaboration:** Collaboration among stakeholders in the agricultural value chain is crucial for effective data sharing and establishing transparent, visible value chains (L. Zhu & Li, 2021). Future research should explore novel cognitive computing approaches and blockchain to optimize distribution routes and enhance data collaboration among stakeholders.

3. **Consumer Involvement:** The thematic map reveals that the role of consumers in the agricultural value chain is an underexplored area. Understanding how to integrate consumers into the value chain and leverage Industry 4.0 technologies for this purpose holds critical importance for sustainability (Corallo et al., 2020).

2.4.3 Consumption and Recycling

In the Consumption & Recycling stage of the agricultural value chain, where efficiency and improvement of recycling stand out as significant themes, our examination reveals key areas for future research:

1. **Sustainability Integration:** While consumption and recycling are intricately linked to sustainability, the thematic map underscores an underexplored aspect of

sustainability within this stage. Recognizing sustainability as a crucial challenge for both I4.0 and SA, future studies should focus on integrating more sustainability approaches with cutting-edge technologies in the third stage of the value chain (Alreshidi, 2019).

2. **Environmental Impact and Ecosystem:** The thematic map highlights a developing area related to environmental impact and ecosystem considerations. Future studies should concentrate on improving technologies, particularly in terms of data storage and energy consumption, to enhance the environmental sustainability of the Consumption & Recycling stage (Alreshidi, 2019).

3. **Rural Areas and Protection:** The underrepresented theme of rural agriculture and rural SA surfaces as a notable gap in the literature. Given the projected increase in the global population residing in rural environments by 2070 (Pradhan et al., 2023), future studies should prioritize the protection and development of rural SA.

The thematic evaluation map presented here has been generated using Biblioshiny, an R package recognized for its interactive platform facilitating bibliometric analyses (Aria & Cuccurullo, 2017). Notably, Biblioshiny stands out for its proficiency in creating thematic evolution maps, visually illustrating the evolution of research themes over various time periods. These themes are composed of clusters of abstracts extracted from individual papers. The map creation process involves building a network for each time frame, with nodes representing words found in the abstracts, and edges indicating the frequency of co-occurrence. The strength of these edges, indicative of keyword similarity, intensifies as the number of articles featuring the paired keywords increases. By employing a clustering algorithm, keywords are organized based on their similarities, resulting in thematic clusters that articulate distinct research themes.

Due to notable spikes in document numbers in 2000, 2007, 2013, and 2019, the temporal analysis delineated five distinct periods (**Figure 2.11**). The theme of PA persistently spans all time stages, initially focusing on the control of all inputs in agricultural production (Q. Zhang, 2023).

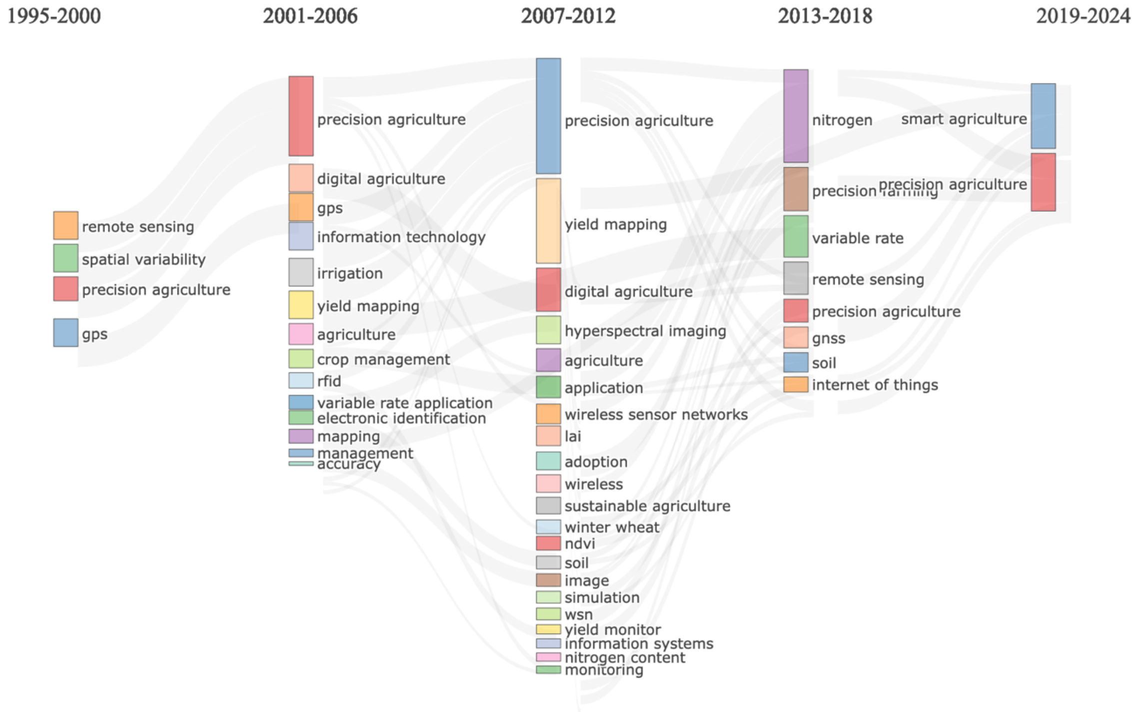

Figure 2.11: Thematic evaluation for SA literature.

The landscape evolves in 2007 with the emergence of the "digital agriculture" theme, signifying an integration of various themes into the literature, marked by a heightened emphasis on technology compared to previous periods (Sott et al., 2021). The time zone from 2019 to 2024 predominantly features two main themes: SA and PA. A closer examination of these themes is detailed in the following figure (**Figure 2.12**).

In the examination of the thematic map for studies conducted between 2019 and 2024 (early access studies), two predominant themes emerge, each occupying distinct quadrants based on the relevance degree (centrality) and development degree (density). The theme "*Smart Agriculture, Agriculture, and IoT*" is positioned in the right-bottom quadrant, characterized by very high centrality and very low density, indicating a Core area with high importance and development. This placement signifies a continued emphasis on connectivity, particularly in the context of the IoT, underscoring its central role in future studies (Atalla et al., 2023). Conversely, the theme "*Precision Agriculture, Machine Learning, Deep Learning*" is situated in the left-top quadrant, showcasing very high density but very low centrality, aligning with the Mature quadrant. This suggests that while these themes are highly developed, their centrality is relatively lower, emphasizing the importance of ML and DL in shaping the future landscape of SA (Benos et al., 2021). Evidently, achieving greater precision and robust algorithms is imperative for informed decision-making in agrarian ecosystems (Cravero et al., 2022).

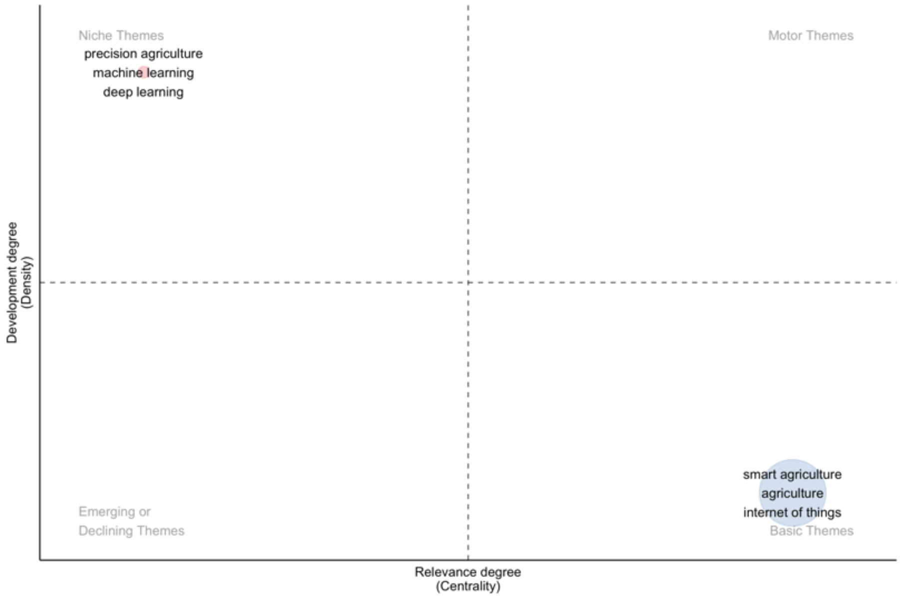

Figure 2.12: Thematic map for studies between years 2019-2024.

This review highlights the necessity for tailored technologies at different stages of the agricultural value chain, with sensors/WSNs and IoT emerging as primary enablers. While these technologies play a pivotal role, the importance of data storage and real-time data acquisition for resource optimization is equally emphasized. To transition towards an efficient SA system, comprehensive knowledge of each component and its properties is essential (Masram & Patkar, 2021). This comprehensive approach prompts the inquiry explored in Reseacr question (RQ): Can we formulate an evaluation model facilitating a seamless transition to SA by harnessing the advantages offered by I4.0 technologies? One of the objectives of this thesis is to establish a foundational roadmap that guides practitioners in designing SA and selecting the most suitable and enabling technologies tailored to their specific needs.

3 PROPOSED METHODOLOGIES FOR THESIS

In the intricate landscape of designing and modelling SA, the foundations upon which our research rests extend beyond conventional frameworks. This chapter embarks on a journey through the theoretical realms that not only frame but also propel our investigation into SA design. Central to our exploration are FFSs, entities that encapsulate nuanced uncertainties within our data. Building upon this, we delve into the realm of 2-TLFFS, introducing linguistic nuances to the precision of FFSs.

Moreover, the thesis navigates the strategic and environmental dimensions with the 2TLFFS-DEMATEL integrated SWOT/PESTLE approach, dissecting the intricacies that shape the context of our inquiry. As we navigate these theoretical landscapes, each step is a deliberate move toward a more holistic understanding of SA systems. Additionally, we integrate the QFD framework, illuminating the path towards aligning the inherent complexities of SA design.

Through this multifaceted theoretical lens, our aim is not only to comprehend the existing discourse but to carve a niche that extends the boundaries of knowledge within SA. By intertwining FFSs, 2-TLFFS, SWOT/PESTLE, DEMATEL and QFD, and VIKOR the thesis constructs a conceptual framework that underpins the very essence of our exploration, connecting the threads of these diverse theories into a coherent tapestry that informs and guides our research endeavors.

3.1 Overview of FFSs

It can be said that ambiguous and fuzzy situation exists in every subject related to the real world. Evaluation problems often share a common characteristic of ambiguous information. The real world contains uncertainties as well as precise information. In daily life, it is impossible to define everything with 0 and 1 and to place it under certain values such as black-white, right-wrong, or good-bad. Furthermore, even if individuals use the exact words when expressing an opinion, their meanings can differ significantly as each has a different subjective perception. In other words, people can soften the definite limits by adding value and meaning to the information (Akram et al., 2022). Reaching a correct and precise result by analyzing ambiguous and imprecise information can be achieved with fuzzy logic, which emerges as opposed to classical logic (Zadeh, 1965). Existing methods are not as effective as fuzzy sets in handling numerical values, as the latter can mitigate the impact of sharp boundaries through their fuzzy nature (Peng & Luo, 2021).

Fuzzy set theory was first introduced by Zadeh (1965). The fuzzy set is an extension of the characteristic function in classical sets and is characterized by a belonging function. Here, the Decision-Makers (DMs) can determine the membership degree in the range of [0, 1]. Elements have a certain degree of membership in that set. It has a definition that enables the inclusion of variable real-life judgments into calculations. The interest in fuzzy logic is growing gradually (Entemann, 2002; Jana & Mahanta, 2023; J.-S. Pan et al., 2023). In addition to engineering, fuzzy logic is used in many fields, such as artificial intelligence, computer, robotics, and space technologies. The increased interest in fuzzy logic also shows itself in scientific studies (Hentout et al., 2023; Lima et al., 2021).

After fuzzy sets were defined, Intuitionistic Fuzzy Sets (IFS) were introduced by K.T. Atanassov (1986) as a generalization of fuzzy sets. While classical fuzzy sets are represented by membership degree only, IFSs are characterized by membership and non-membership degrees of all objects in the universe, and their sum is always in the range of [0, 1] (Atanassov, 2012). IFS cannot be defined when the sum of the membership and non-membership grades is greater than 1. Therefore, to address this deficiency, the Pythagorean Fuzzy Set (PFS) was developed by Yager (2013) to generalize the IFS concept. While the sum of membership degrees in IFS is in the range of [0, 1], in PFS, the sum of the squares of the degrees of membership and non-membership falls into the range of [0, 1]. This shows that PFS includes IFS (X. Zhang & Xu, 2014).

They are both commonly used in decision-making applications, yet they have some differences in their definition and properties. PFSs are defined based on the Pythagorean theorem, which allows the representation of uncertainty in terms of distance. PFS has attracted the attention of many experts and researchers in a short time and has been applied to decision-making problems in many different fields (Joshi, 2019; Y. Liu et al., 2020), such as technological innovation risk evaluation (Liang et al., 2015), investment decision (Aghamohagheghi et al., 2019), assessment on emergency response capabilities (Du et al., 2017), transportation problem applications (Saikia et al., 2023), renewable energy resource evaluation (Geetha et al., 2022) and technology provider selection (F. Zhou & Chen, 2022). It has been observed that there are cases where the square sum of membership and non-membership degrees is greater than 1. IFS or PFS could not explain and solve these problems (F. Zhou & Chen, 2022). Senapati and Yager (2020) proposed the Fermatean Fuzzy Set (FFS) in this direction.

Senapati and Yager (2020) conducted an analysis of the interrelationships among FFS, IFS, and PFS. They observed that IFS is a specific instance or special case within the broader framework of PFS, and, conversely, FFS is an extension or generalization of PFS. The limit of squares sums of the membership and non-membership degrees" determined by the PFS has been expanded by defining the FFS Senapati and Yager (2020). In FFS, the cubic sum of membership and non-membership values of an object are in the range of [0, 1] (Akram et al., 2022). FFS theory plays an important role in various fields, as it is an advantageous and powerful concept for dealing with uncertain information (D. Liu, Liu, & Chen, 2019).

The main aim of Fuzzy Logic based approaches is soften the impacts of sharp borders. Therefore, FFS by providing a cubic sum of membership and non-membership values is seemed to be promising to handle vagueness better that IFS and PFS (Senapati and Yager 2019a). In literature, FFSs are seemed to be more flexible for capturing uncertainty of information (Keshavarz-Ghorabaee et al. 2020). The primary objective of methodologies rooted in Fuzzy Logic is the mitigation of the rigidity associated with distinct boundaries

(Zadeh, 1976). In this context, FFSs exhibit promise by presenting a cubic summation of membership and non-membership values. This feature positions FFS as a potentially superior approach for managing vagueness when compared to IFSs and PFSs, as indicated by the work of Senapati and Yager (2019a). Notably, within the academic discourse, FFSs are recognized for their heightened flexibility in capturing the nuances of uncertain information, as highlighted in the scholarly contributions of Keshavarz-Ghorabaee et al. (2020).

FFSs, being a relatively nascent concept within the realm of fuzzy logic, is presently undergoing a phase of initial development. Despite its emergent status, the field has witnessed a notable surge in research activity in recent years. Substantive contributions have been made in both conceptual and analytical domains. One pivotal facet of this exploration involves the development of innovative FFS operators, encompassing union, intersection, and negation (Akram, Bibi, & Ali Al-Shamiri, 2022). These operators are meticulously crafted to accommodate the extended range of membership values intrinsic to FFSs. Concurrently, scholars are delving into the application of FFSs in decision-making realms, encompassing MCDM and GDM (Akram et al., 2022; Keshavarz-Ghorabaee et al., 2020). This line of inquiry seeks to distinguish the potential of FFSs in enhancing the difficulties of decision-making processes. Furthermore, researchers are actively investigating the utilization of FFSs in pattern recognition applications, ranging from image recognition to data clustering (Ashraf et al., 2023). This exploration is poised to elucidate the adaptability and efficacy of FFSs across diverse recognition scenarios. In parallel, there is a concerted effort to scrutinize the mathematical properties of FFSs, particularly their ordering and aggregation characteristics (Chang et al., 2023; Fahmi, Maqbool, et al., 2023). Such analytical endeavors aim to unravel the inherent traits and capabilities of FFSs, contributing to a deeper understanding of this emerging fuzzy logic paradigm. Collectively, this research trajectory underscores the vibrant academic landscape surrounding FFSs and its potential to significantly impact various facets of fuzzy logic applications.

Let X be a universe of discourse. An FFS $\mathcal{F}$ in X is an object having the form:

$$\mathcal{F} = \{\langle x, \alpha_F(x), \beta_F(x)\rangle : x \in X\} \tag{3.1.1}$$

Where $\alpha_F(x): X \to [0,1]$ and $\beta_F(x): X \to [0,1]$, including the condition

$$0 \le (\alpha_F(x))^3 + (\beta_F(x))^3 \le 1 \tag{3.1.2}$$

for all $x \in X$. The numbers $\alpha_F(x)$ and $\beta_F(x)$ denote, respectively, the degree of membership and the degree of non-membership of the element x in the set $\mathcal{F}$. For any FFS $\mathcal{F}$ and $x \in X$,

$$\pi_F(x) = \sqrt[3]{1 - (\alpha_F(x))^3 - (\beta_F(x))^3} \tag{3.1.3}$$

Identified as the degree of indeterminacy of x to $\mathcal{F}$.

Let $\mathcal{F} = (\alpha_F, \beta_F), \mathcal{F}_1 = \left(\alpha_{F_1}, \beta_{F_1}\right)$ and $\mathcal{F}_2 = \left(\alpha_{F_2}, \beta_{F_2}\right)$ be three FFS and $\lambda, \lambda_{1,} \lambda_2 > 0$, then their operations are defined as follows:

$$\mathcal{F}_1 \boxplus \mathcal{F}_2 = \left(\sqrt[3]{\alpha_{F_1}^3 + \alpha_{F_2}^3 - \alpha_{F_1}^3 \alpha_{F_2}^3}, \beta_{F_1}\beta_{F_2}\right) \tag{3.1.4}$$

$$\mathcal{F}_1 \otimes \mathcal{F}_2 = \left(\alpha_{F_1}\alpha_{F_2}, \sqrt[3]{\beta_{F_1}^3 + \beta_{F_2}^3 - \beta_{F_1}^3 \beta_{F_2}^3}\right) \tag{3.1.5}$$

$$\lambda\mathcal{F} = \left(\sqrt[3]{1 - (1 - \alpha_F^3)^\lambda}, \beta_F^\lambda\right) \tag{3.1.6}$$

$$\mathcal{F}^\lambda = \left(\alpha_F^\lambda, \sqrt[3]{1 - (1 - \beta_F^3)^\lambda}\right) \tag{3.1.7}$$

3.1.1 FFS Literature Review

In this section of the thesis, the literature review of FFS literature will be examined using aggregation operators (AOs), exploring extensions and integrated methods. Subsequently, the primary technique for the thesis, 2TLFFS, will be elaborated in detail.

3.1.1.1 FFS Aggregation Operators

In the realm of real-world management and decision-making, the challenge of amalgamating data and reconciling preferences looms large. Navigating through complex environments and addressing intricate decision problems often involves contending with uncertainty and incomplete information. DMs, in expressing their opinions, may exhibit varying degrees of confidence, and instances of hesitation on certain evaluations are not uncommon. These factors collectively present formidable obstacles to the development of effective solutions. Traditional numerical approaches, ill-equipped to grapple with such nuances, fall short in these scenarios. Enter FFS, offering a robust solution to these challenges.

However, a critical concern arises in the process of capturing fuzzy information without incurring loss, underscoring the pivotal role of FFS information aggregation in MCDM. At the heart of this lies the significance of aggregation operators, mathematical entities that adeptly amalgamate information into a singular datum. These operators assume a crucial role in facilitating the intricate process of information fusion within the FFS framework. The literature boasts a multitude of proposed and analyzed FFS information aggregation operators, each successfully contributing to the seamless amalgamation of information. For a comprehensive insight, **Table 3.1** furnishes an overview of some key operators commonly employed in the field.

Table 3.1: FFS AOs and Their Brief Description

FFS AOs	Source	Properties	Advantages	Limitations
Algebraic AOs	(D. Liu, Liu, & Chen, 2019; Senapati & Yager, 2019a; S. Yang et al., 2022)	Idempotency, monotonicity, boundedness, commutativity.	Applicability in different areas. Flexible and ease of use.	Cannot consider the interaction between membership and non-membership functions.
Hamacher AOs	(Akram, Niaz, & Feng, 2022; Deveci, Gokasar, et al., 2023; Hadi et al., 2021; Shahzadi et al., 2023)	Idempotency, monotonicity, commutativity.	Flexibility and effectiveness.	Lack of parametrization property.
Yager AOs	(H. Garg et al., 2020; Simic, Torkayesh, et al., 2022)	Idempotency, boundedness, monotonicity, reducibility.	More precise results in MADM problems. Flexible and ease of use.	Parameter changes effects score values.
Hamy mean AOs	(Akram, Bibi, & Ali Al-Shamiri, 2022; Akram, Ramzan, et al., 2022)	Idempotency, monotonicity, boundedness.	Considers the correlation between different parameters. Enables a dynamic decision process.	Lack of real-life applications.
Einstein AOs	(Rani, Mishra, Deveci, et al., 2022; Rani & Mishra, 2021)	Idempotency, monotonicity, boundedness.	Flexibility and effectiveness. More strength than algebraic operators.	Cannot consider the interaction between membership and non-membership functions.

FFS AOs	Source	Properties	Advantages	Limitations
Dombi AOs	(Shit & Ghorai, 2021)	Idempotency, monotonicity, boundedness, commutativity.	Flexibility with a general parameter.	Computationally intensive. Lack of consensus on best practices.
Power AOs	(Senapati & Yager, 2019a; Verma, 2021)	dempotency, monotonicity, boundedness, commutativity.	Considers the correlation among the arguments.	Lack of real-life applications.
Aczel-Alsina AOs	(Haq et al., 2023; Rong et al., 2022)	Idempotency, monotonicity, boundedness, commutativity.	Higher consensus and adaptability.	Cannot consider how the criteria are related to each other.
Schweizer –Sklar AOs	(Wei et al., 2022)	Idempotency, boundedness, commutativity.	Flexibility and effectiveness.	Consider the consistency of experts.
Maclaurin symmetric mean AOs	(A. Mishra, Rani, Saha, Senapati, et al., 2022)	Idempotency, monotonicity, commutativity.	More realistic aggregation process. Considers the interrelationships of multiple attributes.	In real-life applications relation may not exist between attributes.
Frank AOs	(Tan et al., 2022)	Idempotency, monotonicity, boundedness.	Flexibility and effectiveness.	Lack of real-life applications.
Heronian mean AOs	(A. R. Mishra, Rani, et al., 2023; Rani, Mishra, Saha, et al., 2022)	Idempotency, monotonicity, boundedness.	Considers the correlation among the arguments.	Lack of real-life applications.
Bonferroni mean AOs	(Chakraborty & Saha, 2023; H. Wang et al., 2019)	Idempotency, monotonicity, boundedness, commutativity.	Reflects the interdependence of individual criteria.	Computationally intensive.

3.1.1.2 FFS Extensions

The FFS is also extended with existing fuzzy approaches to fortify its benefits while dealing with ambiguous information. By discussing the advantages and disadvantages of each extension, this analysis aims to shed light on how FFS can be further developed and improved to meet the needs of different applications and scenarios. The following **Table 3.2** provides the relevant references and extensions of FFS.

Table 3.2: FFS Extensions

FFS Extensions	References
Interval-valued FFS	(Akram, Shah, Al-Shamiri, et al., 2022b; Alkan & Kahraman, 2022; Biswas et al., 2023; Bouraima et al., 2023; Deveci, Gokasar, et al., 2023; Görçün, Aytekin, et al., 2023; Hezam, Rani, et al., 2023; Ilieva & Yankova, 2022; Jeevaraj, 2021; Kirişci, 2023; Kirişci & Simsek, 2023; Luqman & Shahzadi, 2023; A. R. Mishra, Rani, et al., 2023; Moktadir & Ren, 2023a, 2023b; Mondal et al., 2023; Qi et al., 2024; Qin et al., 2023; Rani, Mishra, Deveci, et al., 2022; Rani & Mishra, 2022; S. et al., 2023; Seikh & Mandal, 2023; Shahzadi et al., 2023)
Hesitant FFS	(Lai et al., 2022; Luo & Liu, 2022; Sha & Shao, 2023; H. Wang et al., 2019; Y. Wang et al., 2023)
2-Tuple FFS	(Akram, Bibi, & Ali Al-Shamiri, 2022; Akram, Bibi, et al., 2023; Akram, Niaz, & Feng, 2022; Akram, Ramzan, et al., 2023; Akram & Bibi, 2023a)
Trapezoidal FFS	(Fahmi, Maqbool, et al., 2023)
Triangular FFS	(Akram, Shahzadi, et al., 2023; Fahmi, 2023)
FF Linguistic Sets	(Akram, Ramzan, et al., 2022; Q. Chen et al., 2022)
FF Soft Sets	(Akram et al., 2022; Zeb et al., 2022)
Fermatean Cubic Fuzzy Sets	(Niu et al., 2022; Rong et al., 2022)

3,4-Quasirung Fuzzy Set	(M. Gul & Ak, 2022)
Rough-FF	(Albahri et al., 2023; Kao et al., 2022)
FF N-Soft Sets	(Akram et al., 2022)
Interval-valued Hesitant FFS	(P. Liu et al., 2022)
FF Bipolar Soft Set	(G. Ali & Ansari, 2022)
Dempster–Shafer Theory-Based FFS	(Deng & Wang, 2021)

Furthermore, the following **Table 3.3** provides the summarized advantages and drawbacks of FFS extension.

Table 3.3: Benefits and Drawbacks of FFS Extensions.

FFS Extensions	Source/Ref.	Advantages	Limitations
Interval-valued FFS	(Akram, Shah, Al-Shamiri, et al., 2022b; Ilieva & Yankova, 2022)	More accurate and flexible. representation of uncertainty Applicable to a wider range of problems.	Longer computation times. Ambiguity and uncertainty in the data. Sensibility to data sparsity.
Hesitant FFS	(Lai et al., 2022)	Effective in handling the human hesitation. Robust to outliers and noise in the data.	Validating an HFFS model can be challenging. The use of hesitant membership degrees in HFFS can introduce additional uncertainty.
2-Tuple FFS	(Akram, Bibi, & Ali Al-Shamiri, 2022; Akram, Niaz, & Feng, 2022)	Improved accuracy. Flexibility in modeling uncertain information.	Unable to account for the neutral aspect of human decisions. Cannot deal with m-polar data.
Trapezoidal FFS	(Fahmi, Maqbool, et al., 2023)	Deals with the complexities in numerical data.	Lack of applications.

FFS Extensions	Source/Ref.	Advantages	Limitations
Triangular FFS	(Fahmi, 2023)	Improved accuracy.	Lack of applications.
FF Linguistic Sets	(Akram, Ramzan, et al., 2022; Verma, 2021)	Offers high flexibility.	Difficulty in handling the situations where the attributes have some interaction and prioritization relationship between them.
FF Soft Sets	(Akram et al., 2022)	More accurate, reliable, and precise results. Successfully applied for Group Decision Making (GDM) problems.	Longer computation times with the increase of the parameters. Changes in rank of alternatives when a parameter is added/removed.
Fermatean Cubic Fuzzy Sets	(Niu et al., 2022; Rong et al., 2022)	Successfully overcome the vagueness and uncertainty.	In the expert knowledge aggregation process, the interrelationship of Fermatean cubic fuzzy numbers is not considered.
3,4-Quasirung Fuzzy Set	(M. Gul & Ak, 2022)	Allows the DMs to exploit additional areas such as flexibility. Reduces uncertainty.	Lack of integration with MCDM methods. Lack of applications.
Rough-FF	(Kao et al., 2022)	Processes uncertain information flexibly.	Lack of applications.
FF N-Soft Sets	(Akram et al., 2022)	Deals with vagueness and periodicity of parameterized graded information simultaneously.	Loses flexibility if the cubic sum of amplitude or phase terms or both exceed 1.
Interval-valued Hesitant FFS	(P. Liu et al., 2022)	Can deal with more complex and realistic problems. Includes more information. Effortlessness of computation steps.	Difficulties in dealing with the correlative MCDM problems. Complexity of assessment procedure.

FFS Extensions	Source/Ref.	Advantages	Limitations
FF Bipolar Soft Set	(G. Ali & Ansari, 2022)	More feasible and accurate results.	Longer computation times with the increase of the parameters. Changes in rank of alternatives when a parameter is added/removed.
Dempster–Shafer Theory-Based FFS	(Deng & Wang, 2021)	Reduced information loss. More accurate results.	Lack of applications.

3.1.1.3 Integrated MCDM Methods in FFS

Currently, researchers are exploring the potential of FFS and applying it to various decision-making problems. Most of the FFS studies that have been conducted so far have focused on MCDM problems. FFSs provide a nuanced way of modeling uncertainties and imprecisions, which can be particularly useful in decision-making scenarios where precise information is hard to come by. The following **Table 3.4** gives the integrated MCDM methods used with FFS with their relevant references.

Table 3.4: MCDM methods used in FFS studies with their application areas.

MCDM Method	References	Application Areas
TOPSIS	(Akram, Shahzadi, & Davvaz, 2022; Alahmadi et al., 2023; Amman et al., 2023; Aydoğan & Ozkir, 2024; Bouraima et al., 2023; Fahmi, 2023; Fahmi, Maqbool, et al., 2023; Golui et al., 2024; Hooshangi et al., 2023; Karuppiah & Sankaranarayanan, 2023; Kirişci & Simsek, 2023; D. Liu, Liu, & Chen, 2019; Qi et al., 2024; Senapati & Yager, 2019a, 2020; Shahzadi et al., 2023; S. Yang et al., 2022; Zeng, Gu, et al., 2023)	Health, Logistics and Supply Chain Management, Finance, Agriculture, Project Investment, Risk Management, Construction, Sustainable Development, Energy, Construction

MCDM Method	References	Application Areas
CRITIC	(Aro et al., 2022; Erdogan & Ayyildiz, 2022; R. Gonzales et al., 2022; Hezam, Mishra, et al., 2023; A. Mishra, Bullet, et al., 2022; A. R. Mishra, Chen, et al., 2023; A. R. Mishra, Rani, et al., 2023; Qin et al., 2023; Rani, Mishra, Deveci, et al., 2022; Saraji et al., 2021; Tan et al., 2022)	Logistics and Supply Chain Management, Health, Sustainable Development, Education, Risk Management, Finance, Transportation
COPRAS	(Akram, Ramzan, et al., 2022; Görçün, Aytekin, et al., 2023; Korucuk et al., 2022; P. Liu et al., 2022; A. Mishra, Rani, Saha, Senapati, et al., 2022; Rani, Mishra, Deveci, et al., 2022; Saraji et al., 2021)	Sustainable Development, Manufacturing, Energy, Industry 4.0 adoption
CODAS	(Akram, Niaz, & Feng, 2022; Aro et al., 2022; Biswas et al., 2021; Erdogan & Ayyildiz, 2022; Farid et al., 2023; R. Gonzales et al., 2022; Simic, Gokasar, et al., 2022)	Logistics and Supply Chain Management, Construction, Health, Education, Technology, Transportation
DEMATEL	(G. Gonzales et al., 2022; Kao et al., 2022; Karuppiah et al., 2022, 2023; Karuppiah & Sankaranarayanan, 2023; Moktadir & Ren, 2023b; Y. Yang et al., 2024)	Economy, Sustainable Development, Education, Energy, Waste Management
SWARA	(Aydoğan & Ozkir, 2024; Ayyildiz, 2022; Deveci, Varouchakis, et al., 2023; Görçün, Aytekin, et al., 2023; Hezam, Mishra, et al., 2023; Korucuk et al., 2022; Seikh & Mandal, 2023)	Energy, Risk Management, Waste Management
CoCoSo	(Q. Chen et al., 2022; Hezam, Rani, et al., 2023; Lai et al., 2022; A. Mishra, Rani, Saha, Hezam, et al., 2022; Simic, Ivanovic, et al., 2022; Wei et al., 2022)	Risk Management, Logistics and Supply Chain Management, Blockchain, Waste Management, Urban Planning, Manufacturing
MULTI-MOORA	(Akram & Bibi, 2023a; Deveci, Gokasar, et al., 2023; Luo & Liu, 2022; Narayanamoorthy et al., 2022; Rani & Mishra, 2021; Y. Yang et al., 2024)	Energy, Sustainable Development, Transportation, Urban Planning

MCDM Method	References	Application Areas
WASPAS	(Çolak & Lezki, 2023; Keshavarz-Ghorabaee et al., 2020; A. Mishra & Rani, 2021; Rani & Mishra, 2022; Rao & Sujatha, 2023)	Waste Management, Logistics and Supply Chain Management
AHP	(Alkan & Kahraman, 2022; Bouraima et al., 2023; Karuppiah et al., 2023; Karuppiah & Sankaranarayanan, 2023; Zeng et al., 2022)	Education, Logistics and Supply Chain Management, Waste Management, Construction
MEREC	(Deveci, Gokasar, et al., 2023; Fetanat et al., 2023; Narayanamoorthy et al., 2022; Rani, Mishra, Saha, et al., 2022; Simic, Ivanovic, et al., 2022)	Energy, Urban Planning, Waste Management, Transportation, Sustainable Development
MARCOS	(Rong et al., 2022; Saha et al., 2023; Simic, Torkayesh, et al., 2022; W. Wang et al., 2023)	Waste Management, Logistics, and supply management, Risk Management, Manufacturing
BWM	(Gao et al., 2024; M. Gul & Ak, 2022; Wei et al., 2022; Zeng, Chen, et al., 2023)	Aviation, Logistics and Supply Chain Management, Waste Management
ELECTRE	(Akram, Bibi, et al., 2023; Kirisci et al., 2022; L.-P. Zhou et al., 2021)	Health, Technology
EDAS	(A. Mishra, Bullet, et al., 2022; Niu et al., 2022; Zeng, Chen, et al., 2023)	Urban Planning, Logistics and Supply Chain Management
TODIM	(D. Liu, Liu, & Wang, 2019; Moktadir & Ren, 2023a; Y. Pan et al., 2023)	Construction, Logistics and Supply Chain Management, Waste Management
ARAS	(S. Gul, 2021; Rani, Mishra, Saha, et al., 2022)	Waste Management, Health
MABAC	(Biswas et al., 2023; Tan et al., 2022)	Risk Management, Technology

MCDM Method	References	Application Areas
FUCOM	(Biswas et al., 2021; Görçün, Pamucar, et al., 2023)	Technology
PROMETHEE	(Akram & Bibi, 2023a; Seikh & Mandal, 2023)	Finance, Waste Management
VIKOR	(Gao et al., 2024; S. Gul, 2021)	Health, Waste Management
WPM	(Senapati & Yager, 2019c)	Construction
SMART	(Keshavarz-Ghorabaee et al., 2020)	Logistics and Supply Chain Management
SAW	(S. Gul, 2021)	Health
DEA	(Akram, Shah, Al-Shamiri, et al., 2022a)	Transportation
BRAW	(Q. Chen et al., 2022)	Risk Management
LOPCOW	(Niu et al., 2022)	Urban Planning
ITARA	(Simic, Torkayesh, et al., 2022)	Waste Management
QFD	(Seker & Aydin, 2023)	Transportation
MAIRCA	(Görçün, Pamucar, et al., 2023)	Technology
WINGS	(Moktadir & Ren, 2023a)	Waste Management

3.1.1.4 3.1.1.1 FFS Linguistic Sets

Linguistic variables play a significant role in managing the complexity and difficulty of the data collection process, particularly in decision-making scenarios (Akram, Ramzan, et al., 2022). FF Linguistic Sets (FFLSs) are a recent extension of the FFSs and fuzzy linguistic approach, designed to manage comparative linguistic expressions. Based on the review conducted for FFS studies the most common linguistic sets are provided in **Figure 3.1**.

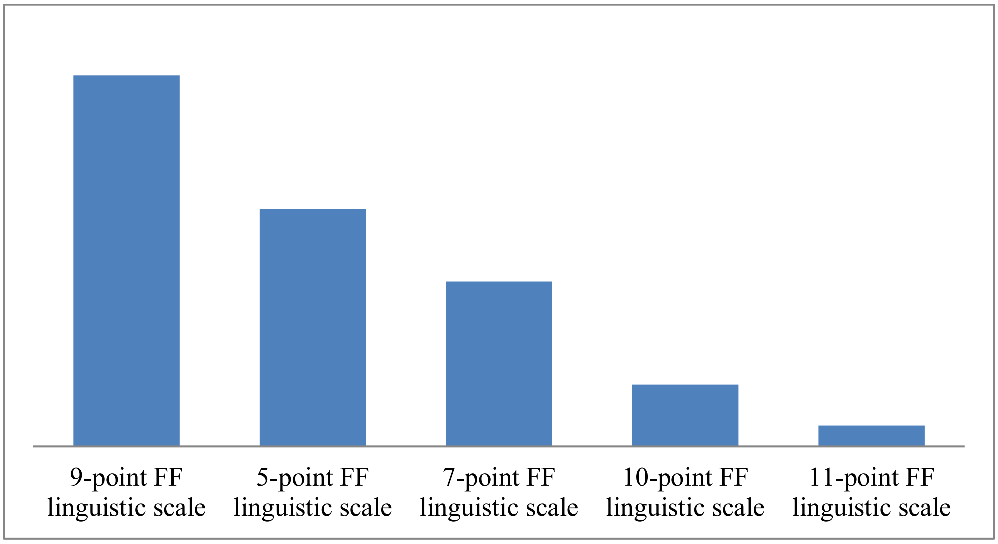

Figure 3.1: Most commonly used FFLSs.

Linguistic sets play a crucial role in decision-making by providing a means to express and quantify subjective judgments and preferences. They enable DMs to describe and evaluate criteria, alternatives, and expert opinions using linguistic terms rather than precise numerical values. Linguistic sets bridge the gap between qualitative and quantitative assessments, allowing for a more intuitive and human-centric approach to decision-making (Herrera-Viedma et al., 2021). By incorporating linguistic sets, DMs can capture the nuances and uncertainties inherent in complex decision problems, leading to more accurate and meaningful results.

3.1.2 Thematic Analysis of FFS Literature

Designed as an open-source R-tool, Bibliometrix serves as a robust instrument for comprehensive science mapping analysis, offering a suite of tools tailored for quantitative research in bibliometrics and scientometrics (Aria & Cuccurullo, 2017). This analysis adheres to a recommended workflow, employing bibliometric methodologies to gather valuable insights from the vast landscape of FFS literature. Thematic maps, a product of this analytical process, are generated by scrutinizing co-occurrence networks of keywords, authors, or journals. Leveraging various algorithms and statistical methods, these maps unveil clusters of related items, painting a vivid picture of the thematic landscape in a visual format. By interpreting these maps, this section endeavors to discern research trends, identify hot topics, and shed light on emerging areas within the realm of FFS (Aras & Büyüközkan, 2023).

In this analytical pursuit, thematic map derived from author keywords is presented, offering distinct lenses through which to understand the key themes in FFS literature. Author keywords, selected with precision, serve as deliberate indicators of core themes and research contributions, providing a direct reflection of authors' intended concentrations. Thematic maps based on author keywords (**Figure 3.2**) often reveal a higher degree of consistency and repetition, signifying recurring core concepts across diverse articles. This consistency underscores the thematic depth and emphasis on specific dimensions within FFS research.

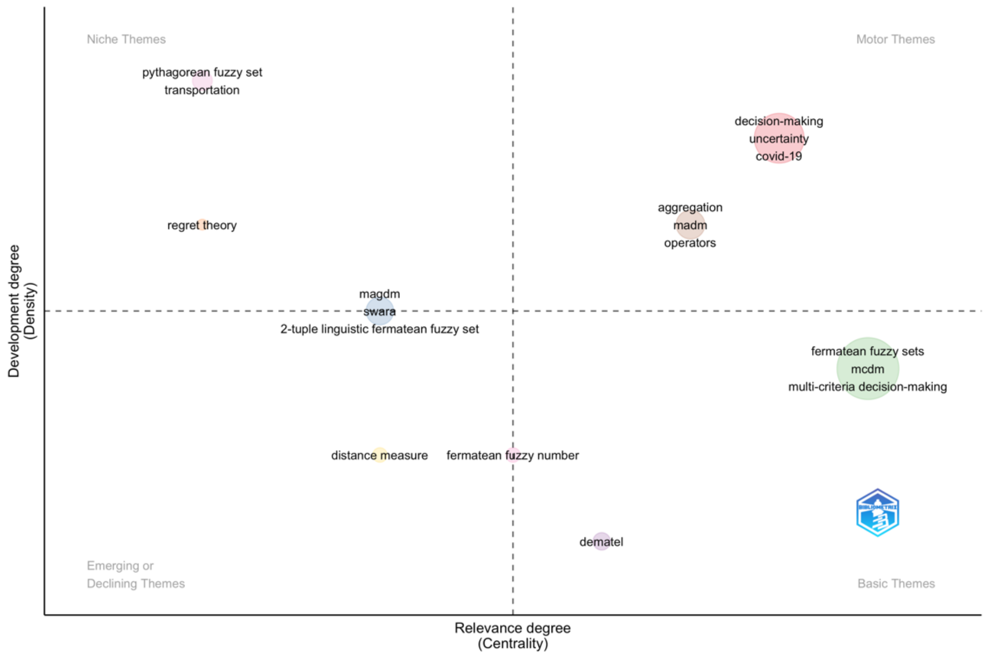

Figure 3.2: Thematic map derived from author keyword via Bibliometrix tool.

The interpretation of thematic maps hinges on two key metrics: centrality and density. Centrality illuminates the importance of a theme by assessing its connections within the network—high centrality denotes a pivotal theme with widespread connections, while low centrality signifies more specialized or peripheral concepts. Density gauges the cohesion among themes, indicating the degree of interconnectedness—high density reflects closely related themes forming cohesive clusters, while low density suggests diverse or distinct subfields. Analyzing both metrics concurrently unveils nuanced insights; high centrality coupled with high density highlights central themes tightly interconnected, high centrality with low density points to central themes with specialized subtopics, low centrality with high density indicates related but not necessarily central themes, and low centrality with low density suggests isolated or less interconnected themes. This comprehensive approach facilitates the identification of hub and peripheral themes, providing a holistic understanding of the thematic composition within a research field.

The identified Basic Themes, namely "fermatean fuzzy sets" and "MCDM," stand out with high centrality in the thematic analysis of FFS literature. Positioned strategically in the fourth quadrant, these Basic Themes signify their foundational importance and specialized focus within the broader FFS discourse. "Fermatean fuzzy sets" represent the core conceptualization, while "MCDM" underscores the integral role of multiple criteria decision-making methodologies in the context of FFS (Akram et al., 2022; Aydin, 2021; Narayanamoorthy et al., 2022; Senapati & Yager, 2019b).

On the other hand, Motor Themes, characterized by their high centrality and cohesive influence, emerge as pivotal contributors to the thematic landscape. Themes like "decision-making," "uncertainty," and “covid-19” stand out as central elements with specialized subtopics, underscoring their foundational role in FFS research. The former acknowledges the contemporary context of decision-making amidst the challenges posed by the COVID-19 pandemic, showcasing the adaptability of FFS in addressing real-world scenarios (Akram et al., 2020; Alsattar et al., 2022; H. Garg et al., 2020). The second group, featuring "aggregation operators" and "MADM," further reinforces the Motor Themes category. Positioned in the first quadrant, these themes exhibit high centrality and cohesive influence, indicating their pivotal roles in the overall thematic landscape. "Aggregation operators" and "MADM" are essential components that contribute to the robustness and applicability of FFS models, showcasing their influence in decision-making scenarios (Akram, Bibi, & Ali Al-Shamiri, 2022; Akram, Ramzan, et al., 2022; Aydemir & Gunduz, 2020; Chakraborty & Saha, 2023; H. Garg et al., 2020; Hadi et al., 2021).

The thematic analysis further unveils Niche Themes within the FFS literature, revealing distinctive elements that contribute to the nuanced understanding of the field. The first group encompasses "Pythagorean fuzzy set" and "transportation," positioned in a manner that distinguishes them as themes with a specialized focus. These Niche Themes occupy spaces in the thematic map that suggest their relevance in specific subtopics within FFS research. "Pythagorean fuzzy set" and "transportation" contribute to the diversity of topics explored in the literature, demonstrating their specialized roles within the broader thematic landscape (Akram, Shah, Al-Shamiri, et al., 2022a, 2022b; Saikia et al., 2023). In the second group, "regret theory" emerges as another Niche Theme, reflecting a specialized area of investigation with a unique focus. Positioned strategically on the thematic map, this theme indicates its importance in addressing specific aspects of regret theory within the context of FFS (Fahmi, Ahmed, et al., 2023; Niu et al., 2022). As a Niche Theme, "regret theory" contributes to the depth and diversity of perspectives within the FFS literature. A third group, intriguingly positioned in the middle ground between Emerging and Niche Themes, includes "SWARA" and "2-Tuple linguistic fuzzy set." (Akram, Bibi, & Ali Al-Shamiri, 2022; Akram & Bibi, 2023a; Akram & Niaz, 2022) These themes are represented by smaller squares on the map, underscoring their status as distinctive but potentially evolving concepts. Placed at the intersection of Emerging and Niche Themes, "SWARA" and "2-Tuple linguistic fuzzy set" signify areas of exploration that are gaining attention but may still be in the early stages of development within the FFS literature.

Within the emerging trends of FFS literature, two distinct groups stand out, providing valuable insights into the evolving facets of the field. The first small group centers around "distance measure," positioning itself as an emerging theme with unique characteristics (Deng & Wang, 2022; Ganie, 2022; Kirisci, 2023). This theme suggests a growing interest and exploration within the FFS literature, indicating an emerging discourse around the measurement of distances within the context of FFSs. In the second small group, strategically positioned between Basic Themes and Emerging Themes, "fermatean fuzzy number" takes center stage (Fahmi, Ahmed, et al., 2023; Fahmi, Maqbool, et al., 2023; Senapati & Yager, 2019b). This theme signifies a nuanced exploration that bridges foundational concepts with emerging perspectives. Its placement suggests that "fermatean fuzzy number" is gaining recognition as a concept of interest within the evolving landscape of FFS literature.

In light of the evolving landscape within the academic discourse, the prevalence of FFSs in the domain of MCDM is unmistakable. The proclivity for FFS in decision-making scenarios stems from its adept representation of uncertainty, positioning it as a favored tool in addressing complex decision problems. Upon scrutinizing areas within the corpus of published works that have received comparatively less attention yet exhibit significant potential, the 2TLFFS emerges as a compelling extension of FFS. Given its underexplored nature and inherent capacities, the 2TLFFS has been discerningly chosen as the principal technique for deployment in this thesis. The subsequent section will meticulously unravel the intricacies of 2TLFFS, shedding light on its theoretical foundations and application nuances.

3.2 Overview of 2TLFFSs

In the 2TL model, where the linguistic information is expressed by the means of two tuples, the expressions are composed of a linguistic term and a numeric value assessed in $[-0.5,0.5)$. (Martínez et al., 2015)

Let $S = \{s_0, s_1, \dots, s_g\}$ be a linguistic term set and $\beta \in [0,1]$ a value indicating the symbolic aggregations operation's outcome. The generalized translation function (Δ) can be defined as follows (Tai & Chen, 2009) :

$$\Delta: [0,1] \rightarrow S \times \left[-\frac{1}{2g}, \frac{1}{2g}\right)$$
$$\Delta(\beta) = (s_i, \alpha), \text{ with } \begin{cases} s_i, i = \text{round } (\beta \cdot g) \\ \alpha = \beta - \dfrac{i}{g}, \alpha \in \left[-\dfrac{1}{2g}, \dfrac{1}{2g}\right) \end{cases} \quad (3.2.1)$$

Furthermore, as defined by Herrera & Martínez, (2000) the conversion of a linguistic term into a linguistic 2-tuple involves incorporating a symbolic translation value of 0.

$$s_i \in S \Rightarrow (s_i, 0) \tag{3.2.2}$$

FFSs introduced membership and non-membership values to create more robust assessment possibilities for the experts. The FFSs are suggested and accepted as a powerful solution to overcome the impreciseness in decision-making. Consequently, a hybrid technique, where the benefits of FFS and 2TL methodology are composed, is introduced to the field (Akram, Bibi, & Ali Al-Shamiri, 2022). The fuzzy tool is the 2TLFFS. This section gives the details about 2TLFFS laws, operations, and aggregation operators. Here are the main motivations behind choosing 2TLFFS:

- In classical FFS, the membership and nonmembership degrees are given by numerical values that lie within the interval [0,1], while in 2TLFFS, the membership and non-membership degrees are given by the 2TL model. This is more useful for tackling those real-life multi-attribute GDM (MAGDM) problems in which experts express their opinion through linguistic labels.

- The 2TLFFS operators are also general, and they are compatible with 2TLIF and 2TLPF data. Thus, they overcome the drawbacks and limitations of the existing operators.

- Plus, the 2TLFFS operators produce more exact findings when applied to real-life MAGDM problems based on 2TLFF data because these operators can account for correlated arguments.

Akram et al (2022), introduced the 2TLFFS in 2022. The basis of the 2TLFFS model are as follows. For further details about 2TLFFS readers can refer to (Akram, Ali, et al., 2023; Akram, Bibi, & Al-Shamiri, 2022; Akram, Niaz, & Feng, 2022; Akram & Bibi, 2023b; Akram & Niaz, 2022).

Let $S = \{s_1, \ldots, s_g\}$ be linguistic term set with odd cardinality *g+1* and let $S_{[o,g]} = \{(s_\alpha, \alpha) \mid s_i \in S, \alpha \in [-1/2, 1/2)\}$ be a set of all 2TL terms defined on [0,1]. A 2TLFFS is defined as

$$A = \{(s_\alpha, \alpha), (s_\beta, \beta)\}, \tag{3.2.3}$$

where $(s_\alpha, \alpha), (s_\beta, \beta) \in S_{[0,a]}$,

$$0 \leq \left(\Delta^{-1}(s_\alpha, \alpha)\right) \leq g, 0 \leq \left(\Delta^{-1}(s_\beta, \beta)\right)^2 \leq g, \tag{3.2.4}$$

satisfying the condition

$$0 \leq \left(\Delta^{-1}(s_\alpha, \alpha)\right)^3 + \left(\Delta^{-1}(s_\beta, \beta)\right)^3 \leq g^3 \tag{3.2.5}$$

(s_α, α) and (s_β, β) represent the membership degree and non-membership degree by 2TL terms.

2TLFF Weighted Hamy Mean Operator (2TLFFWHM)

Let $S_j = \left\{\left(s_{\alpha_j}, \alpha_j\right), \left(s_{\beta_j}, \beta_j\right)\right\} (j = 1,2,3, \ldots, k)$ be a collection of 2TLFF numbers with weight vector $w = (w_1, w_2, \ldots, w_k)^T$, thereby satisfying $w_i \in [0,1]$ and $\sum_{j=1}^{k} = 1.$ The 2TLFFWHM operator is defined as follows (Akram, Bibi, & Al-Shamiri, 2022):

$$2\text{ TLFFWHM } M_w^x(S_1, S_2, \ldots, S_k) = \frac{\bigoplus_{1 \leq i_1 \leq \cdots, i_x \leq k} \left(\otimes_{j=1}^{x} \left(S_{i_j}\right)^{w_{ij}}\right)^{\left(\frac{1}{x}\right)}}{C_k^x} \tag{3.2.6}$$

The studies on 2TLFFSs were listed in the preceding section within the FFS literature. The thematic analysis of FFS literature revealed the potential for further development in the area of 2TLFFS, making it a prospective field for future research. Considering both the open avenues for advancement in the FFS literature and the advantages inherent in the 2TL model, 2TLFFS has been chosen as the main technique for this thesis.

The selection of 2TLFFS as the primary technique is motivated by its ability to effectively capture linguistic uncertainties, providing a nuanced representation of complex agricultural decision-making scenarios. The unique attributes of 2TLFFS, such as its capacity to handle imprecise information and linguistic expressions, align well with the inherent uncertainties in agricultural contexts.

3.3 Overview of SWOT and PESTLE Analysis

This research endeavors to provide a comprehensive understanding of the intricacies and current state of Turkish agriculture through the concurrent application of SWOT and PESTLE analysis methods. The SWOT analysis will serve as the foundational framework, emphasizing key dimensions that encompass internal strengths and weaknesses as well as external opportunities and threats. Subsequently, the PESTLE analysis will be intricately examined to delve into the nuanced political, economic, social, technological, legal, and environmental factors shaping the agricultural landscape in Türkiye.

The integration of these two analytical methods aims to unveil strategic insights for facilitating the transition of Turkish agriculture towards smart farming practices. By prioritizing the essential elements identified through the SWOT analysis and delving into the broader environmental factors highlighted by PESTLE, the research aspires to articulate strategies that can foster a seamless and informed evolution in the agricultural sector. This approach not only ensures a holistic exploration of the internal and external dimensions of Turkish agriculture but also seeks to propose actionable strategies that align with the principles of precision agriculture, thus contributing to the sustainable development of the Turkish agricultural sector.

3.3.1 SWOT Analysis

SWOT analysis is a strategic assessment tool used in business to assess both internal strengths and weaknesses and external opportunities and threats. The acronym SWOT stands for Strengths, Weaknesses, Opportunities, and Threats.

Strengths represent the favorable attributes of a business, including aspects like a unique value proposition, a skilled workforce, or a strong brand image (Benzaghta et al., 2021). Weaknesses are areas where a business may be lacking, such as financial underperformance, outdated technology, or ineffective marketing tactics. Opportunities encompass external factors that a business can leverage to its advantage, like emerging markets, technological advancements, or shifts in consumer behavior. Threats are external factors that could adversely affect a business, including heightened competition, economic downturns, or regulatory changes.

SWOT analysis helps businesses gain a comprehensive understanding of their market position and formulate strategies for improvement. It can be conducted through methods such as brainstorming, surveys, or stakeholder interviews. Overall, SWOT analysis is a straightforward yet effective tool that supports informed decision-making and competitiveness in the industry (Firoozzare et al., 2023; Nigjeh et al., 2023).

Benzaghta et al., (2021) identified five prevalent domains in which SWOT analysis finds common application: general management, education, marketing, healthcare, and agriculture. Their study encompassed an integrative literature review of SWOT analysis within these domains. The primary objective was to furnish a comprehensive historical perspective of SWOT analysis, thereby facilitating the potential formulation of novel theoretical viewpoints and frameworks.

SWOT analysis finds valuable application within the agricultural sector (E. Ali et al., 2021; Nigjeh et al., 2023). For instance, it serves as a means to assess the inherent strengths and weaknesses of farms or agricultural enterprises, alongside the opportunities and threats prevalent in the agricultural industry. This analytical approach aids farmers and agricultural entities in pinpointing areas for enhancement, crafting strategies for heightened productivity and profitability, and maintaining competitiveness within the market.

Through SWOT analysis, agricultural stakeholders can acquire a comprehensive understanding of the potential advantages and disadvantages associated with these innovations, and subsequently, formulate strategies to capitalize on strengths and opportunities while mitigating inherent weaknesses and threats.

In their study, Benzaghta et al., (2021) conducted a comprehensive review of SWOT-related research and its various application domains up to the year 2021. This paper, in turn, focuses on a more recent examination, specifically concentrating on the utilization of SWOT analysis within the agricultural context from 2021 onward. The following **Table 3.5** gives the recent SWOT studies within agricultural context.

Table 3.5: Recent SWOT studies within agricultural context.

Author(s)	Objective of the study	Country	Integrated MCDM methods
(Firoozzare et al., 2023)	Enhancing Rain-Fed Agriculture Sustainability	Mashhad, Iran	BWM - WASPAS
(Obbineni et al., 2023)	Analyzing Strategies for Developing Organic Farming	Tamil Nadu, India	neutrosophic cognitive maps (NCM)
(Maity et al., 2023)	Analyzing Agrivoltaic System Implementation Factors	-	TOWS matrix analysis
(Nigjeh et al., 2023)	Determining Agricultural Bank's Education Strategy	Iran	AHP
(Ermetin, 2023)	Assessing Precision Livestock Farming (PLF) Technologies in Water Buffalo Farming	Yozgat, Türkiye	-
(K. Khan et al., 2022)	Enhancing Concrete with Date Palm Biochar	Kingdom of Saudi Arabia	-
(Das et al., 2022)	Advancing Sustainable Agriculture with Nanofibers	-	TOWS matrix analysis

Author(s)	Objective of the study	Country	Integrated MCDM methods
(Firsova & Abrhám, 2021)	Analyzing Blockchain in Czech Agriculture	Czech Republic	-
(Abid & Jie, 2021)	Analyzing COVID-19's Impact on Agricultural Food	Pakistan	-
(Goli et al., 2021)	Improving Rice Water Productivity	Northern Iran, Sari	-
(Tabash et al., 2021)	Analyzing Herbicide Use in Indian Agriculture	Sikhar block of Mirzapur District in Uttar Pradesh, India	-
(Gkoltsiou & Mougiakou, 2021)	Holistic Landscape Assessment for Small Islands	Greek island of Gavdos	-
(Voicilas & Certan, 2021)	Analyzing Cross-Border Cooperation Effects	Romania, the Republic of Moldova, and Ukraine	-
	Analyzing Ghana's Planting for Food and Jobs (PFJ) Initiative	Ghana	AHP

3.3.2 PESTLE Analysis

PESTLE analysis, an instrumental framework, serves as a means of discerning and assessing the external elements that exert influence upon an entity or enterprise. It derives its terminology from the following features: Political, Economic, Sociocultural, Technological, Legal, and Environmental factors (E. Ali et al., 2021; Sakrabani et al., 2023). This analytical tool is indispensable in affording organizations insight into the macro-environmental forces that possess the potential to influence their functioning and necessitates the formulation of corresponding strategies for mitigation.

PESTLE analysis finds application across various domains, encompassing strategic planning, product development, risk management, and market research. When PESTLE analysis is paired with SWOT analysis, it becomes a valuable tool for organizational development, aiding in the assessment of an organization's current state, capacity, strategic orientation, as well as its growth or decline prospects. As elucidated by Benzaghta et al. (2021), while SWOT analysis predominantly scrutinizes internal factors, PESTLE analysis casts a wider net by acknowledging the external influences that often lie beyond a business's realm of control. Consequently, the amalgamation of SWOT and PESTLE analyses affords a more holistic perspective of the business landscape. Wu, (2020) seamlessly integrated the PESTEL framework and the Five Forces model with SWOT analysis to scrutinize IKEA's international and cost leadership strategy. More recently, Tran et al., (2023) used SWOT/PESTLE analysis in the agricultural context to assess the adoption potential of an autonomous laser-based weeding system (ALWS) for sustainable weed control. The study utilizes both SWOT and PESTLE analyses to thoroughly assess factors impacting the adoption of ALWS. SWOT analysis captures stakeholder perceptions, identifying strengths, weaknesses, opportunities, and threats. In contrast, PESTLE analysis focuses on macro-environmental factors encompassing political, economic, social, technological, legal, and environmental aspects. This comprehensive approach offers a well-rounded understanding of adoption potential, enabling more informed and effective strategies for promoting ALWS adoption in sustainable agriculture. Moreover, in 2021, Parra-Lopez et al., (2021) used SWOT and PESTLE analyses together to assess factors influencing digital transformation and design effective policies in agri-food sector. The combined use of SWOT and PESTLE analyses offers a comprehensive assessment of both internal and external factors influencing digital transformation in the agri-food sector, guiding the design of customized policies for DT promotion while engaging diverse expert stakeholders in a complex and data-scarce environment.

In summary, the integration of SWOT analysis with complementary methodologies such as PESTLE analysis significantly enhances the depth of comprehension regarding the business environment. Consequently, it enriches the quality of strategic insights and bolsters the foundation for well-informed decision-making Parra-Lopez et al., (2021). In this research, our approach initiates with a fundamental SWOT analysis framework. However, it is essential to underscore that we judiciously incorporate PESTLE dimensions throughout the assessment of relevant factors and the formulation of strategic initiatives, acknowledging the value of this combined analytical approach.

3.4 Overview of Quality Function Deployment (QFD)

During the 1970s, the inception of QFD took place in Japan; however, it wasn't until the 1980s that the Western hemisphere recognized its value as a technique, subsequently adopting it as a decision-making tool (Zare, 2010). In Japan, QFD has proven instrumental in enhancing processes and establishing a competitive edge for numerous organizations. Presently, QFD stands as a formidable instrument employed by companies worldwide, effectively addressing strategic and operational decisions within the business realm. As articulated in literature, "QFD serves as a mechanism for translating customer requirements into pertinent technical specifications at each phase of product development and production, encompassing marketing strategies, planning, product design, engineering, prototype evaluation, production process development, production, and sales construction (Akao & Mazur, 2003).

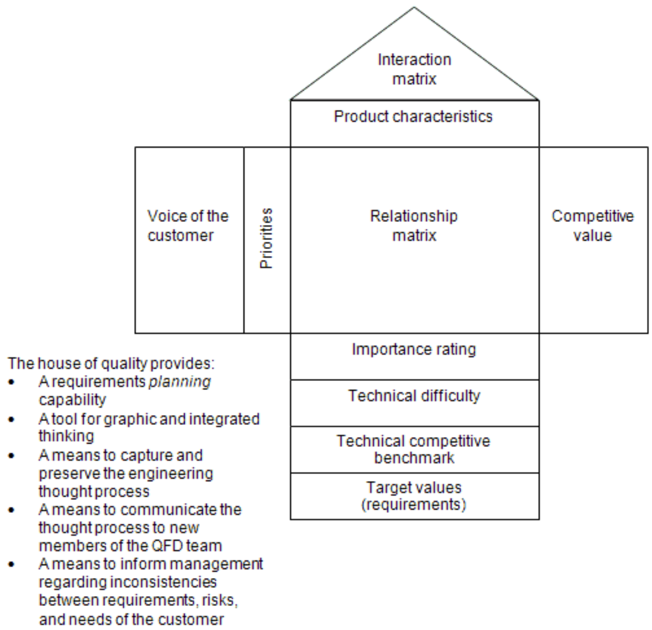

Figure 3.3: House of Quality (Chan & Wu, 2002).

The House of Quality (HoQ) (**Figure 3.3**) stands as a pivotal component in the QFD methodology, structured akin to a house with six primary sections:

1. Customer Needs: Enumerates the fundamental needs and expectations of the target audience.
2. Technical Specifications: Precisely delineates the measurable features and characteristics inherent to the product or service.
3. Relationship Matrix: Illustrates the correlation between customer needs and technical specifications, categorizing them as strong, medium, or weak.
4. Target Values: Identifies the optimal levels for each technical specification to meet customer expectations.
5. Competitive Assessment: Evaluates and compares the product or service against its competitors.
6. Prioritization: Systematically ranks the importance of technical specifications based on their alignment with customer needs and their overall impact.

Following the prioritization of attributes and qualities, QFD orchestrates their dissemination to the pertinent organizational functions, as delineated in following **Figure 3.4.** Consequently, QFD manifests as the systematic deployment of customer-centric attributes to the accountable functions within an organizational framework. This strategic alignment ensures that identified qualities are effectively translated into actionable initiatives, embodying a fundamental process in the integration of customer-driven perspectives into organizational functions.

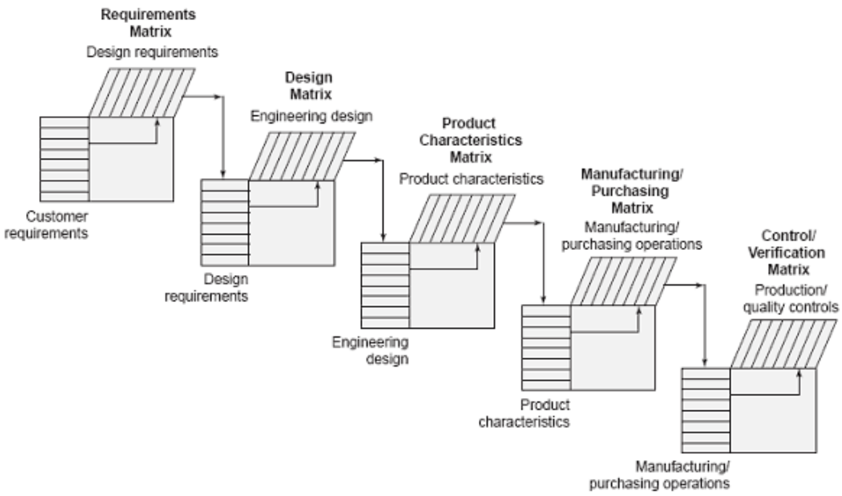

Figure 3.4: The relationships of QFD matrices (Akao & Mazur, 2003).

3.4.1 QFD Literature Review

In this section, a comprehensive analysis of scholarly articles featuring the QFD methodology has been conducted. The examination is grounded in a systematic review of articles published over the past decade (2013-2023) within the WoS database, utilizing "Quality Function Deployment" as the designated search keyword. The outcome of this meticulous search yielded a corpus of 1,805 papers for critical evaluation.

To offer a thorough perspective on the evolving terrain of QFD literature, a dedicated presentation of a trending topics' map is provided by using Bibliometrix tool. This visual depiction concisely encapsulates the dynamic interrelationships among terms, enriching the comprehension of semantic connections within the extensive body of literature. This deliberate adjustment serves to provide a focused and insightful portrayal of the progressive trajectory of QFD discourse spanning the past decade.

These analytical tools are employed purposefully to contend with the substantial volume of studies and distill essential patterns, providing a foundation for a nuanced understanding of the QFD landscape. Subsequently, this section transitions to a focused exploration of QFD applications within the realm of agriculture. This targeted investigation aims to substantiate the applicability of QFD in the design of SA systems, establishing a vital link to the central theme of this thesis.

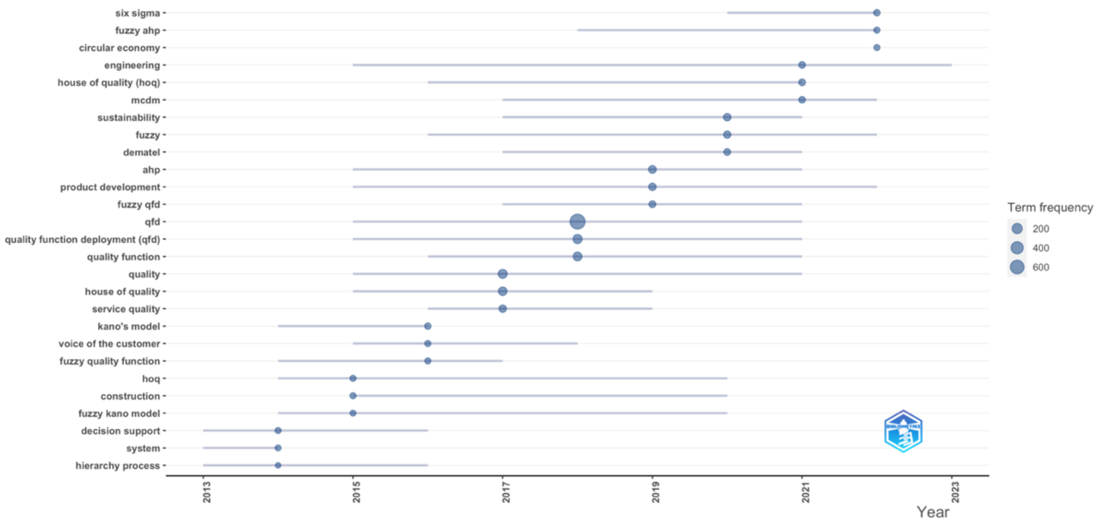

Figure 3.5: Trending topics in QFD literature between 2013 and 2023.

The enduring prominence of QFD and its various iterations is evident across the depicted timeframe, underscoring its sustained relevance within the realm of multi-objective optimization (Yazdani et al., 2019). Furthermore, the emergence of fuzzy QFD and the incorporation of the fuzzy Kano model signal a continued interest in integrating fuzzy logic into QFD methodologies, thereby enriching the analytical toolkit available for decision-makers (Ozalp et al., 2020).

Contrastingly, a discernible decline in interest is observed for conventional QFD tools such as the HoQ, and the voice of the customer. This shift in attention may be attributed to the advent of more advanced and specialized techniques. However, it is imperative to acknowledge that these traditional tools retain intrinsic value within specific contexts, potentially experiencing fluctuations in popularity corresponding to contextual demands.

The landscape of QFD applications is evolving, with a discernible surge in interest witnessed in domains like the circular economy, sustainability, and construction (Akao & Mazur, 2003; Büyüközkan & Çifçi, 2020; X. Chen et al., 2020). This expanding scope underscores the versatility and potential of QFD in addressing an array of optimization challenges, reflecting its adaptive capacity to meet the demands of diverse industries.

Complementing QFD, the concurrent emergence of decision support systems and hierarchy processes signals a growing acknowledgment of the benefits derived from amalgamating distinct optimization approaches. These complementary techniques not only augment the analytical depth but also provide nuanced insights, fostering informed decision-making in complex optimization scenarios.

As discerned from the trend plot, the trajectory of QFD literature portrays a dynamic field characterized by evolving interests and the promise of novel advancements. Staying attuned to emerging trends is imperative, providing avenues to explore innovative applications of QFD methodologies that are poised to confront the intricate challenges inherent in multi-objective optimization within the manufacturing domain.

3.4.2 QFD in Agriculture

Within this section, an examination of QFD studies, with a deliberate emphasis on applications in the agricultural domain, will be undertaken. Given the primary emphasis of this thesis on the design of SA systems, a strategic decision has been made to concentrate on QFD applications specifically within this realm. The ensuing table (**Table 3.6**) encapsulates a compendium of these studies, scrutinized through the dual lenses of Application Objective and Application Type, providing a nuanced exploration of their contextual relevance and contributions to the field.

Table 3.6: Review of QFD studies in Agriculture.

Authors	Application Objective	Application Type
(Ayyildiz et al., 2023)	Help hazelnut producers to improve their cultivation process by ensuring maximum customer satisfaction by listening to the voices of customers.	Case Study
(P. Singh & Agrawal, 2022)	Propose a framework for weather index insurance (WII) service design for agriculture.	Case Study
(Castiblanco Jimenez et al., 2021)	Utilize the QFD methodology as a structural framework to systematically identify and prioritize prevalent external factors influencing the fundamental constructs of the Technology Acceptance Model (TAM) in the contexts of e-learning, agricultural innovations, and virtual reality applications.	Illustrative Example
(Yazdani et al., 2019)	Translate customer requirements into tangible and measurable attributes of the product design within an agriculture supply chain framework.	Case Study
(Yazdani et al., 2017)	Design a decision support system that seamlessly integrates QFD and the TOPSIS to provide a	Case Study

	comprehensive solution for analyzing decision problems within the agricultural supply chain.	
(Ocampo Jimenez & Baeza Serrato, 2016)	Illustrate how QFD enhances municipal services to align with citizen expectations, with a specific focus on the Rural Development Directorate of Moroleón City Hall in Guanajuato, Mexico, supporting various agricultural initiatives.	Case Study

The abundance of studies focusing on QFD applications in the last decade, as mentioned in the previous section, is notable. However, when we turn our attention to more niche application areas of QFD, particularly those related to the subject matter of this thesis, it is observed that the number of studies is relatively limited. QFD emerges as a significant design tool, especially in specific focal points within the field of agriculture, such as irrigation and supply chain improvement, with a limited number of studies coming to our attention. Nevertheless, the existence of QFD applications in agriculture, validated in the literature, substantiates the suitability of employing this method in the thesis. However, as indicated, while in the literature, QFD is suggested to be applied separately to distinct areas within agricultural systems, this thesis proposes its comprehensive use as a design tool for the development of a SA system.

3.5 Overview of DEMATEL

One of the chapters of this thesis is concentrates on DEMATEL (Fontela & Gabus, 1976), recognized as one of the preeminent MCDM methods and ranked as the seventh most frequently applied approach in decision-making (Šmidovnik & Grošelj, 2023). Originating from the Geneva Research Centre of the Battelle Memorial Institute, DEMATEL facilitates the visualization of intricate causal relationships through matrices and digraphs. Its particular strength lies in dissecting cause-and-effect relationships within a system and identifying critical factors (Gabus & Fontela, 1972). The DEMATEL approach can be implied by dividing into various stages.

Step 1: Generation of the group influence matrix G.

At this stage, to evaluate the relationships between n factors $C = \{C_1, C_2, \dots, C_n\}$ in a system, suppose that l decision-makers (DMs) in a decision group $E = \{E_1, E_2, \dots, E_l\}$ are asked to designate the direct influence that factor C_i has on factor C_j. The scale used to assess these relations are as follows: "no influence (0)", "low influence (1)", "medium influence (2)", "high influence (3)" and very high influence (4)".
Accordingly the individual direct-influence matrix $G_k = \left[g_{ij}^k\right]_{n\times n}$ provided by the kth DM can be formed, where all principal diagonal elements are equal to zero and d_{ij}^k represents the judgement of DM E_k on the degree to which factor C_i affects factor C_j. By aggregating l DMs' opinions, the group direct-influence matrix $G = \left[g_{ij}\right]_{n\times n}$ can be obtained by the following equation:

$$g_{ij} = \frac{1}{l}\sum_{k=1}^{l} g_{ij}^k, i, j = 1,2, \dots, n \tag{3.4.1}$$

Step 2: Obtaining the normalized direct-influence matrix *N*.
After acquiring group direct-influence matrix *G* normalized direct-influence matrix *N* is obtained by the following equations:

$$X = \frac{G}{s} \tag{3.4.2}$$

$$s = max\left(\max_{1\le i\le n}\sum_{j=1}^{n} g_{ij}, \max_{1\le i\le n}\sum_{i=1}^{n} g_{ij}\right) \tag{3.4.3}$$

All elements in the matrix *N* are fulfilling $0 \le n_{ij} < 1$, $0 \le \sum_{j=1}^{n} n_{ij} \le 1$, and at least one *i* such that $\sum_{j=1}^{n} g_{ij} \le s$.

Step 3: Constructing total-influence matrix *T*.

With the help of the normalized direct-influence matrix *N,* the total-influence matrix $T = [t_{ij}]_{n\times n}$ is computed by the following equation:

$$T = N + N^2 + N^3 + \cdots + N^h = N(I - N)^{-1}, \text{ when } h \longrightarrow \infty \tag{3.4.5}$$

in which *I* is denoted as identity matrix.

Step 4: Obtaining the influential relation map.

This step is for obtaining vectors *D* and *R* by using the total-influence matrix *T,* can be generated by the following equations:

$$\begin{aligned} D &= [d_i]_{n\times 1} = \left[\sum_{j=1}^{n} n_{ij}\right]_{n\times 1} \\ R &= [r_j]_{1\times n} = \left[\sum_{i=1}^{n} n_{ij}\right]_{1\times n}^{T} \end{aligned} \tag{3.4.6}$$

The horizontal axis vector *(D+R)* named "Prominence" shows the strength of influences that are given and received of the factor. That means *(D+R)* represents the degree of central role that the factor plays in the system. The vertical axis vector *(D-R)* named "Relation" represents the net effect that the factor contributes to the system. If "Relation" value for the factor C_i is positive, that means the factor C_i has a net influence on the other factors and can be grouped into cause group. If the "Relation" value for the factor C_i is negative, then the factor C_i is being influenced by the other factors on the whole and should be grouped into effect group. The ultimate map can be obtained by mapping the data set of *(D+R, D-R)* as in the following **Figure 3.6**

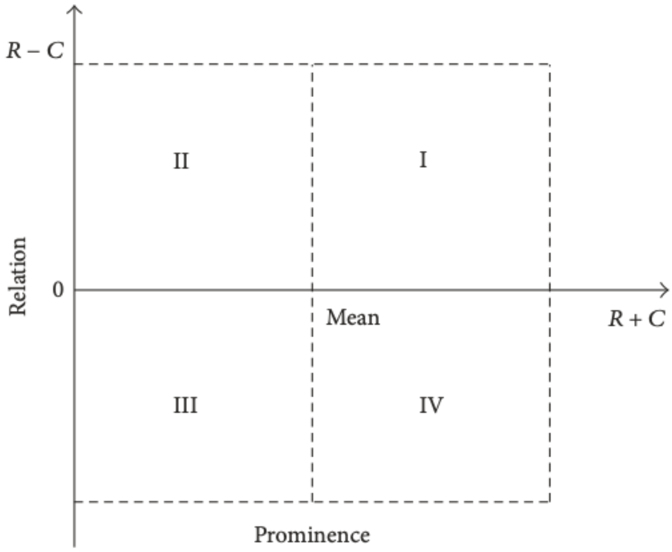

Figure 3.6: Four quadrant influential relation map.

By computing the mean of *(D +R)*, we discriminate factors residing in quadrant I as core or intertwined contributors, given their elevated prominence and interrelation. In quadrant II, factors are designated as driving or autonomous contributors, characterized by low prominence but high interrelation. Quadrant III encompasses factors with low prominence and interrelation, deemed independent or autonomous receivers due to their relative disconnection from the system. Quadrant IV accommodates factors with high prominence but low interrelation, termed impact factors or intertwined receivers. The latter, impacted by other factors, cannot be directly enhanced.

3.5.1 Literature Review of DEMATEL

DEMATEL has gained widespread application in diverse fields, including business management, engineering, healthcare, and social sciences (Si et al., 2018). Notably, its ability to handle both quantitative and qualitative data, coupled with its visual representation of relationships, makes it particularly valuable for researchers and practitioners alike.

This thesis concentration on the SA design and analysis, suggested DEMATEL methodology for strategy generation. Accordingly, “DEMATEL” AND “Smart Agriculture” is searched only one study can be obtained from WoS database.

Sharma et al., (2022) discern and analyze the enablers of blockchain technology adoption in both developed and developing economies. Their investigation involves identifying hierarchical relationships among these enablers, ranking them based on significance, and determining cause-effect groups within the identified enablers. Utilizing DEMATEL analysis, the study categorizes factors influencing the adoption of blockchain technology in the agriculture supply chain according to their causal relationships. In this study, the DEMATEL method is used with The ISM (Interpretive Structural Modeling) technique to investigate the hierarchy of the identified enablers.

3.6 Overview of VIKOR

VIKOR, an acronym for VIsekriterijumsko KOmpromisno Rangiranje, stands as a robust MCDM method. Its primary purpose is to aid decision-makers in the challenging task of ranking and selecting the most suitable alternative from a set of options that inherently possess conflicting criteria. Developed to handle scenarios where decisions involve multiple dimensions, VIKOR uniquely seeks to strike a balance between achieving the "closeness to the ideal" and optimizing the "maximal group utility."

One distinctive feature of VIKOR lies in its compensatory nature. This means that assigned weights to criteria can accommodate trade-offs, allowing commendable performance in one criterion to compensate for deficiencies in another. The method employs a dual-ranking mechanism where alternatives are evaluated based on their proximity to the ideal solution and maximal group utility. This dual-ranking strategy ensures a comprehensive assessment of each alternative, offering decision-makers a nuanced perspective. VIKOR's strength is particularly evident in its ability to pinpoint a compromise solution that effectively addresses conflicting criteria, providing a well-rounded perspective for DMs.

3.6.1 Literature Review of VIKOR

In this thesis, as aforementioned VIKOR methodology is suggested for the technology provider assessment framework. Accordingly, since the thesis mainly focuses on SA, SA studies for VIKOR studies are listed here in order to show its applicability in the SA context. Plus, the previous section of FFS literature shows its applicability with the FFS integration.

In the SA literature, two applications of VIKOR methodology comes forward. Ecer et al., (2023) propose an innovative integrated group decision-making framework to overcome previous limitations in the evaluation of agricultural UAVs for PA. Their study is geared towards identifying key criteria for assessing the optimal agricultural UAV, specifically targeting smallholder farmers operating in uncertain environments. Employing the q-rung fuzzy LOPCOW-VIKOR model, the approach integrates various techniques: q-rung orthopair fuzzy numbers for UAV selection, expert weight determination through regret measure, weighted logarithmic percentage change-driven objective weighting for criteria calculation, and a ranking algorithm that combines VIKOR with the Copeland strategy. VIKOR is chosen for its notable advantages: it mirrors human-driven decision-making, is computationally less complex than methods like AHP, avoids consistency issues common in AHP, represents unique outranking cases, outperforms TOPSIS, and accommodates personal choices for a powerful and rational ranking algorithm aligned with human-driven decision processes. This comprehensive approach convincingly addresses the complexities of selecting the best agricultural UAV for PA.

Furthermore Tang et al. (2023) propose a new comprehensive evaluation method based on user requirements for the design of agricultural intelligent robots. The study seeks to enhance the practicality and science of the program by integrating the Kano model, combined empowerment method, and VIKOR method into the evaluation process. The VIKOR methodology stands as an advantageous tool in the comprehensive evaluation and decision-making processes inherent in agricultural intelligent robot design. It is geared towards optimizing collective benefits while concurrently minimizing individual regret, thereby furnishing a compromise solution that closely aligns with the ideal scenario. Notably, this method augments the objectivity and precision of the solution evaluation, rendering it a valuable asset for decision-making within intricate systems. The inherent strengths of VIKOR render it particularly apt for tackling the challenges of MCDM in the realm of agricultural intelligent robot design, given its emphasis on prioritizing group benefits, mitigating regret, and enhancing overall objectivity and decision-making accuracy.

The VIKOR methodology emerges as a highly suitable tool for agricultural studies due to its inherent strengths in dealing with complex MCDM problems. Its ability to prioritize group benefits, minimize individual regret, and achieve compromise solutions closely aligns with the practical needs of agricultural decision-making. This is exemplified through its successful applications in evaluating agricultural UAVs for precision agriculture and designing agricultural intelligent robots. VIKOR's human-driven decision-making approach, computational efficiency, and capacity to handle unique outranking cases further solidify its position as a valuable instrument for navigating the complexities of agricultural decision-making. The VIKOR methodology, further enhanced by its 2TLFFS extension, proves exceptionally well-suited for tackling complex MCDM problems arising in agricultural studies.

4 STRATEGIC ANALYSIS OF TURKISH AGRICILTURE ENVIRONMENT

In the contemporary discourse, SA stands out as a potent driver for sustainable economic growth, particularly in its role as a facilitator for the transition to a circular economy. The challenges of navigating this transition are notably intricate in developing nations. To effectively embark on this transformative journey, strategic approaches are imperative, necessitating a thorough examination of the prevailing agricultural ecosystem. This study seeks to formulate strategies that advance Tütkiye's agricultural sector, leveraging strategic insights and linguistic-based decision-making integration. The primary research questions revolve around optimizing the benefits of SA by aligning strengths and opportunities with diverse socio-economic and environmental factors. Additionally, the study investigates effective strategies to mitigate the impact of weaknesses and threats within the agricultural landscape. To achieve this objective, the utilization of the 2TLFFS integrated DEMATEL methodology in conjunction with SWOT and PESTLE analyses is proposed. The integration of linguistic variables enhances the capacity to delve deeper into system analysis, aligning more closely with human cognitive processes.

The research commences with SWOT and PESTLE analyses applied to Türkiye's agricultural sector. Subsequently, the 2TLFFS-DEMATEL approach is employed to investigate interrelationships among analysis components. This inquiry aims to establish causal relations, facilitating the derivation of relevant strategies. The case study centers on Türkiye, a developing country, with outcomes indicating that the highest-priority strategies revolve around addressing "*economical strengthens and opportunities.*" Importantly, both the results and strategies undergo rigorous validation, drawing upon insights from recent literature and field experts. Significantly, these findings align seamlessly with the Sustainable Development Goals (SDGs), substantiating the study's broader significance in fostering a sustainable future for Turkey.

By addressing critical aspects of environmental resilience and economic stability, the study contributes to actionable strategies that resonate with global sustainability objectives for efficient SA transition.

4.1 Analyzing Turkish Agriculture Through SWOT/PESTLE

The imperative transition towards SA is an inevitable response to the imperatives of dynamic market and climatic conditions. Agricultural production, as a pivotal component of any nation's economy, remains significantly susceptible to the fluctuations within its ecosystem. To mitigate this vulnerability and enhance production efficiency, the adoption of SA emerges as a paramount focus (Garg & Alam, 2023).

The term "smart agriculture" pertains to the application of data-centric technologies aimed at the enhancement of agricultural methodologies with a focus on elevating productivity, sustainability, and profitability (Zhang, 2023). The essence of SA encompasses a multifaceted process that encompasses the acquisition, retention, processing, and comprehensive analysis of substantial datasets emanating from diverse origins, including but not limited to sensors, UAVs, and satellite systems (Q. Zhang, 2023). This sophisticated approach stands as a transformative force within the agricultural domain, poised to revolutionize and optimize farming practices through the efficient utilization of data-driven insights and advanced technology integration.

Developed nations have, in response, formulated and initiated comprehensive strategies and objectives to facilitate their agricultural transformation (Schroeder et al., 2021). This commitment extends to developing countries, particularly in the case of Türkiye, which holds strong ties with EU member states. However, the consistent challenge remains the effective implementation of these devised strategies, highlighting a persisting gap in the application of these initiatives (Pakeerathan, 2023). To bridge this disparity, this study places its emphasis on conducting an exhaustive analysis of both external and internal determinants influencing the state of Turkish agriculture. This analysis will be carried out through the application of SWOT/PESTLE methodologies. When used together, SWOT and PESTLE analyses provide a comprehensive, balanced view of the agricultural landscape, supporting well-informed decision-making and strategic planning, and helping to manage risks and seize opportunities effectively in the agriculture sector (Tran et al., 2023).

Motivated by the inherent advantages derived from the concurrent utilization of SWOT and PESTLE tools, this study endeavors to strategically propel Türkiye, a developing nation, toward the seamless integration of SA. The principal motivation behind this research lies in the imperative need to formulate efficacious strategies that facilitate a harmonious transition to SA within the Turkish agricultural landscape. The proposed framework is presented in detail in the following **Figure 4.1**.

4.1.1 Internal Factors of SWOT/ PESTLE Analysis

Internal factors within this analysis encompass the intrinsic attributes of the Turkish agricultural sector, characterized by strengths and weaknesses. These two dimensions are meticulously evaluated within the framework of six distinct dimensions: Political, Economic, Social, Technological, Legal, and Environmental.

4.1.1.1 Strengths

Political Strengths: Türkiye exhibits notable political strengths within its agricultural sector. Firstly, the country maintains robust ties with international organizations, a prime example being its close association with the European Union (Keskin, 2021). This engagement reflects a commitment to uphold international standards and agreements, ultimately enhancing the quality and competitiveness of Turkish agricultural products in the global market. Additionally, the designation of extensive plains as agricultural protected areas underpins Turkey's dedication to preserving crucial agricultural lands. This strategic move safeguards agricultural sustainability, bolsters food security, and supports the livelihoods of rural communities (Santarius et al., 2023).

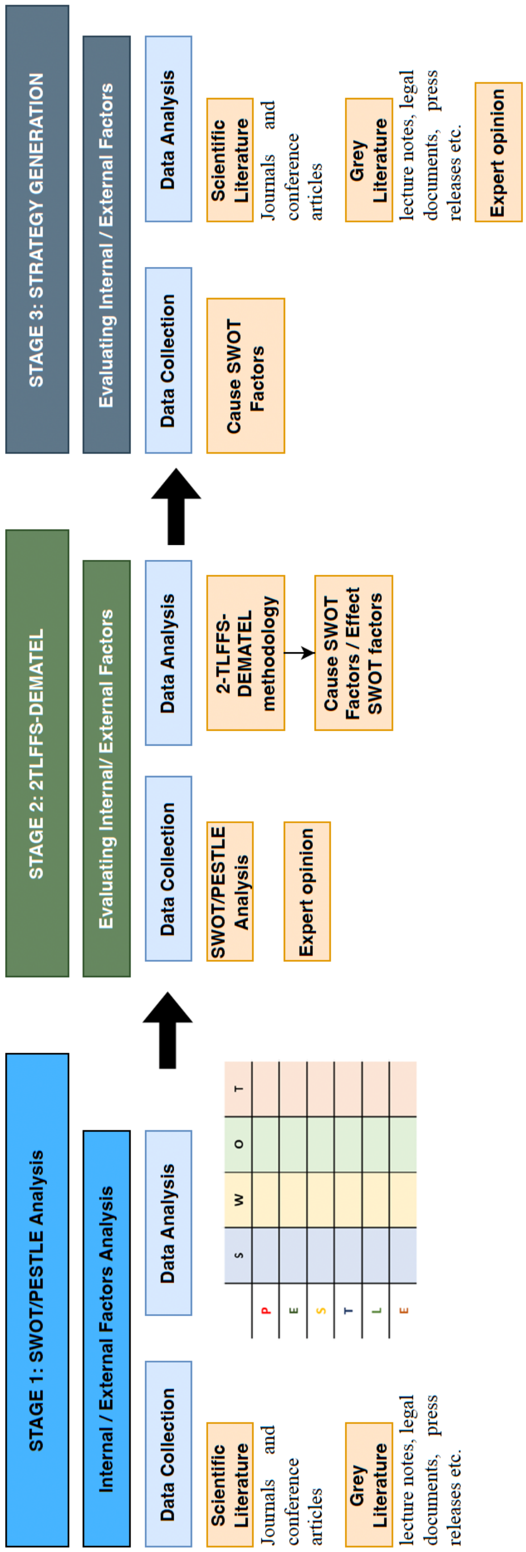

Figure 4.1: Suggested 2TLFFS-DEMATEL-SWOT/PESTLE methodology.

Economic Strengths: A critical economic strength in Turkish agriculture is the regional product diversity, which includes products with geographical indications (Yılmaz et al., 2019). This diversity is far more than a mere assortment of crops; it plays a significant role in marketing and trade. By showcasing unique regional products, Turkey creates niche markets and adds substantial value to its agricultural sector. This not only fosters economic growth at the local and national levels but also sets Turkish agricultural products apart in a global marketplace.

Social Strengths: The cultural significance of agriculture within Turkish society serves as a remarkable social strength. This cultural attachment goes beyond mere nostalgia for traditional farming practices; it instills a deep appreciation for agriculture and rural life (Akdemir et al., 2021). This cultural underpinning cultivates a strong sense of community support, encourages the preservation of age-old farming traditions, and, importantly, inspires the younger generation to engage in and carry forward the agricultural legacy.

Technological Strengths: Technological advancements in Turkish agriculture are underpinned by the reduction of product and input costs through innovation. This represents a pivotal technological strength, as it not only enhances efficiency in farming practices but also significantly reduces production expenses (Tekin, 2019). The embrace of technology drives the sector's competitiveness, allowing Turkish agriculture to remain at the forefront of sustainable and efficient practices.

Legislative Strengths: Turkey's government exhibits a proactive approach in aligning the country's agricultural policies with those of the EU, a legislative strength that holds considerable weight (dongusel.csb.gov.tr, n.d.). This alignment ensures compliance with international standards, fosters increased trade opportunities, and promotes sustainable agricultural practices that are in line with EU directives. By doing so, Turkey positions itself to reap the benefits of a harmonized regulatory environment, enhancing the growth and resilience of its agricultural sector.

Environmental Strengths: Turkey boasts a notable environmental strength in the form of diverse climate and geography. This diversity enables the cultivation of an extensive range of crops and agricultural products (Sarica et al., 2023). Moreover, it provides resilience to climatic fluctuations and supports year-round production of various goods. This environmental advantage contributes to enhanced food security and export potential, making Turkey a formidable player in the global agricultural arena.

4.1.1.2 Weaknesses

Political Weaknesses: Political weaknesses in Turkish agriculture include shortcomings in long-term agricultural policies, which have the potential to hinder the sector's strategic planning and adaptability (Nizam & Yenal, 2020). Additionally, the designation of large plains as agricultural protected areas, while a strength in some contexts, can also be seen as a political weakness if it restricts land use and development opportunities. Inadequate or inconsistent agricultural policies may lead to uncertainties and hinder farmers' abilities to make informed decisions regarding investments and resource allocation, potentially affecting the sector's long-term sustainability.

Economic Weaknesses: Economic instability is a pressing economic weakness faced by Turkish agriculture (Basak et al., 2022). Factors such as currency exchange rate fluctuations and inflation can lead to income volatility for farmers, affecting their financial stability and the sector's overall economic resilience (Yılmaz et al., 2019). This economic vulnerability can disrupt the ability of farmers to make strategic investments and effectively manage financial risks.

Social Weaknesses: Among the social weaknesses, the lack of interest and awareness among the new generation about agricultural production is a concerning trend. As urbanization and modernization take precedence, the appeal of non-agricultural careers has led to a declining interest in farming among the younger generation (Akdemir et al., 2021). This shift in societal values could lead to a decreasing agricultural workforce, potentially diminishing overall agricultural productivity. Additionally, the decrease in the elderly farmer population due to migration and the challenges associated with accessing traditional agricultural knowledge further erode the sector's social fabric, hindering the transfer of vital farming expertise.

Technological Weaknesses: A notable technological weakness in Turkish agriculture is the sector's struggle to adapt to technological advancements effectively (Tekin, 2019). The inability to fully harness modern agricultural technologies, such as precision farming and data-driven practices, can hinder productivity and risk management. Barriers such as limited access to technology, insufficient education, and financial constraints can lead to inefficiencies in production and overall risk management (FAO, 2014).

Legislative Weaknesses: Land ownership and fragmentation present significant legislative weaknesses (Adalet, 2022). Land parcels fragmented into smaller, less efficient units impede farmers' abilities to optimize land use and invest in modern agricultural equipment, thereby limiting their potential for economies of scale. This fragmentation can lead to decreased agricultural productivity and competitiveness in the long term.

Environmental Weaknesses: The vulnerability of Turkish agriculture to climate change is an environmental weakness of critical concern. Increasingly unpredictable weather patterns, coupled with more frequent droughts and extreme events, have the potential to significantly impact crop yields and livestock production (N. Ahmed et al., 2023; Pilevneli et al., 2023). The sector's vulnerability to climate change necessitates the development of adaptation strategies and investments in resilient agricultural practices to mitigate the environmental risks it faces.

4.1.2 External Factors of SWOT /PESTLE Analysis

External factors in this analysis encapsulate the overarching influences on the Turkish agricultural sector. These factors are examined across six key dimensions: Political, Economic, Social, Technological, Legal, and Environmental. This comprehensive approach delves into how the sector is impacted by external forces, shaping its opportunities and threats within the broader socio-economic and regulatory context.

4.1.2.1 Opportunities

Political Opportunities: The Turkish agricultural sector stands to benefit from its participation in international treaties, representing a significant political opportunity. These treaties foster international cooperation and trade, offering access to broader markets and potential partnerships (Nizam & Yenal, 2020). Compliance with international agreements, particularly those with the European Union, can open doors to trade and technological exchange, enhancing the sector's global reach and competitiveness.

Economic Opportunities: Within the realm of economic opportunities in the Turkish agricultural sector, two crucial prospects come to the fore (Kaya & Kadanalı, 2021). The first opportunity revolves around the continuity of market demand, which highlights the sector's stability and its ability to maintain consistent outlets for agricultural products. The second opportunity stems from the escalating demand for natural products across diverse sectors. This trend capitalizes on the global movement toward natural and sustainable products, offering the sector new pathways for market expansion and value enhancement, particularly within the realm of export markets.

Social Opportunities: Consumer behavior tendencies and habits present social opportunities for the Turkish agricultural sector. As consumer preferences evolve towards healthier, locally sourced, sustainably produced goods, the sector can cater to these demands (Zerssa et al., 2021). This evolution includes a growing interest in products with geographical indications (GIs), which highlight the unique qualities and origins of certain regional agricultural products. By aligning with this trend and offering GI products, the sector can forge a stronger connection with consumers and access new market segments, capitalizing on the appeal of authentic and regionally distinctive agricultural items.

Technological Opportunities: Technological integration in the form of transparent value chains and data-driven decision-making presents technological opportunities. Transparent value chains, enabled by technology, enhance accountability and traceability, ensuring product quality and safety (FAO, 2014). Data-driven decision-making boosts production efficiency, allowing the sector to optimize processes, reduce waste, and enhance overall productivity.

Legislative Opportunities: The harmonization of Turkish agricultural standards with EU standards represents a legislative opportunity. This alignment not only facilitates trade but also ensures compliance with international quality and safety standards (Yeni & Teoman, 2022). It fosters a regulatory environment that encourages sustainable and responsible agricultural practices.

Environmental Opportunities: The use of renewable energy sources presents an economic opportunity for the Turkish agricultural sector. As renewable energy technologies continue to advance, they offer a sustainable and cost-effective means to power agricultural operations, reducing both operational expenses and environmental impact (Bakirci & Kirtiloglu, 2022).

4.1.2.2 Threats

Political Threats: War and political uncertainties represent critical political threats to the Turkish agricultural sector. These uncertainties can lead to disruptions in trade, market instability, and potential challenges in accessing essential resources (Adalet, 2022). Political instability can hinder the sector's ability to make long-term plans and investments, posing a significant risk to its resilience and sustainability.

Economic Threats: Two noteworthy economic threats include rapid urbanization and income volatility due to the increase in extreme weather events. Rapid urbanization can result in the encroachment of urban areas on agricultural land, potentially limiting the availability of arable land and creating land use conflicts. Income volatility caused by extreme weather events, such as droughts or floods, can disrupt agricultural production, impacting the financial stability of farmers and the sector as a whole (Kaya & Kadanalı, 2021).

Social Threats: Food security is a vital social threat to the Turkish agricultural sector. Ensuring a consistent and sufficient food supply to meet the needs of the growing population is a complex challenge. Any disruptions in food production, distribution, or access can jeopardize the well-being of the population, highlighting the need for resilience in the agricultural sector (Akdemir et al., 2021).

Technological Threats: The Turkish agricultural sector faces technological threats related to cybersecurity risks and dependency on technology and data. Cybersecurity vulnerabilities can compromise the integrity and security of critical digital systems, potentially disrupting agricultural operations (Caviglia et al., 2023). Overreliance on technology and data without sufficient safeguards can lead to data breaches, financial losses, and operational disruptions.

Legislative Threats: Climate regulations pose a critical legislative threat to the Turkish agricultural sector. Evolving climate-related regulations may require the sector to comply with new standards and sustainability practices. These regulations can impose additional costs and administrative burdens, potentially affecting the sector's operations, compliance, and competitiveness (Nizam & Yenal, 2020). Therefore, it's essential for the sector to adapt to changing legislative landscapes to ensure long-term viability.

Environmental Threats: Environmental threats, on the other hand, encompass climate change and environmental pollution. Climate change can lead to shifting weather patterns, altered precipitation levels, and more frequent extreme weather events, which pose significant risks to agricultural production (Department of Agricultural Economics, Faculty of Agriculture, Ege University, Izmir-35100 Turkey et al., 2020). Environmental pollution, including soil and water contamination, can harm the land's fertility and water resources, jeopardizing the sector's sustainability and the quality of agricultural products. These environmental challenges necessitate the development of adaptive strategies and sustainable agricultural practices to mitigate risks and ensure the sector's resilience in the face of environmental changes.

The SWOT and PESTLE analysis of the Turkish agricultural sector reveals a multifaceted landscape. Internally, the sector exhibits strengths such as international ties and rich product diversity but faces weaknesses in long-term policies, technology adoption, and generational shifts. Externally, opportunities lie in market continuity, increased demand for natural products, and evolving consumer behavior, including an interest in products with geographical indications. However, the sector confronts external threats, including political uncertainties, economic challenges tied to urbanization and extreme weather events, social concerns regarding food security, technological vulnerabilities, and the need to comply with evolving legislative standards, especially climate regulations. Environmental challenges posed by climate change and pollution further underscore the necessity for resilient and sustainable practices within the sector.

The following
Figure 4.2 provides a comprehensive summary of the structured SWOT/PESTLE analysis and the identified factors. These factors will serve as essential components in the 2TLFFS-DEMATEL methodology, where they will undergo a weighting process and in-depth causal analysis. This meticulous investigation aims to discern the interrelationships and causal links among these factors, providing a more nuanced understanding of their impact on the Turkish agricultural sector.

PESTLE/SWOT	Internal		External	
	Strenghts	Weaknesses	Opportunities	Threats
Political	**SP1** Strong ties with international organizations and the obligation to comply with international agreements, especially the European Union. **SP2** Designation of large plains as agricultural protected areas.	**PW1** Shortcomings in long-term agricultural policies.	**PO1** Being subject to international treaties.	**PT1** War and political uncertainties.
Economical	**EcS1** Regional product diversity, including products with geographical indications, is also significant for marketing purposes.	**EcW1** Economical instability.	**EcO1** Continuity of market demand. **EcO2** Increasing demand for natural products in different sectors.	**EcT1** Rapid urbanization. **EcT2** Income volatility due to increase in extreme weather events.
Social	**SS1** Cultural significance of agriculture.	**SW1** Lack of interest and awareness among the new generation about agriculture production. **SW2** The decrease in the elderly farmer population and the difficulty in accessing traditional knowledge due to migration.	**SO1** Consumer behavior tendencies and habits.	**ST1** Food security.
Technological	**TS1** Reduction of product/input costs through technology.	**TW1** Weakness in adapting to technological advancements and effectively utilizing technology for risk and production management.	**TO1** Transparent value chains with technological integration. **TO2** Data-driven decision-making for production efficiency.	**TT1** Cybersecurity risks. **TT2** Dependency on technology and data.
Legislative	**LS1** The government's efforts to align Turkish agricultural policies with EU agricultural policies.	**LW1** Land ownership and fragmentation.	**LO1** Harmonization with EU Standards.	**LT1** Climate regulations.
Environmental	**ES1** Diverse climate and geograpghy.	**EW1** Vulnerability to climate change.	**EO1** Opportunities for the use of renewable energy.	**ET1** Climate change and environmental pollution.

Figure 4.2: SWOT/PESTLE analysis factors for Turkish agriculture.

4.2 SWOT/PESTLE Factor Weighting and Assessment through 2TLFFS-DEMATEL

In this section, we will employ the 2TLFFS-DEMATEL methodology to analyze the identified SWOT/PESTLE factors. To ensure a comprehensive assessment, we have assembled a decision-making team comprising five experts/decision-makers (DMs) with substantial experience in the agricultural sector. These experts possess diverse backgrounds, specializing in various facets of the agricultural ecosystem, including agri-food supply chain management, agricultural production, technological farming, sustainability consultancy for the agri-food sector, and academia. Given their multifaceted expertise, different weights have been assigned to each expert within the 2TLFFS-DEMATEL framework. Their details are provided in the following **Table 4.1.** The overarching objective of this 2TLFFS-DEMATEL analysis is to discern the causal factors that will inform the development of effective strategies for a seamless transition toward intelligent and sustainable agriculture in Türkiye. To achieve this, we will follow a structured sequence of steps within the 2TLFFS-DEMATEL application.

Table 4.1: DM's background.

DM#	**Experience**
DM1	An academic who works on the use of smart technologies (mostly in supply chains).
DM2	A Ph.D. consultant about digital transformation.
DM3	A manager from an international company that produces smart technology.
DM4	An academician who works on sustainable and SA.
DM5	A consultant whose expertise is the digital transformation in agriculture.

4.2.1 Computational steps of 2TLFFS-DEMATEL

Step 1. Creating the average matrix (G).

In this phase, individual meetings are arranged with experts, each conducted separately. The identified SWOT/PESTLE factors are presented to the expert group, who are then tasked with evaluating these factors through pairwise comparisons, using provided linguistic set. The weighting of their assessments is determined by their experience in the field, measured in working years. The following **Table 4.2** presents the linguistic set provided to DMs. These linguistic set play a pivotal role in the DEMATEL application, where they serve as the basis for assessing the relative importance of each factor in relation to every other factor. This evaluation process is instrumental in deciphering the interrelationships and causal dependencies among the identified factors. The weightings for the DM group is given in order:

$w_n = \{(0.27, 0.21, 0.25, 0.17,0.10)\}$

, n representing the number of experts, $n = 1,2,3,4,5$.

Table 4.2: 2TLFFS Linguistic sets provided to DMs.

Linguistic Variables	Abbreviations	Membership	Non-membership
Extremely Low Importance	ELI	ELI	EHI
Very Low Importance	VLI	VLI	VHI
Low Importance	LI	LI	HI
Moderately Low Importance	MLI	MLI	MHI
Fair	F	F	F
Moderately High Importance	MHI	MHI	MLI
High Importance	HI	HI	LI
Very High Importance	VHI	VHI	VLI
Extremely High Importance	EHI	EHI	ELI

The following **Table 4.3** presents the assessment of first DM as an example with membership and nonmemberhsip values. Also following **Table 4.4** gives the ultimate aggregated matrix with 2TLFFS beta values. The aggregated values are obtained by using Eq. (3.2.6). Here the DM numver is 5 and thw weights are assigned as previously mentioned.

Table 4.3a: DM1's pairwise assessment for 2TLFFS-DEMATEL.

	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
	SP1		**SP2**		**EcS1**		**SS1**		**TS1**		**LS1**		**ES1**		**PW1**		**EcW1**		**SW1**		**SW2**		**TW1**		**LW1**		**EW1**		**PO1**	
SP1	0	0	ML	H	AE	AH	H	ML	AH	AE	E	E	AH	AE	H	ML	ML	H	ML	H	AE	AH	AE	AH	E	E	ML	H	E	E
SP2	AH	AE	0	0	ML	H	ML	H	AE	AH	AH	AE	ML	H	ML	H	H	ML	ML	H	ML	H	ML	H	AH	AE	E	E	AH	AE
EcS1	H	ML	VH	L	0	0	AE	AH	E	E	H	ML	AE	AH	AH	AE	H	ML	ML	H	ML	H	ML	H	H	ML	AH	AE	H	ML
SS1	AH	AE	H	ML	AE	AH	0	0	ML	H	AH	AE	ML	H	AE	AH	AH	AE	ML	H	ML	H	AE	AH	AH	AE	ML	H	AH	AE
TS1	ML	H	AH	AE	VH	L	AH	AE	0	0	ML	H	H	ML	H	ML	ML	H	AE	AH	AE	AH	E	E	ML	H	AH	AE	ML	H
LS1	E	E	E	E	E	E	AE	AH	ML	H	0	0	ML	H	AH	AE	ML	H	AE	AH	AE	AH	ML	H	E	E	ML	H	E	E
ES1	AE	AH	H	ML	E	E	H	ML	ML	H	AE	AH	0	0	AH	AE	AH	AE	ML	H	ML	H	ML	H	AE	AH	E	E	AE	AH
PW1	AE	AH	H	ML	AE	AH	AH	AE	ML	H	AE	AH	ML	H	0	0	AH	AE	ML	H	ML	H	ML	H	AE	AH	AH	AE	AE	AH
EcW1	VH	L	P	EL	ML	H	E	E	AE	AH	VH	L	AE	AH	H	ML	0	0	ML	H	ML	H	AE	AH	VH	L	ML	H	VH	L
SW1	VH	L	VH	L	VH	L	VH	L	H	ML	VH	L	H	ML	VH	L	H	ML	0	0	H	ML	ML	H	VH	L	H	ML	VH	L
SW2	H	ML	P	EL	P	EL	VH	L	H	ML	H	ML	VH	L	VH	L	H	ML	E	E	0	0	ML	H	H	ML	H	ML	H	ML
TW1	H	ML	AH	AE	AE	AH	H	ML	VH	L	H	ML	H	ML	VH	L	H	ML	AH	AE	AH	AE	0	0	H	ML	H	ML	H	ML
LW1	E	E	E	E	ML	H	AE	AH	ML	H	E	E	ML	H	AE	AH	AE	AH	ML	H	ML	H	ML	H	0	0	E	E	E	E
EW1	H	ML	VH	L	H	ML	H	ML	H	ML	H	ML	VH	L	H	ML	E	E	ML	H	ML	H	ML	H	H	ML	0	0	H	ML
PO1	AH	AE	AE	AH	AE	AH	E	E	ML	H	AH	AE	ML	H	H	ML	ML	H	AE	AH	AE	AH	ML	H	AH	AE	ML	H	0	0
EcO1	ML	H	AH	AE	H	ML	AE	AH	ML	H	ML	H	ML	H	AE	AH	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H
EcO2	ML	H	AH	AE	H	ML	AE	AH	ML	H	ML	H	AE	AH	AE	AH	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H
SO1	AE	AH	AH	AE	AE	AH	AE	AH	ML	H	AE	AH	ML	H	AE	AH	L	VH	ML	H	ML	H	ML	H	AE	AH	AE	AH	AE	AH
TO1	AE	AH	H	ML	H	ML	H	ML	AH	AE	AE	AH	AH	AE	H	ML	AH	AE	ML	H	ML	H	AH	AE	AE	AH	AH	AE	AE	AH
TO2	ML	H	VH	L	H	ML	VH	L	AH	AE	ML	H	AH	AE	H	ML	H	ML	ML	H	ML	H	AH	AE	ML	H	AH	AE	ML	H
LO1	ML	H	E	E	E	E	E	E	E	E	ML	H	ML	H	H	ML	ML	H	ML	H	AE	AH	ML	H	ML	H	ML	H	ML	H
EO1	ML	H	AH	AE	AH	AE	AH	AE	E	E	ML	H	AH	AE	AH	AE	AE	AH	AE	AH	AE	AH	ML	H	ML	H	AE	AH	ML	H
PT1	H	ML	ML	H	ML	H	AH	AE	ML	H	H	ML	ML	H	ML	H	E	E	ML	H	ML	H	ML	H	H	ML	ML	H	H	ML
EcT1	H	ML	VH	L	P	EL	P	EL	H	ML	H	ML	H	ML	VH	L	H	ML	AH	AE	H	ML	H	ML	H	ML	H	ML	H	ML
EcT2	H	ML	AH	AE	H	ML	H	ML	AE	AH	H	ML	AE	AH	AE	AH	E	E	AE	AH	AE	AH	ML	H	H	ML	AE	AH	H	ML
ST1	VH	L	P	EL	VH	L	VH	L	E	E	VH	L	H	ML	VH	L	VH	L	H	ML	VH	L	VH	L	VH	L	VH	L	VH	L
TT1	H	ML	AH	AE	E	E	AH	AE	E	E	H	ML	H	ML	AH	AE	H	ML	H	ML	H	ML	AH	AE	H	ML	AH	AE	H	ML
TT2	AE	AH	ML	H	H	ML	E	E	E	E	AE	AH	AH	AE	H	ML	H	ML	H	ML	VH	L	AH	AE	AE	AH	H	ML	AE	AH
LT1	E	E	AE	AH	AH	AE	AH	AE	ML	H	E	E	E	E	ML	H	ML	H	ML	H	ML	H	ML	H	E	E	E	E	E	E
ET1	H	ML	H	ML	VH	L	H	ML	H	ML	H	ML	AH	AE	ML	H	ML	H	ML	H	ML	H	ML	H	H	ML	E	E	H	ML

Table 4.3b: DM1’s pairwise assessment for 2TLFFS-DEMATEL.

	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
	EcO1		**EcO2**		**SO1**		**TO1**		**TO2**		**LO1**		**EO1**		**PT1**		**EcT1**		**EcT2**		**ST1**		**TT1**		**TT2**		**LT1**		**ET1**	
SP1	AH	AE	AH	AE	H	ML	AH	AE	H	ML	E	E	H	ML	ML	H	ML	H	ML	H	L	VH	AH	AE	AH	AE	E	E	AE	AH
SP2	AH	AE	AH	AE	AH	AE	AE	AH	AE	AH	AH	AE	AH	AE	H	ML	ML	H	H	ML	AE	AH	AE	AH	AE	AH	AH	AE	AH	AE
EcS1	H	ML	AH	AE	AH	AE	E	E	E	E	H	ML	H	ML	H	ML	ML	H	H	ML	AE	AH	E	E	E	E	H	ML	H	ML
SS1	AH	AE	AH	AE	AH	AE	ML	H	ML	H	AH	AE	H	ML	AH	AE	ML	H	AH	AE	AE	AH	ML	H	ML	H	AH	AE	AH	AE
TS1	ML	H	H	ML	H	ML	H	ML	H	ML	ML	H	VH	L	ML	H	AH	AE	ML	H	AH	AE	E	E	E	E	ML	H	ML	H
LS1	E	E	H	ML	H	ML	ML	H	ML	H	0	0	H	ML	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	E	E	E	E
ES1	AE	AH	AH	AE	AH	AE	ML	H	ML	H	AE	AH	E	E	AH	AE	ML	H	AH	AE	ML	H	ML	H	ML	H	AE	AH	AE	AH
PW1	AE	AH	AH	AE	AH	AE	ML	H	ML	H	AE	AH	ML	H	AH	AE	ML	H	AH	AE	L	VH	ML	H	ML	H	AE	AH	AE	AH
EcW1	VH	L	AH	AE	AH	AE	AE	AH	AE	AH	VH	L	AE	AH	E	E	ML	H	AE	AH	ML	H	AE	AH	AE	AH	VH	L	VH	L
SW1	VH	L	AH	AE	AH	AE	H	ML	H	ML	VH	L	AH	AE	H	ML	ML	H	H	ML	E	E	H	ML	H	ML	VH	L	VH	L
SW2	H	ML	AH	AE	AH	AE	H	ML	H	ML	H	ML	AH	AE	H	ML	ML	H	H	ML	E	E	H	ML	H	ML	H	ML	H	ML
TW1	H	ML	AH	AE	AH	AE	VH	L	VH	L	H	ML	H	ML	H	ML	ML	H	H	ML	E	E	VH	L	VH	L	H	ML	H	ML
LW1	E	E	AH	AE	AH	AE	ML	H	ML	H	E	E	ML	H	AE	AH	ML	H	AE	AH	AE	AH	ML	H	ML	H	E	E	E	E
EW1	H	ML	AH	AE	AH	AE	H	ML	H	ML	H	ML	AH	AE	E	E	ML	H	E	E	E	E	H	ML	H	ML	H	ML	H	ML
PO1	AH	AE	AH	AE	AH	AE	ML	H	ML	H	AH	AE	H	ML	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	AH	AE	AH	AE
EcO1	0	0	AH	AE	AH	AE	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H
EcO2	ML	H	0	0	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H
SO1	AE	AH	AH	AE	0	0	ML	H	ML	H	AE	AH	ML	H	L	VH	ML	H	L	VH	ML	H	ML	H	ML	H	AE	AH	AE	AH
TO1	AE	AH	AH	AE	AH	AE	0	0	AH	AE	AE	AH	H	ML	AH	AE	ML	H	AH	AE	AH	AE	AH	AE	AH	AE	AE	AH	AE	AH
TO2	ML	H	AE	AH	AE	AH	AH	AE	0	0	ML	H	H	ML	H	ML	ML	H	H	ML	H	ML	AH	AE	AH	AE	ML	H	ML	H
LO1	ML	H	AH	AE	AH	AE	E	E	AE	AH	0	0	H	ML	ML	H	ML	H	ML	H	AH	AE	E	E	E	E	ML	H	ML	H
EO1	ML	H	AH	AE	AH	AE	E	E	AE	AH	ML	H	0	0	AE	AH	ML	H	AE	AH	ML	H	E	E	E	E	ML	H	ML	H
PT1	H	ML	AH	AE	AH	AE	ML	H	ML	H	H	ML	ML	H	0	0	ML	H	E	E	ML	H	ML	H	ML	H	H	ML	H	ML
EcT1	H	ML	AH	AE	AH	AE	H	ML	H	ML	H	ML	VH	L	H	ML	0	0	H	ML	E	E	H	ML	H	ML	H	ML	H	ML
EcT2	H	ML	AH	AE	AH	AE	AE	AH	AE	AH	H	ML	ML	H	E	E	ML	H	0	0	ML	H	AE	AH	AE	AH	H	ML	H	ML
ST1	VH	L	P	EL	P	EL	E	E	AH	AE	VH	L	ML	H	VH	L	ML	H	VH	L	0	0	E	E	E	E	VH	L	VH	L
TT1	H	ML	VH	L	VH	L	E	E	E	E	H	ML	VH	L	H	ML	E	E	H	ML	AE	AH	0	0	E	E	H	ML	H	ML
TT2	AE	AH	H	ML	H	ML	E	E	E	E	AE	AH	H	ML	H	ML	E	E	H	ML	AH	AE	E	E	0	0	AE	AH	AE	AH
LT1	E	E	AH	AE	AH	AE	ML	H	ML	H	E	E	AE	AH	ML	H	ML	H	ML	H	ML	H	ML	H	ML	H	0	0	H	ML
ET1	H	ML	AH	AE	AH	AE	H	ML	H	ML	H	ML	AE	AH	ML	H	H	ML	ML	H	AE	AH	H	ML	H	ML	H	ML	0	0

Table 4.4a: Ultimate aggregated matrix with 2TLFFS beta values.

	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
	SP1		SP2		EcS1		SS1		TS1		LS1		ES1		PW1		EcW1		SW1		SW2		TW1		LW1		EW1		PO1	
SP1			1.159	7.569	3.000	5.000	3.717	6.145	2.998	6.632	2.354	7.004	2.998	6.632	3.717	6.145	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309	2.354	7.004	1.159	7.569	2.354	7.004
SP2	2.998	6.632			1.159	7.569	1.159	7.569	1.747	7.309	2.998	6.632	1.159	7.569	1.159	7.569	3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	2.998	6.632	2.354	7.004	2.998	6.632
EcS1	3.717	6.145	4.617	5.404			1.747	7.309	2.354	7.004	3.717	6.145	1.747	7.309	2.998	6.632	3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	3.717	6.145	2.998	6.632	3.717	6.145
SS1	2.998	6.632	3.717	6.145	1.747	7.309			1.159	7.569	2.998	6.632	1.159	7.569	1.747	7.309	2.998	6.632	1.159	7.569	1.159	7.569	1.747	7.309	2.998	6.632	1.159	7.569	2.998	6.632
TS1	1.159	7.569	2.998	6.632	4.617	5.404	2.998	6.632			1.159	7.569	3.717	6.145	3.717	6.145	1.159	7.569	1.747	7.309	1.747	7.309	2.354	7.004	1.159	7.569	2.998	6.632	1.159	7.569
LS1	2.354	7.004	2.354	7.004	2.354	7.004	1.747	7.309	1.159	7.569			1.159	7.569	2.998	6.632	1.159	7.569	1.747	7.309	1.747	7.309	1.159	7.569	2.354	7.004	1.159	7.569	2.354	7.004
ES1	1.747	7.309	3.717	6.145	2.354	7.004	3.717	6.145	1.159	7.569	1.747	7.309			2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	2.354	7.004	1.747	7.309
PW1	1.747	7.309	3.717	6.145	1.747	7.309	2.998	6.632	1.159	7.569	1.747	7.309	1.159	7.569			2.998	6.632	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	2.998	6.632	1.747	7.309
EcW1	4.617	5.404	8.000	0.000	1.159	7.569	2.354	7.004	1.747	7.309	4.617	5.404	1.747	7.309	3.717	6.145			1.159	7.569	1.159	7.569	1.747	7.309	4.617	5.404	1.159	7.569	4.617	5.404
SW1	4.617	5.404	4.617	5.404	4.617	5.404	4.617	5.404	3.717	6.145	4.617	5.404	3.717	6.145	4.617	5.404	3.717	6.145			3.717	6.145	1.159	7.569	4.617	5.404	3.717	6.145	4.617	5.404
SW2	3.717	6.145	8.000	0.000	8.000	0.000	4.617	5.404	3.717	6.145	3.717	6.145	4.617	5.404	4.617	5.404	3.717	6.145	2.354	7.004			1.159	7.569	3.717	6.145	3.717	6.145	3.717	6.145
TW1	3.717	6.145	2.998	6.632	1.747	7.309	3.717	6.145	4.617	5.404	3.717	6.145	3.717	6.145	4.617	5.404	3.717	6.145	2.998	6.632	2.998	6.632			3.717	6.145	3.717	6.145	3.717	6.145
LW1	2.354	7.004	2.354	7.004	1.159	7.569	1.747	7.309	1.159	7.569	2.354	7.004	1.159	7.569	1.747	7.309	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569			2.354	7.004	2.354	7.004
EW1	3.717	6.145	4.617	5.404	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145	4.617	5.404	3.717	6.145	2.354	7.004	1.159	7.569	1.159	7.569	1.159	7.569	3.717	6.145			3.717	6.145
PO1	2.998	6.632	1.747	7.309	1.747	7.309	2.354	7.004	1.159	7.569	2.998	6.632	1.159	7.569	3.717	6.145	1.159	7.569	1.747	7.309	1.747	7.309	1.159	7.569	2.998	6.632	1.159	7.569		
EcO1	1.159	7.569	2.998	6.632	3.717	6.145	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569
EcO2	1.159	7.569	2.998	6.632	3.717	6.145	1.747	7.309	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569
SO1	1.747	7.309	2.998	6.632	1.747	7.309	1.747	7.309	1.159	7.569	1.747	7.309	1.159	7.569	1.747	7.309	0.578	7.796	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309	1.747	7.309
TO1	1.747	7.309	3.717	6.145	3.717	6.145	3.717	6.145	2.998	6.632	1.747	7.309	2.998	6.632	3.717	6.145	2.998	6.632	1.159	7.569	1.159	7.569	2.998	6.632	1.747	7.309	2.998	6.632	1.747	7.309
TO2	1.159	7.569	4.617	5.404	3.717	6.145	4.617	5.404	2.998	6.632	1.159	7.569	2.998	6.632	3.717	6.145	3.717	6.145	1.159	7.569	1.159	7.569	2.998	6.632	1.159	7.569	2.998	6.632	1.159	7.569
LO1	1.159	7.569	2.354	7.004	2.354	7.004	2.354	7.004	2.354	7.004	1.159	7.569	1.159	7.569	3.717	6.145	1.159	7.569	1.159	7.569	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569
EO1	1.159	7.569	2.998	6.632	2.998	6.632	2.998	6.632	2.354	7.004	1.159	7.569	2.998	6.632	2.998	6.632	1.747	7.309	1.747	7.309	1.747	7.309	1.159	7.569	1.159	7.569	1.747	7.309	1.159	7.569
PT1	3.717	6.145	1.159	7.569	1.159	7.569	2.998	6.632	1.159	7.569	3.717	6.145	1.159	7.569	1.159	7.569	2.354	7.004	1.159	7.569	1.159	7.569	1.159	7.569	3.717	6.145	1.159	7.569	3.717	6.145
EcT1	3.717	6.145	4.617	5.404	8.000	0.000	8.000	0.000	3.717	6.145	3.717	6.145	3.717	6.145	4.617	5.404	3.717	6.145	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145
EcT2	3.717	6.145	2.998	6.632	3.717	6.145	3.717	6.145	1.747	7.309	3.717	6.145	1.747	7.309	1.747	7.309	2.354	7.004	1.747	7.309	1.747	7.309	1.159	7.569	3.717	6.145	1.747	7.309	3.717	6.145
ST1	4.617	5.404	8.000	0.000	4.617	5.404	4.617	5.404	2.354	7.004	4.617	5.404	3.717	6.145	4.617	5.404	4.617	5.404	3.717	6.145	4.617	5.404	4.617	5.404	4.617	5.404	4.617	5.404	4.617	5.404
TT1	3.717	6.145	2.998	6.632	2.354	7.004	2.998	6.632	2.354	7.004	3.717	6.145	3.717	6.145	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	2.998	6.632	3.717	6.145	2.998	6.632	3.717	6.145
TT2	1.747	7.309	1.159	7.569	3.717	6.145	2.354	7.004	2.354	7.004	1.747	7.309	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	4.617	5.404	2.998	6.632	1.747	7.309	3.717	6.145	1.747	7.309
LT1	2.354	7.004	1.747	7.309	2.998	6.632	2.998	6.632	1.159	7.569	2.354	7.004	2.354	7.004	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	2.354	7.004	2.354	7.004	2.354	7.004
ET1	3.717	6.145	3.717	6.145	4.617	5.404	3.717	6.145	3.717	6.145	3.717	6.145	2.998	6.632	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	3.717	6.145	2.354	7.004	3.717	6.145

Table 4.4.b: Ultimate aggregated matrix with 2TLFFS beta values.

	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
	EcO1		EcO2		SO1		TO1		TO2		LO1		EO1		PT1		EcT1		EcT2		ST1		TT1		TT2		LT1		ET1	
SP1	2.998	6.632	2.998	6.632	3.717	6.145	2.998	6.632	3.717	6.145	2.354	7.004	3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	0.578	7.796	2.998	6.632	2.998	6.632	2.354	7.004	1.747	7.309
SP2	2.998	6.632	2.998	6.632	2.998	6.632	1.747	7.309	1.747	7.309	2.998	6.632	2.998	6.632	3.717	6.145	1.159	7.569	3.717	6.145	1.747	7.309	1.747	7.309	1.747	7.309	2.998	6.632	2.998	6.632
EcS1	3.717	6.145	2.998	6.632	2.998	6.632	2.354	7.004	2.354	7.004	3.717	6.145	3.717	6.145	3.717	6.145	1.159	7.569	3.717	6.145	1.747	7.309	2.354	7.004	2.354	7.004	3.717	6.145	3.717	6.145
SS1	2.998	6.632	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	2.998	6.632	3.717	6.145	2.998	6.632	1.159	7.569	2.998	6.632	1.747	7.309	1.159	7.569	1.159	7.569	2.998	6.632	2.998	6.632
TS1	1.159	7.569	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145	1.159	7.569	4.617	5.404	1.159	7.569	2.998	6.632	1.159	7.569	2.998	6.632	2.354	7.004	2.354	7.004	1.159	7.569	1.159	7.569
LS1	2.354	7.004	3.717	6.145	3.717	6.145	1.159	7.569	1.159	7.569	0.000	0.000	3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	2.354	7.004	2.354	7.004
ES1	1.747	7.309	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	1.747	7.309	2.354	7.004	2.998	6.632	1.159	7.569	2.998	6.632	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309
PW1	1.747	7.309	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	1.747	7.309	1.159	7.569	2.998	6.632	1.159	7.569	2.998	6.632	0.578	7.796	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309
EcW1	4.617	5.404	2.998	6.632	2.998	6.632	1.747	7.309	1.747	7.309	4.617	5.404	1.747	7.309	2.354	7.004	1.159	7.569	1.747	7.309	1.159	7.569	1.747	7.309	1.747	7.309	4.617	5.404	4.617	5.404
SW1	4.617	5.404	2.998	6.632	2.998	6.632	3.717	6.145	3.717	6.145	4.617	5.404	2.998	6.632	3.717	6.145	1.159	7.569	3.717	6.145	2.354	7.004	3.717	6.145	3.717	6.145	4.617	5.404	4.617	5.404
SW2	3.717	6.145	2.998	6.632	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	2.998	6.632	3.717	6.145	1.159	7.569	3.717	6.145	2.354	7.004	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145
TW1	3.717	6.145	2.998	6.632	2.998	6.632	4.617	5.404	4.617	5.404	3.717	6.145	3.717	6.145	3.717	6.145	1.159	7.569	3.717	6.145	2.354	7.004	4.617	5.404	4.617	5.404	3.717	6.145	3.717	6.145
LW1	2.354	7.004	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	2.354	7.004	1.159	7.569	1.747	7.309	1.159	7.569	1.747	7.309	1.747	7.309	1.159	7.569	1.159	7.569	2.354	7.004	2.354	7.004
EW1	3.717	6.145	2.998	6.632	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	2.998	6.632	2.354	7.004	1.159	7.569	2.354	7.004	2.354	7.004	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145
PO1	2.998	6.632	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	2.998	6.632	3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	2.998	6.632	2.998	6.632
EcO1			2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569
EcO2	1.159	7.569			1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569
SO1	1.747	7.309	2.998	6.632			1.159	7.569	1.159	7.569	1.747	7.309	1.159	7.569	0.578	7.796	1.159	7.569	0.578	7.796	1.159	7.569	1.159	7.569	1.159	7.569	1.747	7.309	1.747	7.309
TO1	1.747	7.309	2.998	6.632	2.998	6.632			2.998	6.632	1.747	7.309	3.717	6.145	2.998	6.632	1.159	7.569	2.998	6.632	2.998	6.632	2.998	6.632	2.998	6.632	1.747	7.309	1.747	7.309
TO2	1.159	7.569	1.747	7.309	1.747	7.309	2.998	6.632			1.159	7.569	3.717	6.145	3.717	6.145	1.159	7.569	3.717	6.145	3.717	6.145	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569
LO1	1.159	7.569	2.998	6.632	2.998	6.632	2.354	7.004	1.747	7.309			3.717	6.145	1.159	7.569	1.159	7.569	1.159	7.569	2.998	6.632	2.354	7.004	2.354	7.004	1.159	7.569	1.159	7.569
EO1	1.159	7.569	2.998	6.632	2.998	6.632	2.354	7.004	1.747	7.309	1.159	7.569			1.747	7.309	1.159	7.569	1.747	7.309	1.159	7.569	2.354	7.004	2.354	7.004	1.159	7.569	1.159	7.569
PT1	3.717	6.145	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	3.717	6.145	1.159	7.569			1.159	7.569	2.354	7.004	1.159	7.569	1.159	7.569	1.159	7.569	3.717	6.145	3.717	6.145
EcT1	3.717	6.145	2.998	6.632	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	4.617	5.404	3.717	6.145			3.717	6.145	2.354	7.004	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145
EcT2	3.717	6.145	2.998	6.632	2.998	6.632	1.747	7.309	1.747	7.309	3.717	6.145	1.159	7.569	2.354	7.004	1.159	7.569			1.159	7.569	1.747	7.309	1.747	7.309	3.717	6.145	3.717	6.145
ST1	4.617	5.404	8.000	0.000	8.000	0.000	2.354	7.004	2.998	6.632	4.617	5.404	1.159	7.569	4.617	5.404	1.159	7.569	4.617	5.404			2.354	7.004	2.354	7.004	4.617	5.404	4.617	5.404
TT1	3.717	6.145	4.617	5.404	4.617	5.404	2.354	7.004	2.354	7.004	3.717	6.145	4.617	5.404	3.717	6.145	2.354	7.004	3.717	6.145	1.747	7.309			2.354	7.004	3.717	6.145	3.717	6.145
TT2	1.747	7.309	3.717	6.145	3.717	6.145	2.354	7.004	2.354	7.004	1.747	7.309	3.717	6.145	3.717	6.145	2.354	7.004	3.717	6.145	2.998	6.632	2.354	7.004			1.747	7.309	1.747	7.309
LT1	2.354	7.004	2.998	6.632	2.998	6.632	1.159	7.569	1.159	7.569	2.354	7.004	1.747	7.309	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569	1.159	7.569			3.717	6.145
ET1	3.717	6.145	2.998	6.632	2.998	6.632	3.717	6.145	3.717	6.145	3.717	6.145	1.747	7.309	1.159	7.569	3.717	6.145	1.159	7.569	1.747	7.309	3.717	6.145	3.717	6.145	3.717	6.145		

Step 2. Calculating the initial direct influence matrix (*D*)

D matrix is obtained by applying Eq. (3.2.6).

Here the caluclations are done with the 2TLFFS operations.

Step 3. Calculating the total direct/indirect influence matrix (*T*).

This matrix is calculated by using Eq. (3.2.7). In the *T* matrix, *D* and *R* values can be derived to determine the direct/indirect relationships between criteria. So these values are obtained by using Eq. (3.2.8). **Table 4.5** presents the related values for factor weighting.

Table 4.5: *(D+R)* and *(D-R)* values for SWOT/PESTLE factors.

	D	**R**	**D+R**	**D-R**	**C/E**
SP1	1.00	0.83	1.83	0.17	Cause
SP2	1.46	0.77	2.24	0.69	Cause
EcS1	1.26	1.01	2.27	0.24	Cause
SS1	1.18	0.75	1.92	0.43	Cause
TS1	0.76	0.88	1.64	-0.12	Effect
LS1	1.00	0.66	1.66	0.34	Cause
ES1	0.85	0.66	1.51	0.19	Cause
PW1	1.10	0.61	1.70	0.49	Cause
EcW1	0.88	1.05	1.93	-0.17	Effect
SW1	0.55	1.48	2.03	-0.94	Effect
SW2	0.62	1.51	2.13	-0.89	Effect
TW1	0.56	1.38	1.94	-0.82	Effect
LW1	1.00	0.57	1.57	0.43	Cause
EW1	0.82	1.16	1.98	-0.34	Effect
PO1	0.99	0.66	1.65	0.33	Cause
EcO1	1.03	0.47	1.50	0.55	Cause
EcO2	1.23	0.44	1.67	0.79	Cause
SO1	1.22	0.46	1.68	0.76	Cause
TO1	0.77	0.92	1.69	-0.15	Effect

TO2	0.77	0.93	1.71	-0.16	Effect
LO1	1.07	0.62	1.69	0.44	Cause
EO1	1.02	0.63	1.66	0.39	Cause
PT1	0.88	0.72	1.60	0.16	Cause
EcT1	0.45	1.63	2.08	-1.18	Effect
EcT2	0.87	0.87	1.74	0.01	Cause
ST1	0.59	1.81	2.40	-1.22	Effect
TT1	0.76	1.24	2.00	-0.48	Effect
TT2	0.76	1.04	1.80	-0.28	Effect
LT1	1.00	0.61	1.61	0.39	Cause
ET1	0.99	1.06	2.05	-0.07	Effect

Step 4. Analyzing the cause-and-effect diagrams.

In this step, influence diagrams are obtained to investigate the cause-effect relations between criteria. Following **Figure 4.3** provides the cause-effect diagram for SWOT/PESTLE factors.

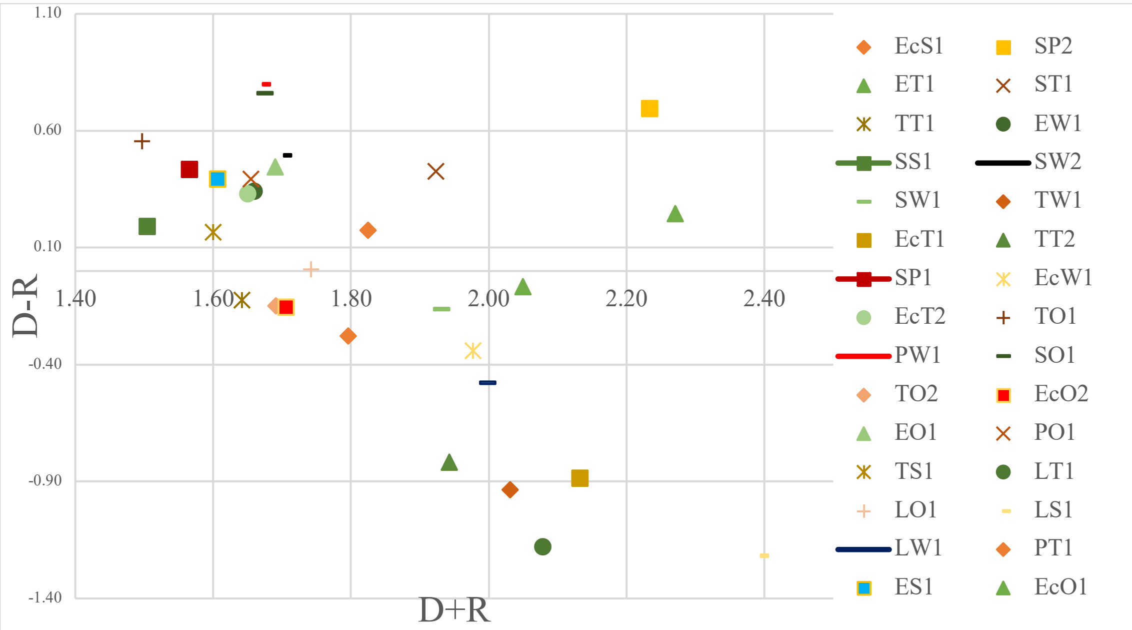

Figure 4.3: 2TLFFS-DEMATEL results for the SWOT/PESTLE Factors for Turkish agriculture.

Calculation of both *(D+R)* and *(D−R)* values is carried out for each factor pertaining to SWOT/PESTLE for Türkiye's agriculture ecosystem. *(D+R)* value delineates the 'prominence' or 'importance degree' of each factor. A higher *(D+R)* value underscores the factor's pronounced impact and its interplay with other factors. Conversely, *(D−R)* values are classified into two groups: the effect group and the cause group. Positive *(D−R)* values pertain to the cause group, signifying independence, while negative *(D−R)* values belong to the effect group, implying their susceptibility to the influence of causal group values. Further assessment of results will be provided in the upcoming subsection.

4.2.2 Results and Discussions for 2TLFFS-DEMATEL SWOT/PESTLE Analysis

In our analysis of the Turkish agricultural sector, we have identified and ranked the most prominent factors that warrant close attention and strategic consideration. Topping the list of these crucial factors is "Food Security" (ST1). The significance of food security cannot be overstated, as it stands as the foremost priority for the sector (N. Ahmed et al., 2023; Berry et al., 2015). The stability and adequacy of food supply are of paramount importance, particularly in a rapidly evolving global landscape (Wijerathna-Yapa & Pathirana, 2022). Ensuring food security within the Turkish agricultural context is both an obligation and a strategic imperative.

Following closely is "Regional Product Diversity" (EcS1), a factor that emphasizes the value of leveraging the region's product diversity, especially those with geographical indications. This diversity offers not only marketing advantages but also signifies the potential for value addition and market expansion, underlining the need to capitalize on unique regional products to enhance the sector's competitiveness (Aydoğdu et al., 2016).

In the third spot, "Designation of Large Plains as Agricultural Protected Areas" (SP2) reflects the importance of preserving and safeguarding fertile agricultural land (Adalet, 2022). Designating large plains as protected areas underscores the critical role these areas play in the sustainability of agricultural practices.

In the fourth spot, “The decrease in the elderly farmer population and the difficulty in accessing traditional knowledge due to migration” (SW2) poses a multifaceted challenge for the agricultural landscape. The exodus of experienced farmers due to migration not only results in a loss of valuable expertise but also disrupts the intergenerational transfer of traditional farming wisdom. This demographic shift can potentially lead to a gap in knowledge continuity, impacting the sustainability and efficiency of agricultural practices. Moreover, the diminished presence of elderly farmers may affect the social fabric of farming communities, altering the dynamics of local knowledge-sharing networks (Akdemir et al., 2021). Addressing this issue becomes crucial for ensuring the preservation and effective transmission of time-tested agricultural practices, thereby contributing to the resilience and adaptability of the agricultural sector in the face of evolving challenges.

Finally, "Rapid Urbanization" (EcT1) holds the fifth position, signifying the encroachment of urban development on agricultural land. Balancing the demands of urbanization with the preservation of fertile agricultural land is a critical challenge for the sector. It necessitates thoughtful urban planning and agricultural preservation to ensure sustainable growth and maintain the sector's productivity (Gunduz et al., 2023).

These top-ranked factors provide valuable insights into the primary areas of concern and opportunity within the Turkish agricultural sector. They are pivotal for strategic planning, policy development, and decision-making to enhance the sector's resilience and competitiveness.

In the context of the analysis, the utilization of the 2TLFFS-DEMATEL methodology provides a unique perspective, enabling an evaluation of factors based on their causal relationships. It becomes evident that assessing the prominence ranking alone does not suffice for the strategic selection of factors to guide the formulation of effective strategies. As mentioned previously, the *(D-R)* values offer insights into the cause-and-effect nature of these factors. After appraising the prominence ranking, the next critical step is to identify the causal group factors. A total of 30 factors are meticulously sorted based on their *(D-R)* values, as detailed in **Table 4.5**.

Among these factors, the top five ranked elements—EcO2, SO1, SP2, EcO1, and PW1—stand out as pivotal determinants with a substantial impact on the overall factor landscape. The profound influence they exert on other factors is indicative of their critical nature in strategic planning. A comparative analysis of the *(D+R)* and *(D-R*) ranking reveals that Threats carry a notably high importance, deemed critical for strategy development. However, Opportunities, due to their causal characteristics, can potentially have an even more profound impact on strategy formulation. Notably, within this context, "Increasing demand for natural products in different sectors" (EcO2) emerges as the utmost influential factor in the cause group. With the highest *(D-R)* value, it indicates its paramount role in the effective transition of Turkish agriculture. Furthermore, EcO2 boasts the third highest *D* value among all factors, signifying its significant impact on guiding the strategic shift of the agricultural sector. This underscores the pivotal role that increased demand for natural products holds in propelling the Turkish agriculture sector toward SA.

Considering the remaining factors, "Consumer behavior tendencies and habits" (SO1) plays a vital role in shaping strategies, reflecting the influence of consumer preferences toward healthier, locally-sourced, and sustainable goods.

With the highest *D* value discerned in the 2TLFFS-DEMATEL analysis, the strategic factor denoted as "SP2: Designation of large plains as agricultural protected areas" assumes paramount significance in the context of SA transition. This outcome underscores the criticality of SP2, emphasizing its pivotal role in shaping and influencing the transition towards SA practices. The elevated *D* value signifies the pronounced impact of SP2 on the interconnected factors within the system under consideration, signifying its centrality in steering the trajectory of SA development.

The factor "Continuity of market demand" (EcO1) signifies a persistent market requirement for agricultural products, providing a stable base for strategic planning. EcO1 having the second highest *D* value among all factors, signifying its critical effect on SA transition. Addressing the "Shortcomings in long-term agricultural policies" (PW1) is essential to ensure the sector's resilience and adaptability.

These findings collectively underscore the importance of a nuanced understanding of the causal dynamics among SWOT/PESTLE factors in shaping effective strategies for the strategic transition of Turkish agriculture.

4.2.3 Comparative Analysis

2TLFFS-DEMATEL application is compared with 2TL-DEMATEL application. The results are provided in the following Figure.

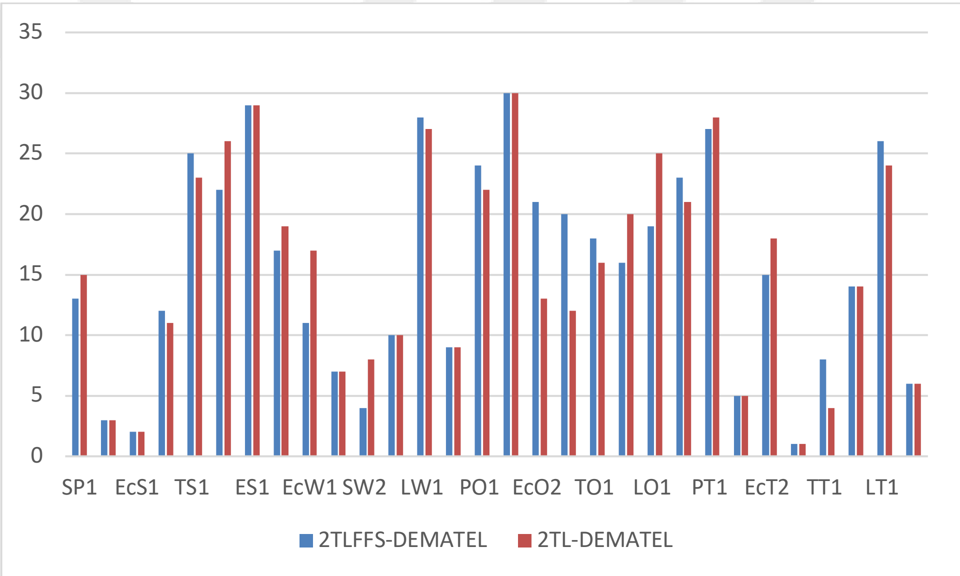

Figure 4.4: Comparative analysis for 2TLFFS-DEMATEL and 2TL-DEMATEL.

4.3 Strategy Generation Based on 2TLFFS-DEMATEL Integrated SWOT/PESTLE Analysis for Turkish Agriculture

The application of the DEMATEL method has been instrumental in categorizing SWOT/PESTLE factors into distinct cause and effect groups. Building on the preceding discussions, it is within the cause group that we find the factors that will inform the formulation of pertinent strategies (Nikjoo & Saeedpoor, 2014). These cause factors will serve as the foundation for deriving multiple strategies. These strategies, informed by relevant literature, will subsequently undergo validation and refinement through the expertise of field experts (DMs) engaged in the SWOT/PESTLE analysis process.

Factors belong to the "cause group" and are considered independent. This means they have a significant influence on the system and are less influenced by other factors. Focusing strategy development on these key drivers will allow you to have a more widespread and lasting impact on the entire system (Nikjoo & Saeedpoor, 2014). On the other hand, focusing on factors with negative *(D-R)* values, which belong to the "effect group," might not be as effective for achieving systemic change. These factors are more susceptible to the influence of other factors, and their impact might be limited or indirect. While addressing these factors may be necessary in some cases, focusing primarily on positive *(D-R)* factors will likely offer a more robust and sustainable approach for affecting the whole system.

The ranking of the cause factors based on their ***(D+R)*** and *(D-R)* values are as follows, respectively: *(D+R)*
EcS1>SP2>SS1>SP1>PW1>EO1>LO1>SO1>LS1>PT1>EcO1>LT1>EcT2>LW1> ES1>EcO2.
(D-R)
EcO2>SO1>SP2>EcO1>PW1>LO1>LW1>SS!>EO1>LT1>LS1>EcS1>ES1>SP1> PT1>EcT2.

When generating strategies based on the provided information, it's advisable to prioritize factors with a combination of high *(D+R)* values and substantial *(D-R)* values, as they not only hold importance but also exert a strong influence on other factors (Nikjoo & Saeedpoor, 2014).

In this context, "EcS1" stands out as the top-ranked factor in terms of prominence, while "EcO2" holds the highest *(D-R)* ranking. Therefore, it is recommended to consider "EcS1" and " EcO2" as primary factors when formulating strategies, given their dual significance and potent impact on the overall factor landscape.

EcS1 which pertains to "Regional product diversity, including products with geographical indications, is also significant for marketing purposes", has secured a prominent position in our rankings. This prominence underscores the critical need for the sector to proactively address *economical strengths* of Turkish agriculture. EcO2 denoting "Increasing demand for natural products in different sectors." has also emerged as a significant influence, as reflected by its (D-R) ranking.

SA stands at the intersection of innovation and sustainability, revolutionizing traditional practices. This synthesis converges on two influential factors, EcS1: Regional Product Diversity with GIs and EcO2: Increasing Demand for Natural Products, delineating strategies to foster a resilient and environmentally conscious agricultural landscape.

EcS1 underscores the imperative of regional product diversity through GIs. This strategy emphasizes the production, processing, and marketing of unique agricultural products specific to regions (Yılmaz et al., 2019). By supporting farmers in obtaining GIs, fostering geographical value chains, and promoting agrotourism, the focus is on creating integrated value chains that connect stakeholders within specific regions. Furthermore, diversification within farms and the cultivation of underutilized crops are highlighted, contributing to a more balanced and resilient agricultural ecosystem (Akdemir et al., 2021).

EcO2 addresses the escalating demand for natural products by promoting organic and sustainable agricultural practices. Financial incentives, technical assistance, and certification processes support the transition to organic and sustainable production methods (Kaya & Kadanalı, 2021). The strategy advocates for short supply chains and direct marketing channels, facilitating connections between farmers and consumers. Initiatives like farmer's markets, online platforms, and Community-supported Agriculture programs directly link consumers with locally grown produce, eliminating intermediaries and enhancing profit margins (Zerssa et al., 2021).

Complementing these strategies, local food initiatives form a crucial aspect of promoting local food systems, such as school programs and restaurant sourcing initiatives.

Technological innovation further fortifies SA, encouraging the use of precision agriculture technologies, blockchain-based traceability systems, and sustainable packaging solutions. These innovations optimize resource use, ensure transparency and authenticity in natural product supply chains, and minimize environmental impact.

In conclusion, the synthesis of strategies for SA revolves around regional product diversity, Geographical Indications, meeting the demand for natural products, and embracing technological innovation. By intertwining these elements, SA not only enhances agricultural efficiency but also fosters sustainability, resilience, and consumer trust. This comprehensive approach sets the stage for a dynamic and environmentally conscious future, aligning agricultural practices with evolving consumer preferences and global sustainability goals. The following **Table 4.6** provides the generated strategies for the causal factors having the highest prominence.

Table 4.6: Strategies for Turkish agriculture transition to SA based on SWOT/PESTLE analysis.

Main Dimensions	Strategies
Developing regional clusters (De Boni et al., 2022; Hadachek et al., 2023)	Create clusters focused on specific regional products and integrate organic and sustainable practices throughout the value chain.
Investing in research and development (Deloitte, 2020)	Fund research initiatives that explore and develop innovative technologies and practices for the production and marketing of regional, natural products.
Building capacity and knowledge sharing (De Boni et al., 2022; Hadachek et al., 2023)	Provide training and education programs for farmers and stakeholders on organic and sustainable practices, regional product development, and marketing strategies.

Supporting infrastructure development (Karunathilake et al., 2023; McKinsey and Co., 2020)	Invest in infrastructure that facilitates efficient and sustainable production, processing, and transportation of regional, natural products.
Promoting collaboration and partnerships (Aksoy, 2023; Çakmakçı et al., 2023)	Encourage collaboration between farmers, cooperatives, research institutions, businesses, and government agencies to drive the SA transition and maximize its impact.

The sustainability of SA systems hinges on the integration of practices and initiatives that prioritize ecological responsibility, resource efficiency, and long-term viability. By weaving sustainability into the fabric of regional clusters, research and development, knowledge-sharing programs, infrastructure development, and collaborative efforts, the foundation for a resilient and environmentally conscious agricultural future is established. In doing so, SA not only enhances productivity and efficiency but also ensures the preservation and health of the agricultural ecosystem for generations to come.

The subsequent section of this thesis aims to expose the comprehensive strategies formulated for Turkish agriculture. This succeeding segment will provide a roadmap for the development of a SA system, integrating key features of digitalization and sustainability. This endeavor seeks to synthesize the strategic insights derived from the preceding analyses, thereby delineating a coherent framework for the advancement of agriculture within the Turkish context. The ensuing discussion will delve into the intricate interplay between digitalization and sustainability, elucidating how their harmonious integration can pave the way for a transformative agricultural landscape characterized by heightened efficiency, environmental responsibility, and technological innovation.

5 DESIGNING SA WITH SUSTAINABILITY AND DIGITALIZATION FEATURES

The current landscape of agriculture is undergoing a transformative shift with the increasing integration of digital technologies (Deloitte, 2020). Traditional farming practices are being complemented and, in many cases, revolutionized by advanced technological solutions. PA, (IoT), automation and robotics, data analytics and farm management software offer unprecedented opportunities to address longstanding challenges in farming, enhance productivity, and move towards more sustainable and resilient agricultural systems (Zhang, 2023). This digital transformation is driven by the need to address challenges such as population growth, climate change, resource constraints, and the demand for sustainable and efficient food production (United Nations, 2023).

Climate change, in particular, has profound effects on various aspects of our food systems and is interconnected with other challenges (Maraseni et al., 2021). Therefore, a comprehensive examination of these interconnected challenges is vital for informing targeted strategies to achieve sustainability and the Sustainable Development Goals (SDGs) (United Nations, 2023). Achieving effective climate change mitigation and addressing other SDGs within food systems requires a paradigm shift (Campbell et al., 2018). This necessitates a comprehensive transformative approach that encompasses a range of sustainability measures and innovations.

Transitioning from this broader context to the specific challenges faced by the agricultural sector, the integration of digital technologies, while promising, introduces its own set of complexities and considerations (Hou et al., 2021). Digitalization in agriculture brings opportunities for increased efficiency, resource optimization, and data-driven decision-making.

However, it also raises concerns related to access, affordability, data security, and ethical implications. Understanding and addressing these challenges are crucial for harnessing the full potential of digitalization in advancing sustainable practices within the agriculture sector.

This leads us to a fundamental question: Does digitalization truly ensure sustainability? Answering this question requires a nuanced exploration of the interactions between digital technologies and sustainability objectives. As we delve into the intricacies of this relationship, we aim to uncover not only the potential benefits but also the pitfalls that may compromise the overall sustainability of agricultural practices in the digital age. This inquiry sets the stage for our first research question (RQ):

RQ1: Does digitalization truly ensure sustainability?

In addressing this question, we aim to identify the specific aspects of digitalization that contribute to sustainability and explore how these principles can be integrated into the design of SA systems. This leads us to our second RQ:

RQ2: From a sustainability perspective, what are the most crucial requirements for digitalization?

In delving into this inquiry, our objective is to unravel the essential components that define sustainable digitalization in agriculture, as understanding these critical requirements is fundamental to shaping the future trajectory of SA systems. Our scrutiny spans across the environmental, social, and economic dimensions, encompassing factors such as resource efficiency, social equity, and economic viability (Del Río Castro et al., 2021). We recognize that true sustainability demands a holistic approach, viewing digitalization not simply as a tool for efficiency but as a means to enhance ecological resilience, promote equitable access to resources, and bolster the economic well-being of agricultural stakeholders (Brenner & Hartl, 2021). The imperative for adopting a holistic approach directs our attention to the third RQ:

RQ3: Can SA systems be feasibly designed to concurrently fulfill both digital and sustainable requirements?

This pivotal query propels our investigation into the pragmatic integration of analytical approaches, seeking to harmonize the imperatives of sustainability and digital requirements within the context of SA. By addressing these research inquiries, the study intends to generate insights into the relationship between smartness, sustainability, and digitalization across different contexts.

In this chapter, the utilization of QFD is recommended as an essential approach, as it offers a systematic methodology for translating customer requirements into engineering characteristics, facilitating the effective design and optimization of SA systems by establishing clear relationships between digital and sustainable criteria (Akao & Mazur, 2003). Differing from the classic QFD application, here, a two-stage HoQ approach will be employed. In the first stage, sustainability criteria will be incorporated as the 'voice of the customer,' aiming to examine the relationship between sustainability and digitalization. In the second stage, the focus will shift to prioritizing the ultimate design for SA by associating digitalization with SA. Moreover, by integrating QFD with the 2TLFFS (Akram et al., 2022), the chapter aims to incorporate DMs assessments more effectively and gain a comprehensive understanding of the relationship between digitalization, sustainability, and SA. This approach allows for a more robust analysis and assessment of the requirements and considerations related to digitalization and sustainability in the SA domain.

5.1 Sustainability and Digitalization

As our world becomes increasingly interconnected, the intersection of sustainability and digitalization emerges as a pivotal force shaping diverse sectors (Brenner & Hartl, 2021). From urban planning to industrial processes, the integration of digital technologies has promised efficiency gains and innovative solutions to complex challenges. Simultaneously, the imperative to foster sustainability has gained prominence, urging industries to reassess practices and mitigate environmental impacts.

Seele (2016)'s study explores leveraging big data for sustainable development, proposing the Digital Sustainability Panopticon—a concept integrating panopticon principles with sustainability. Defined by six criteria, including big data and IoT for sustainability, this framework presents a transformative role in advancing sustainability. In a subsequent study, Seele & Lock, (2017) delve into digitalization's potential for sustainability, emphasizing the governance challenges in the digital age. The study underscores the ambivalent role of digital surveillance, stressing the need for policymakers to balance sustainability goals with privacy rights.

Brenner and Hartl (2021) employ framing and social representations theories to analyze diverse perceptions of the digitalization-sustainability connection. The study emphasizes policymakers' active role in shaping social representations. Santarius et al., (2023) underscore the need to align digital policies with sustainability goals, focusing on energy standards in platform markets like video streaming and social media

Ghobakhloo & Fathi, (2021) identify interconnected functions of Industry 4.0 that promote energy sustainability, emphasizing the role of advanced energy production and distribution equipment. Mihai et al., (2022) explore the digitalization of the energy industry, highlighting the potential of Industry 4.0 pillars to enhance energy efficiency and sustainability.

The reviewed literature highlights the transformative potential of digitalization for sustainability, particularly through Big Data, IoT, and Industry 4.0 technologies. However, important concerns remain regarding governance, the potential for societal impact, and the environmental footprint of digitalization itself (Teng et al., 2023). Researchers emphasize the need for policymakers to balance promoting sustainability with protecting privacy rights and for digitalization strategies to align with broader sustainability objectives.

When reviewing the agricultural studies landscape through the lens of the sustainability and digitalization relationship, three prominent articles emerge in the Web of Science database. Hidalgo et al., (2023) discern two key routes to sustainability within the coffee value chain through digitalization: optimized production for commodity markets and heightened producer visibility in niche markets. The former involves digital advisory services reinforcing a productivist perspective, diffusing conventional-industrial agricultural practices for commodity market coffee production. The latter is connected to digital marketplaces and traceability systems that facilitate communication between producers and buyers, enabling access to differentiated markets with added value.

Stoian et al., (2022) focuses on the benefits and recommendations for enhancing agricultural sustainability through digitalization. The authors advocate for promoting sustainability by encouraging SA practices, utilizing digital tools, fostering data-driven decision-making, and integrating new technologies to optimize processes, emphasizing economic, ecological, and social benefits while minimizing environmental impact.

Teng et al., (2023) primarily focuses on carbon dioxide emissions and their broader implications for environmental sustainability, recognizing their significance across diverse sectors, including agriculture. The study underscores the substantial impact of economic uncertainty on both short- and long-term carbon dioxide emissions, with positive shocks exerting a more pronounced effect than negative shocks. Furthermore, the research reveals an inverse correlation between digitization and carbon dioxide emissions, highlighting digitization's potential to enhance energy efficiency and promote sustainable practices.

Digitalization offers two pathways to sustainability in agriculture: optimized commodity production and heightened producer visibility in niche markets (Hidalgo et al., 2023). It can enhance sustainability through promoting SA practices, data-driven decision-making, and process optimization. While research suggests an inverse relationship between digitization and carbon emissions, there is a lack of comprehensive methodologies for integrating sustainability into SA. This chapter aims to address this gap by providing a framework for achieving this integration.

As stated in Section 2.4, current research on SA primarily focuses on the technical aspects of integrating digital technologies into conventional agricultural practices. While this research is valuable, there remains a significant gap in providing comprehensive guidance for practitioners seeking to transition from conventional farming to SA. This necessitates further research that specifically addresses the challenges and considerations associated with implementing SA. Such research should go beyond mere technical guidance and instead provide a practical roadmap for practitioners, tailored to the unique needs of this transition (Schroeder et al., 2021).

By incorporating sustainability considerations throughout the entire lifecycle of SA, from design and development to implementation and management, stakeholders can effectively address environmental, social, and economic challenges and promote widespread adoption of sustainable agricultural practices (Lugonja et al., 2022). A key element of this approach is the integration of a comprehensive computational framework.

To address this research gap, this study aims to establish the robust relationship between sustainability and digitalization and propose a QFD methodology for designing SA systems that integrate the requirements of both sustainability and digitalization. The proposed methodology will provide a structured approach to guide practitioners in developing sustainable and digitally driven agricultural solutions.

5.2 2TLFFS-HoQ Methodology

This subsection will provide the details of the suggested methodology for SA system design concerning sustainability and digitalization features. The detailed steps of the two staged 2TLFFS-HoQ will be provided. First the general framework of the two-staged methodology is provided in the following **Figure 5.1**.

The first HoQ is applied to address RQ1, focusing on the relation matrix homogeneity and prioritization of digitalization requirements aligned with sustainability needs (SNs). This step facilitates the design of a SA system with digital requirements (DRs) aligning with SNs. The results of the first HoQ provide the weights of DRs, which are then used as “customer’s voice” in the second HoQ to guide the design process and ensure alignment with the identified DRs and SNs. The outcomes of the second HoQ will offer a prioritized path to follow in order to design the SA system. Through the utilization of the DRs derived from the first HoQ, along with the relation matrix, the second HoQ will provide a clear and systematic framework for designing the SA system.

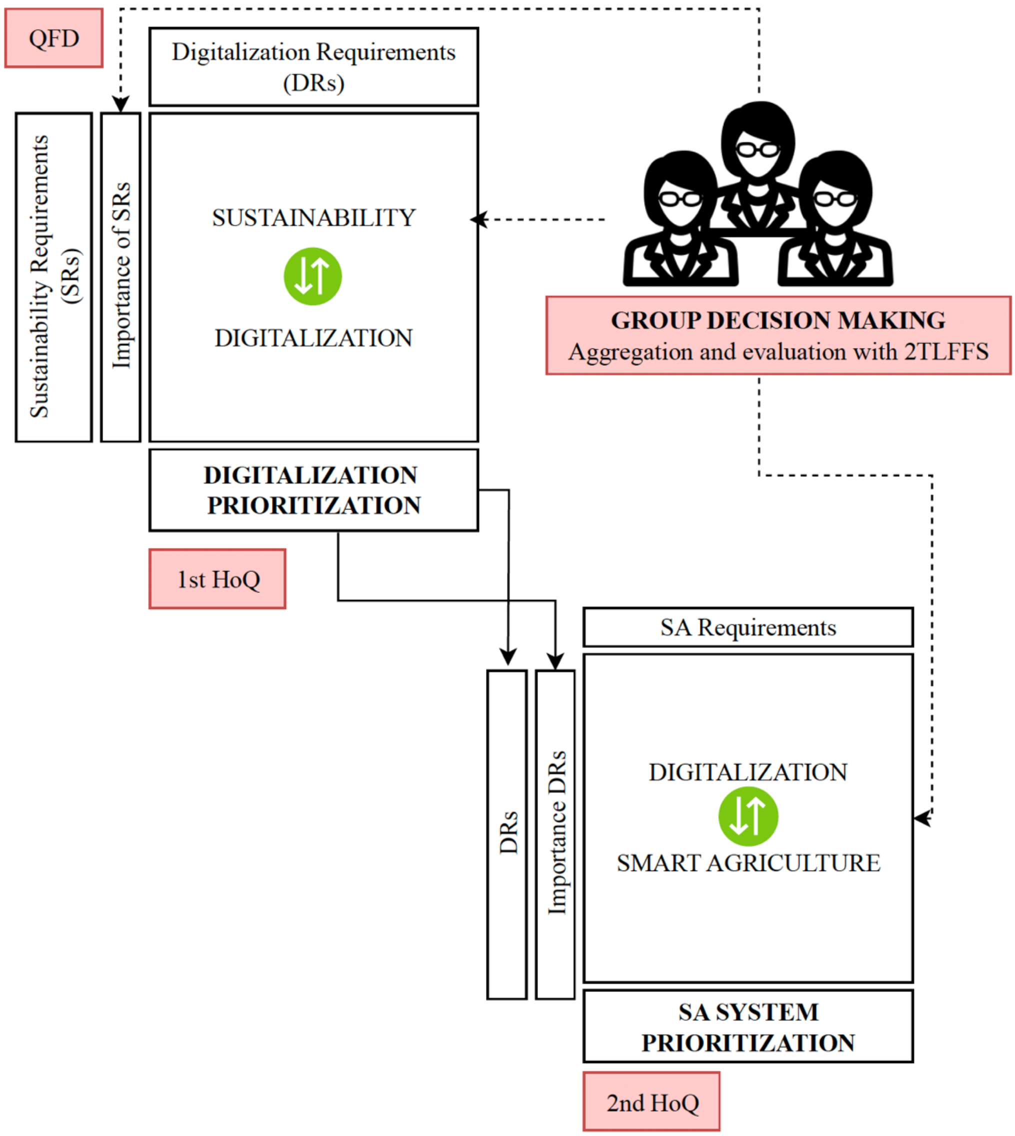

Figure 5.1: Suggested two staged HoQ framework.

Step 1: Capture customer needs (CNs).

At this step, the customer requirements related to the defined objective(s) are defined.

Step 2: Weight CNs (WHATs).

At this step, 2TLFFS linguistic sets are provided to the DMs to assess each customer requirement for their weighting. To obtain the weighting 2TLFFWHM operator can be used as in Eq. (3.2.6).

Step 3: Define "HOWs" as design requirements (DRs).

At this step, the technical requirements are defined based on the defined objective(s).

Step 4: Analyzing the relationships between CNs and DRs.

This step is dedicated to defining the relations between each CN and DR defined related to the objective of the study. This stage contains obtaining the linguistic assessments from each DM for each HOW-WHAT pairs in the relation matrix.

Under this step, the aggregation of all the assessments obtained from DMs (via 2TLFFS linguistic variables) will be performed again by using 2TLFFWHM operator as in Eq. (3.2.6).

Step 5: Obtaining the weighted collective relation matrix (WCRM).

In this step, obtained weights are used to calculate WCRM for HoQ. By doing that, the target is to transfer CN importance into the relation matrix. To obtain the WCRM the following equation is used.

$$k_j.P_{ij} = \left\{ \Delta\left(g\sqrt[3]{\left(1-\left(1-\left(\frac{\Delta^{-1}\left(S_{\alpha_{ij}},\alpha_{ij}\right)}{g}\right)^3\right)\right)^k},\ \Delta\left(g\left(\frac{\Delta^{-1}\left(S_{\beta_{ij}},\beta_{ij}\right)}{g}\right)^k\right)\right)\right\} \qquad (5.2.1)$$

where k_j represents the weight assigned to the jth CN. P_{ij} represents the aggregated linguistic relation for ith DR and jth CN. $g+1$ gives the cardinality of the 2-TL term set. $\left\{\left(S_{\alpha_{ij}},\alpha_{ij}\right),\left(S_{\beta_{ij}},\beta_{ij}\right)\right\}$ represents the membership degree and non-membership degree of relations between ith DR and jth CN by 2-TL terms, respectively.

Moreover, consistency check is always applied by the following equation after every step to control the 2-TLFFNs.

Step 6: Obtain score values for each $\left\{\left(s_{\alpha_{ij}}, \alpha_{ij}\right), \left(s_{\beta_{ij}}, \beta_{ij}\right)\right\}$ terms in the WCRM by applying the following equation.

$$S(P) = \Delta\left\{\frac{g}{2}\left(1 + \left(\frac{\Delta^{-1}\left(s_{\alpha_{ij}}, \alpha_{ij}\right)}{g}\right)^3 - \left(\frac{\Delta^{-1}\left(s_{\beta_{ij}}, \beta_{ij}\right)}{g}\right)^3\right)\right\} \tag{5.2.2}$$

Step 7: Obtaining the DRs prioritization.
This step is the final step where the DR prioritization is obtained by the following equation.

$$\frac{\sum_{j=1}^{n} S(P_{ij})}{n} \tag{5.2.3}$$

Where n is the number of CNs and $S(P_{ij})$ is the score value for *ith* DR and *jth* CN. The following Figure summarizes the flow of the suggested 2TLFFS-HoQ methodology.

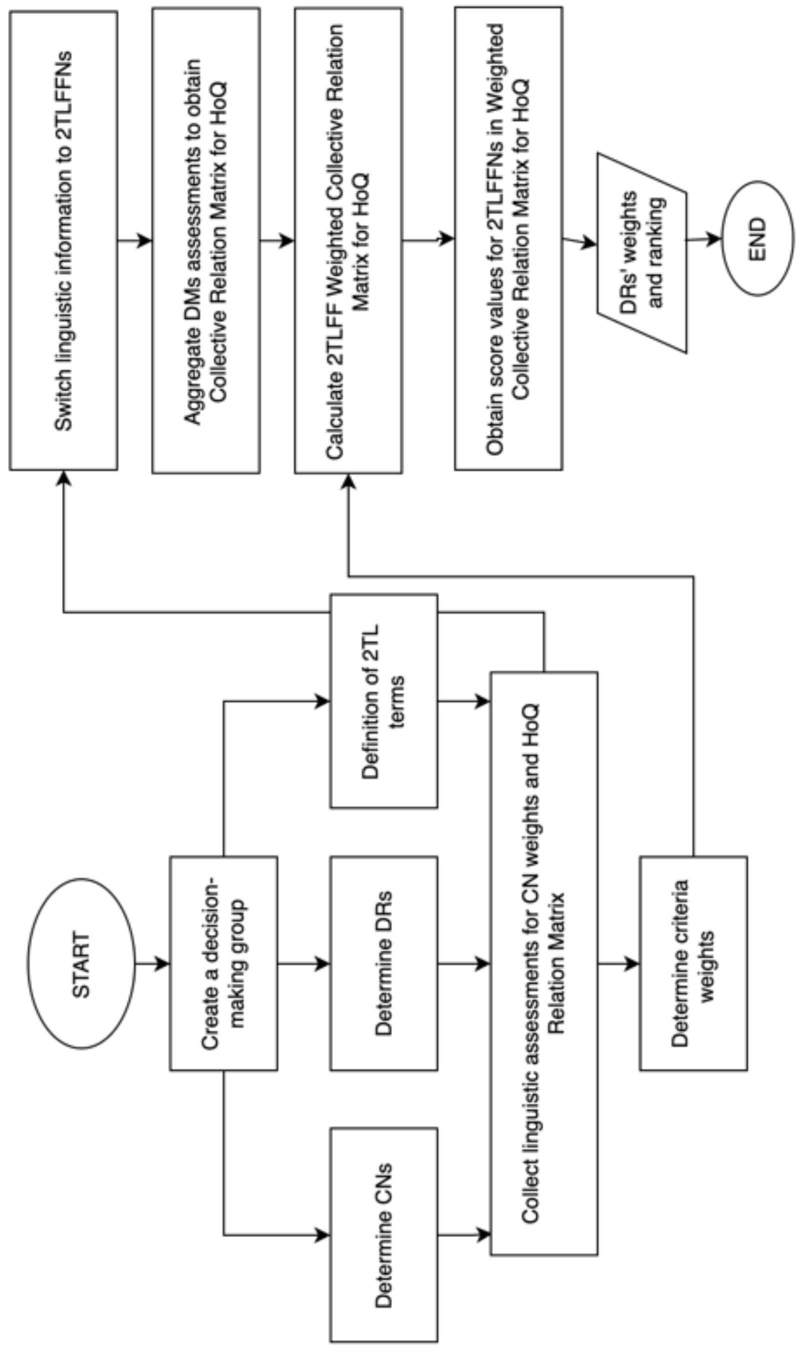

Figure 5.2: Suggested 2-TLFFS-HoQ framework.

5.3 Suggested 2-Staged HoQ Model Components for SA Design

This paper presents two distinct HoQ models for designing SA systems in line with sustainability requirements. The first model focuses on the relationship between sustainability and digitalization, prioritizing DRs. The second model incorporates the weighted DRs as design necessities for SA, prioritizing SARs from both digitalization and sustainability perspectives.

The model components for the HoQs were derived from a comprehensive literature review, providing a solid theoretical foundation for addressing the needs and requirements in the design process. **Table 5.1, Table 5.2, and Table 5.3** provide detailed information about the model components used in the study. **Table 5.1** provides the essential HOWs in the first HoQ, encompassing the fundamental requirements for designing a sustainable system across environmental, social, and economic dimensions. **Table 5.2**outlines the WHATs of the first HoQ, serving as both the HOWs in the second HoQ and the key requirements for achieving a sustainable system. Additionally, **Table 5.3** presents the SARs, which are the WHATs of the second HoQ, specifying the necessary components for designing an effective SA system.

Table 5.1: Sustainability Needs (HOW's of the 1st HoQ).

Sustainability Requirements		**Definition and References**
Environmental	Waste Reduction **(SE1)**	Refers to the efforts and strategies aimed at minimizing the generation and disposal of waste materials in a system or process. (Bhat, 2021; Del Río Castro et al., 2021; Seele and Lock, 2017)
	Energy Efficiency **(SE2)**	Involves the use of technologies and practices that optimize energy consumption and reduce energy waste to achieve maximum productivity and minimal energy usage (Mihai et al., 2022; Santarius et al., 2023).

Sustainability Requirements		Definition and References
Environmental	Reduced emissions **(SE3)**	Focuses on minimizing or eliminating the release of harmful pollutants, such as greenhouse gases, into the environment during the operation of a system (Md Mashud et al., 2021; Santarius et al., 2023).
	Conservation **(SE4)**	Encompasses the preservation and sustainable use of natural resources, including land, water, and biodiversity, to ensure their long-term availability and minimize environmental impact (Brenner and Hartl, 2021; Del Río Castro et al., 2021).
Social	Reduced impact on community **(SS1)**	Refers to minimizing negative effects on the local community, including disruptions, inconveniences, and adverse social impacts, caused by the system or its activities (Boiral and Heras-Saizarbitoria, 2020; Brenner and Hartl, 2021).
	Health and Safety **(SS2)**	Involves ensuring the well-being and protection of individuals involved in or affected by the system, including workers, stakeholders, and the community, by implementing appropriate health and safety measures (Brenner and Hartl, 2021).
	Laws and Regulations **(SS3)**	Pertains to compliance with relevant legal requirements, regulations, and standards applicable to the system, ensuring adherence to ethical, social, and legal norms (Halat et al., 2023; Zhang, 2021).
	Strengthened relationships **(SS4)**	Focuses on fostering positive and mutually beneficial relationships between the system and stakeholders, such as employees, customers, suppliers, and the local community, based on trust, transparency, and collaboration (Brenner and Hartl, 2021).

Sustainability Requirements		Definition and References
Economical	Cost reduction **(SEC1)**	Involves identifying and implementing measures to decrease expenses, optimize resource allocation, and improve operational efficiency, resulting in overall cost savings for the system (Mashud et al., 2022).
	Asset utilization **(SEC2)**	Focuses on maximizing the utilization and efficiency of existing assets and resources within the system, such as machinery, equipment, facilities, and human capital, to enhance productivity and achieve better returns on investment (Arisekola and Madson, 2023; Balafoutis et al., 2020).
	Improved quality **(SEC3)**	Refers to enhancing the quality of products, services, or processes within the system, leading to higher customer satisfaction, reduced waste, and increased competitiveness in the market (Brenner and Hartl, 2021).
	Enhanced customer service **(SEC4)**	Entails providing exceptional customer support, responsiveness, and satisfaction by addressing their needs, expectations, and preferences, leading to improved customer loyalty, retention, and positive brand reputation (Brenner and Hartl, 2021).

Table 5.2: Digitalization Requirements.

DRs	Definitions and References
Interoperability **(DR1)**	The ability of digital systems and technologies to seamlessly communicate and work together (Lopez-Morales et al., 2020; Roussaki et al., 2023).
Virtualization **(DR2)**	The creation of virtual representations or simulations of physical resources or processes using digital technologies (Cesco et al., 2023; Kumar et al., 2021).
Collaboration **(DR3)**	The use of digital tools and platforms to facilitate cooperation and teamwork among individuals and organizations (Lugonja et al., 2022; Seele, 2016).
Efficiency **(DR4)**	The optimization of resource usage and processes through the application of digital technologies (Mihai et al., 2022; Santarius et al., 2023).
Responsiveness **(DR5)**	The ability of digital systems to adapt quickly and effectively to changing conditions or demands (Brenner and Hartl, 2021).
Flexibility **(DR6)**	The capacity of digital solutions to be easily modified or adjusted to accommodate different requirements or scenarios (Lugonja et al., 2022).
Visibility **(DR7)**	The enhanced visibility and transparency of data, processes, and operations enabled by digital technologies (Ivanov et al., 2019; Mantravadi et al., 2018).
Reliability **(DR8)**	The assurance of consistent and accurate performance of digital systems and technologies (Mesbahi et al., 2018; Omar et al., 2020).

DRs	Definitions and References
Cybersecurity **(DR9)**	The protection of digital systems and data from unauthorized access, use, or malicious activities (Caviglia et al., 2023; Lees et al., 2018).
Privacy **(DR10)**	Safeguarding the confidentiality and protection of personal or sensitive information in digital environments (Caviglia et al., 2023; Lees et al., 2018).
Integration **(DR11)**	The seamless incorporation and connectivity of digital technologies and systems with existing infrastructure or processes (Lopez-Morales et al., 2020; Roussaki et al., 2023).
Connectivity **(DR12)**	The establishment of reliable and efficient connections between digital devices, systems, and networks (Lugonja et al., 2022; Seele, 2016).
Traceability **(DR13)**	The ability to track and trace the origin, history, and movement of products or data using digital means (Lin et al., 2018; Salah et al., 2019).
Modularity **(DR14)**	The design and implementation of digital solutions in modular components, allowing for flexibility and scalability (Lopez-Morales et al., 2020; Roussaki et al., 2023).
Availability **(DR15)**	Ensuring uninterrupted access and availability of digital systems, applications, and services (Mesbahi et al., 2018; Omar et al., 2020).
Standardization and compliance **(DR16)**	Adherence to established standards and regulations to ensure compatibility and compliance with industry norms (Halat et al., 2023; Zhang, 2021).
Accurate and real-time data **(DR17)**	The acquisition and utilization of precise and up-to-date information through digital technologies (Lugonja et al., 2022; Seele, 2016).

Table 5.3: SA Requirements (WHATs of the 2nd HoQ) (Balafoutis et al., 2020; Cesco et al., 2023; Debauche et al., 2022, 2021; Deloitte, 2020; Hou et al., 2021; Zscheischler et al., 2022).

SA Requirements	**Related area in SA**
Precision fertilization tools **(SAR1)**	Resource efficiency
Automated irrigation systems **(SAR2)**	Resource efficiency
Crop modelling tools **(SAR3)**	Management
Crop monitoring tools **(SAR4)**	Management and resource efficiency
Harvest planning tools **(SAR5)**	Management and risk management
Agricultural data collection and analysis tools **(SAR6)**	Management and risk management
Agricultural decision-making tools **(SAR7)**	Collaboration across the supply chain and management
Integrated agricultural value chain **(SAR8)**	Collaboration across the supply chain and management
Crop traceability systems **(SAR9)**	Risk Management and compliance with legislation
Crop safety and security systems **(SAR10)**	Risk Management and compliance with legislation
Agricultural digital platforms **(SAR11)**	Management and risk management
Agricultural risk awareness systems **(SAR12)**	Management and risk management
Automated harvesting tools **(SAR13)**	Resource efficiency
Automated fertilization tools **(SAR14)**	Resource efficiency
Disease detection tools **(SAR15)**	Resource efficiency

5.4 Application of the 2-Staged 2TLFFS-HoQ Methodology for SA Design

In this section, the 2TLFFS-HoQ methodology was applied in collaboration with experts from Türkiye. Two expert groups are formed to align with the two-stage HoQ approach. The first group, comprising five experts, examines the sustainability-digitalization relationship. The second group focuses on designing a SA system and exploring the digitalization-SA connection. The characteristics of the decision-makers (DMs) are summarized in **Table 5.4.**

In this study, experts were carefully chosen based on their relevant knowledge and experience to ensure the credibility and dependability of the results (Büyüközkan and Güleryüz, 2016). The valuable insights and input provided by these experts serve to validate the suggested model and methodology. Additionally, the discussion section will comprehensively explore the relevance of the obtained results, considering the existing literature and its alignment with the case study findings. This analysis enhances the overall understanding and significance of the research outcomes.

Table 5.4: Two DM groups for the case study.

DM# and weights	**1st Decision-making Group 1st HoQ**	**2nd Decision-making Group 2nd HoQ**
DM1 0.30	Academician Experience: Ph.D., 20 years. Area: Sustainability, smart and digital systems.	Academician Experience: Ph.D., 10 years. Area: Sustainability, SA.
DM2 0.25	Academician Experience: Ph.D., 10 years. Area: Sustainability, smart and digital systems.	Academician Experience: Ph.D., 10 years. Area: Digitalization, sustainability, SA.
DM3 0.20	Consultant Experience: Ph.D., 10 years.	Consultant Experience: Ph.D., 10 years.

	Area: Sustainability, sustainable energy systems, digitalization.	Area: Sustainability, sustainable energy systems, digitalization.
DM4 0.15	Consultant Experience: 10 years Area: Sustainability, sustainable energy systems, digitalization.	(New age) Farmer Experience: 5 years. Area: Smart/Digital agriculture, vertical farming, precision agriculture.
DM5 0.10	Academician Experience: Ph.D. candidate, 6 years. Area: Digitalization, sustainability, SA.	Academician Experience: Ph.D. candidate, 6 years. Area: Digitalization, sustainability, SA.

Phase 1: The problem is defined as "designing SA system concerning sustainability and digital measures". And a convenient 2TLFFS linguistic sets are defined as follows for weighting and relationship defining, respectively in the following **Table 5.5** (Akram & Bibi, 2023):

Table 5.5: Linguistic sets provided to experts for importance and relation assessment.

To Define Importance			
Linguistic Variables	**Abbreviations**	**Membership**	**Non-membership**
Extremely Low Importance	ELI	ELI	EHI
Very Low Importance	VLI	VLI	VHI
Low Importance	LI	LI	HI
Moderately Low Importance	MLI	MLI	MHI
Fair	F	F	F
Moderately High Importance	MHI	MHI	MLI
High Importance	HI	HI	LI
Very High Importance	VHI	VHI	VLI

Extremely High Importance	EHI	EHI	ELI
To Define Relations			
Linguistic Variables	**Abbreviation**	**Membership**	**Non-membership**
Extremely Poor	EP	EP	EG
Very Poor	VP	VP	VG
Poor	P	P	G
Moderately Poor	MP	MP	MG
Fair	F	F	F
Moderately Good	MG	MG	MP
Good	G	G	P
Very Good	VG	VG	VP
Extreme Good	EG	EG	EP

Phase 2: The SNs, HOWs of the 1st HoQ, are determined according to the relevant literature (**Table 5.1**) and then confirmed with the group of experts (**Table 5.4).**

Phase 3: The importance of each SN is obtained applying Steps 3 and 4 from previous subsection, by using Eq. (3.2.6). The **Table 5.6** provides each DMs assessment and the aggregated IV-2-TL values for SNs' weights.

Table 5.6: SN assessments and aggregated values.

	DM1		**DM2**		**DM3**		**DM4**		**DM5**		**AGGREGATED**	
	M	**NM**	**M**	**NM**	**M**	**NM**	**M**	**NM**	**M**	**NM**	**M**	**NM**
SE1	VHI	VLI	VHI	VLI	VHI	VLI	HI	LI	VHI	VLI	(F,0.2317)	(HI,0.01101)
SE2	EHI	ELI	EHI	ELI	EHI	ELI	HI	LI	VHI	VLI	(MHI,-0.05147)	(F,-0.35841)
SE3	HI	LI	LI	HI	HI	LI	HI	LI	VHI	VLI	(MLI,0.4561)	(VHI,-0.00172)
SE4	MHI	MLI	F	F	MHI	MLI	MHI	MLI	MHI	MLI	(MLI,-0.15139)	(VHI,0.3848)
SS1	LI	HI	F	F	MHI	MLI	MLI	MHI	MHI	MLI	(LI,0.21262)	(EHI,-0.18348)
SS2	HI	LI	F	F	MHI	MLI	HI	LI	VHI	VLI	(MLI,0.40783)	(VHI,-0.03796)
SS3	VHI	VLI	EHI	ELI	EHI	ELI	EHI	VLI	HI	LI	(MHI,-0.10656)	(F,0.26378)
SS4	F	F	F	F	LI	HI	MLI	MHI	F	F	(LI,0.046495)	(EHI,-0.09485)
SEC1	EHI	ELI	EHI	ELI	EHI	ELI	EHI	VLI	EHI	ELI	(MHI,0.33279)	(ELI,0)
SEC2	VHI	VLI	HI	LI	F	F	HI	LI	F	F	(MLI,0.44579)	(VHI,-0.02948)
SEC3	F	F	F	F	F	F	F	F	F	F	(LI,0.34099)	(EHI,-0.29518)
SEC4	VHI	VLI	VHI	VLI	HI	LI	VHI	VLI	VHI	VLI	(F,0.45071)	(HI,-0.43247)

Phase 4: The DRs for the digitalization are defined as in **Table 5.2.**

Phase 5: The HoQ structure is obtained by assessing SN-DR relationships. Each DM provided his/her assessments. Aggregation is performed by applying Eq. (3.2.6). The following **Figure 5.3** gives the aggregated final relation matrix for first and second HoQ.

The aforementioned phases are applicable to the second HoQ as well. The second HoQ also utilizes the same linguistic set as the first HoQ and follows the same steps to determine the final prioritization of SARs. However, there is one key distinction: the results obtained from the first HoQ are employed as the HOWs in the second HoQ, while **Table 5.3** turns into the WHATs for SA in the second HoQ.

	1st HoQ		DR1		DR2		DR3		DR4		DR5		DR6		DR7		DR8		DR9		DR10		DR11		DR12		DR13		DR14		DR15		DR16		DR17	
	Weights		M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
SE1	4.232	6.011					1.747	1.900	8.000	0.000																										
SE2	4.949	3.642					2.354	2.632	8.000	0.000			1.747	7.309									3.787	6.106	3.787	6.106			2.998	6.632			2.998	6.632	2.998	6.632
SE3	3.456	6.998	1.159	7.569	1.747	7.309	1.159	7.569	4.617	5.404			2.998	6.632									3.787	6.106	3.787	6.106			2.998	6.632	2.354	2.632	4.617	5.404	3.787	6.106
SE4	2.849	7.385			3.717	6.145			8.000	0.000					2.354	7.004	1.159	7.569					2.998	6.632	2.998	6.632	4.617	5.404	3.787	6.106	4.617	5.404	4.617	5.404	4.617	5.404
SS1	2.213	7.817			4.617	5.534	8.000	0.000			2.998	6.632	2.354	7.004	1.747	7.309	1.747	7.309	2.998	6.632			2.998	6.632	2.998	6.632	8.000	0.000					8.000	0.000	3.440	6.355
SS2	3.408	6.962																	8.000	0.000	2.998	6.632			2.998	6.632	2.998	6.632			2.354	2.632	8.000	0.000	2.998	6.632
SS3	4.893	4.264	3.787	6.106			3.717	6.145													2.998	6.632											8.000	0.000		
SS4	2.046	7.905					8.000	0.000			2.998	6.632											3.717	6.145					2.998	6.632						
SEC1	5.333	0.000			4.617	5.534			8.000	0.000	2.354	2.632	1.747	7.309	2.998	6.632							2.998	6.632	2.998	6.632			2.998	6.632					2.998	6.632
SEC2	3.446	6.971	3.440	6.355	4.617	5.534	8.000	0.000	3.717	6.145			4.617	5.404					3.787	6.106	3.787	6.106	4.617	5.404	3.787	6.106	2.354	2.632								
SEC3	2.341	7.705	3.717	6.145					4.617	5.404							2.998	6.632					3.787	6.106	2.354	2.632	2.354	2.632			3.787	6.106			2.998	6.632
SEC4	4.451	5.568			2.354	2.632	3.717	6.145			8.000	0.000											2.354	2.632	2.354	2.632	3.787	6.106							3.440	6.355

	2nd HoQ	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM	M	NM
DR weights		**SAR1**		**SAR2**		**SAR3**		**SAR4**		**SAR5**		**SAR6**		**SAR7**		**SAR8**		**SAR9**		**SAR10**		**SAR11**		**SAR12**		**SAR13**		**SAR14**		**SAR15**	
1.472	**DR1**	2.998	6.632	8.000	0.000					8.000	0.000	4.617	5.404	4.617	5.404	8.000	0.000					8.000	0.000			4.617	5.404	4.617	5.404	4.617	5.404
3.532	**DR2**	4.617	5.404	4.617	5.404	8.000	0.000	8.000	0.000	4.617	5.404	2.354	2.632	2.354	2.632	4.617	5.404	8.000	0.000	8.000	0.000			8.000	0.000	4.617	5.404	4.617	5.404	4.617	5.404
5.696	**DR3**															8.000	0.000					4.617	5.404	2.998	6.632						
10.123	**DR4**	8.000	0.000	8.000	0.000	2.354	7.569	2.354	2.632	3.717	6.145	8.000	0.000	4.617	5.404	2.998	6.632	2.354	2.632	2.354	2.632	4.617	5.404			8.000	0.000	8.000	0.000	8.000	0.000
4.028	**DR5**	2.998	6.632	2.998	6.632					1.747	7.309	8.000	0.000	4.617	5.404	2.354	2.632					2.998	6.632	3.717	6.145						
1.606	**DR6**	8.000	0.000	1.215	7.569	2.354	7.569	2.354	2.632	2.354	2.632	4.617	5.404	4.617	5.404	2.354	2.632	2.998	6.632	2.998	6.632					2.998	6.632	2.998	6.632	2.998	6.632
0.986	**DR7**	2.354	2.632			2.998	6.632	2.998	6.632	2.998	6.632					2.354	2.632	2.998	6.632	2.998	6.632										
0.168	**DR8**	1.215	7.569	1.215	7.569	3.717	6.145	3.717	6.145									3.717	6.145	3.717	6.145			3.717	6.145						
1.541	**DR9**											8.000	0.000	8.000	0.000	4.617	5.404					1.747	7.309	3.717	6.145	2.354	2.632	2.354	2.632	2.998	6.632
1.332	**DR10**							2.354	2.632	2.354	2.632	8.000	0.000	8.000	0.000	8.000	0.000	2.998	6.632	2.354	2.632	1.747	7.309								
4.184	**DR11**	4.617	5.404	4.617	5.404					2.998	6.632	3.717	6.145	3.717	6.145	8.000	0.000					1.215	7.569								
4.343	**DR12**	8.000	0.000	8.000	0.000	2.354	2.632	2.354	2.632	4.617	5.404	4.617	5.404	4.617	5.404	4.617	5.404	2.998	6.632	2.354	2.632	2.354	2.632	4.617	5.404	8.000	0.000	8.000	0.000	8.000	0.000
2.272	**DR13**	4.617	5.404							1.215	7.569	2.998	6.632	2.998	6.632	3.717	6.145	8.000	0.000							2.354	2.632	2.354	2.632	2.354	2.632
2.096	**DR14**	2.354	2.632	3.717	6.145	1.215	7.569	1.215	7.569	2.998	6.632	1.215	7.569	1.215	7.569			1.215	7.569	2.354	2.632										
1.516	**DR15**			0.578	7.796	3.717	6.145	3.717	6.145	3.717	6.145	1.747	7.309	1.747	7.309	4.617	5.404	3.717	6.145	3.717	6.145	2.354	2.632	4.617	5.404						
5.749	**DR16**	1.215	7.569							3.717	6.145	2.354	2.632	2.354	2.632	3.717	6.145					2.354	2.632								
3.304	**DR17**	3.717	6.145	3.717	6.145	3.717	6.145	3.717	6.145	4.617	5.404	4.617	5.404	4.617	5.404	3.717	6.145	3.717	6.145	2.998	6.632	2.354	2.632	4.617	5.404	8.000	0.000	8.000	0.000	8.000	0.000

Figure 5.3: Aggregated 1st and 2nd HoQ relation matrices.

5.5 Results and Discussions for 2-Staged 2TLFFS-HoQ Application

The first HoQ in this study focuses on two main objectives: defining the relationship between sustainability and digitalization and prioritizing the DRs based on the identified SNs.

5.5.1 Results of 2TLFFS-HoQ

By examining the homogeneity of the relationship matrix within the 1st HoQ, we can gain insights into how digitalization ensures sustainability. The obtained relation matrix of the 1st HoQ, along with the prioritization of DRs, will provide guidance in answering RQs 1 and 2. The following Table 5.7 gives the DRs' ranking and weighting.

Table 5.7: The results for the DR weighting and ranking.

DRs	2TLFFS	Beta Values	Rank
DR1	(VP,0.47)	1.472	14
DR2	(F, -0.47)	3.532	7
DR3	(G, -0.30)	5.696	3
DR4	(EG,0)	10.123	1
DR5	(F,0.28)	4.028	6
DR6	(P, -0.40)	1.606	11
DR7	(VP, -0.02)	0.986	16
DR8	(EP,0.17)	0.168	17
DR9	(P, -0.46)	1.541	12
DR10	(VP,0.33)	1.332	15
DR11	(F,0.18)	4.184	5
DR12	(F,0.34)	4.343	4
DR13	(P,0.27)	2.272	9
DR14	(P,0.09)	2.096	10

DR15	(P, -0.48)	1.516	13
DR16	(G, -0.25)	5.749	2
DR17	(MP,0.30)	3.304	8

5.5.2 Comparative Analysis

This applied 2TLFFS-QFD methodology is compared with the results derived from 2TL-QFD application. The rankings show similar results. The justification of the applicability, replicability of the results can be derived from the analysis.

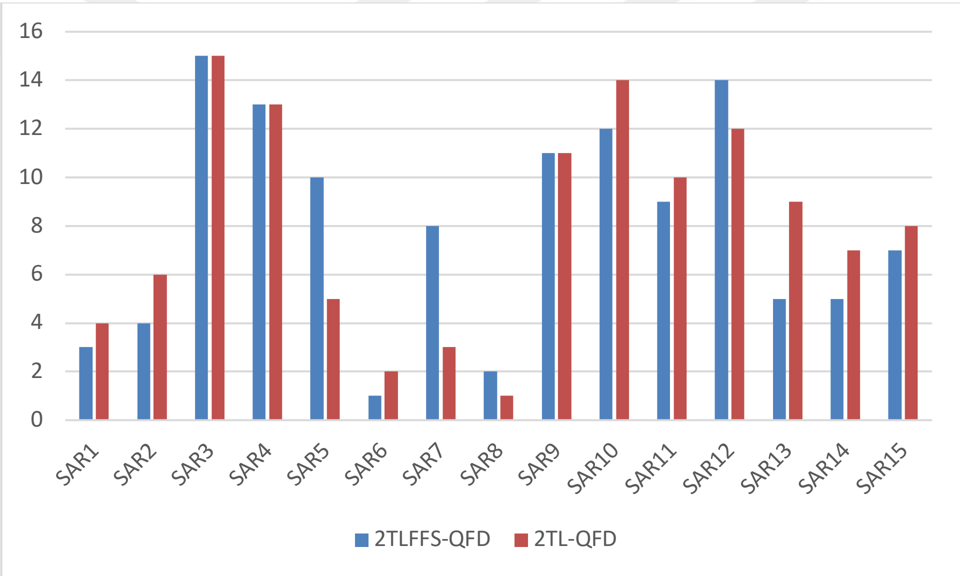

Figure 5.4: Comparative results for 2TLFFS-QFD and 2TL-QFD.

Upon examining the relation matrix depicted in **Figure 5.3**, it is evident that certain SNs exhibit weaker relationships with the DRs in 1st HoQ. In comparison to the 2nd HoQ, the first matrix contains more empty cells, indicating that the connection between digitalization and SA is stronger than the connection between sustainability and digitalization. Specifically, SNs such as SE3 (reduced emissions), SS1 (reduces impact on community), SEC1 (asset utilization), and SEC2 (cost reduction) exhibit strong associations with the DRs. Notably, SS1, which demonstrates the highest level of connections with each DR, represents a significant SN addressed by digitalization. These SNs highlight key aspects of sustainability that can be effectively addressed through digitalization, such as minimizing environmental impacts, enhancing community well-being, optimizing resource utilization, and improving cost-efficiency.

Through the application, the three most critical SNs identified are SEC1 (cost reduction), SE2 (energy efficiency), and SS3 (laws and regulations). These SNs align with the literature's emphasis on the significance of cost reduction, energy efficiency, and adherence to laws and regulations for the development of efficient and sustainable systems (Ghobakhloo and Fathi, 2021). The suggested model implies that the DRs encompass these SNs; however, digitalization exhibits stronger relationships with the SNs highlighted in the previous paragraph. This suggests that digitalization plays a pivotal role in addressing and enhancing these specific SNs, reinforcing its potential to drive efficient and sustainable agricultural systems (Del Río Castro et al., 2021).

The findings of this study have implications for SDGs as well, namely SDG 3 (Good Health and Well-being) and SDG 12 (Responsible Consumption and Production). Regarding SDG 3, the prioritized SNs related to reducing the impact on the community (SS1) and addressing laws and regulations (SS3) directly align with the goal of promoting good health and well-being. By utilizing digitalization to address these SNs, such as through community engagement platforms or enhanced regulatory monitoring systems, the potential exists to improve health outcomes and ensure the well-being of individuals and communities (Del Río Castro et al., 2021).

In terms of SDG 12, the identified SNs of cost reduction (SEC2) and energy efficiency (SE2) have a direct connection to responsible consumption and production. Digitalization can play a vital role in optimizing resource utilization, implementing energy-efficient practices, and promoting sustainable production processes. By leveraging digital technologies and innovative solutions, it becomes possible to advance responsible consumption and production patterns, minimize waste generation, and enhance resource efficiency (FAO, 2018).

The 2nd HoQ focuses on obtaining a ranking of SARs to serve as a roadmap for SA design and find a response to RQ3. The DRs within this HoQ align with the sustainability measures, ensuring a coherent relationship between them. By analyzing the relation matrix and **Figure 5.3**, valuable insights can be gained regarding how the DRs fulfill the SARs, providing guidance on the fulfillment of sustainability requirements within the SA design process.

As previously mentioned, the relationship between digitalization and SA exhibits greater strength compared to the sustainability-digitalization connection. This is understandable considering that SA heavily relies on technological utilization and efficiency. Upon examining the ranked DRs in Table 5.7, it becomes apparent that DR4 (efficiency) emerges as the most critical DR for fulfilling the SARs. This underscores the significance of efficiency in achieving smartness objectives within the SA framework (Bandur et al., 2019). The following **Table 5.8** also gives the ranking of SARs.

Table 5.8: SARs' normalized weights obtained from 2nd HoQ and their ranking.

	Weights	**Rank**
SAR1	0.0870	3
SAR2	0.0779	4
SAR3	0.0306	15
SAR4	0.0495	13
SAR5	0.0557	10
SAR6	0.1001	1
SAR7	0.0725	8
SAR8	0.0941	2
SAR9	0.0510	11
SAR10	0.0502	12
SAR11	0.0612	9
SAR12	0.0378	14
SAR13	0.0779	5
SAR14	0.0779	5
SAR15	0.0765	7

The outcomes of the two-staged HoQ application reveal a strategic hierarchy for the design of SA systems, where specific SARs emerge as pivotal contributors to the integration of sustainability and digitalization measures.

The ranking places SAR6 (agricultural data collection and analysis tools), SAR8 (Integrated agricultural value chain), SAR1 (precision fertilization tools), SAR2 (Automated irrigation systems), and SAR14 (Automated fertilization tools) at the forefront of critical components. This prioritization underscores the significance of an integrated approach within the agricultural value chain, emphasizing the seamless collaboration of various system elements. Moreover, the emphasis on advanced tools for data collection and analysis positions informed decision-making as a cornerstone, fostering a data-driven paradigm for efficient agricultural management (Zscheischler et al., 2022).

Precision fertilization tools (SAR1) and automated irrigation systems (SAR2) occupy strategic positions, emphasizing the imperative of resource optimization. Precision techniques not only enhance the efficacy of fertilization processes but also contribute to sustainable agricultural practices by minimizing resource wastage. Simultaneously, automated irrigation systems play a pivotal role in resource-efficient water management, aligning with the broader ethos of sustainability.

The prioritized SARs collectively underscore the need for a technologically advanced and interconnected SA system. The amalgamation of these components contributes to the efficiency of agricultural operations, offering a robust foundation for sustainability measures. The design considerations presented here, when implemented cohesively, hold the potential to revolutionize agricultural practices, aligning with contemporary demands for both digitalization and sustainability.

In accordance with the prioritization of SARs, a strategic roadmap (Figure 5.5) is proposed to facilitate a seamless transition to SA. This roadmap outlines a systematic approach that leverages the critical components identified for optimal impact.

This thesis outlines a strategic roadmap for the transition to SA, emphasizing the pivotal role of technology provider selection in realizing the full potential of connectivity. At the heart of this transformation lies the imperative to invest in agricultural data collection and connectivity, with a focus on seamlessly integrating CC, IoT, and sensor technologies.

The initial step in this transformative journey underscores the critical need for a robust foundation in agricultural data collection and analysis tools. This foundational investment serves as the linchpin for data-driven decision-making and precision agriculture practices. However, the true power of this foundation is unlocked when coupled with advanced connectivity solutions. Cloud computing, IoT, and sensors emerge as the key enablers, forming an interconnected ecosystem that propels the agricultural sector into the realm of smart and efficient practices.

As the roadmap unfolds, the deployment of agricultural decision-making tools becomes central to supporting farmers in making informed choices regarding crop management, resource allocation, and risk mitigation. Here, the selection of technology providers assumes paramount importance, requiring a comprehensive approach that integrates CC, IoT, and sensors seamlessly. The interconnectedness of these technologies amplifies their impact, offering farmers a holistic platform for enhanced decision support. Therefore, in the next chapter, the selection of technology providers for Cloud Computing, IoT, and sensors will be conducted.

1. Invest in agricultural data collection and analysis tools. This is a critical foundation for enabling data-driven decision-making and precision agriculture practices.
2. Deploy agricultural decision-making tools to support farmers in making informed decisions about crop management, resource allocation, and risk mitigation.
3. • Implement crop monitoring tools to track crop growth and health in real time. This information can be used to identify and address potential problems early on, minimizing crop losses and improving yields.
4. Adopt precision fertilization and automated irrigation systems to optimize nutrient and water use. This can lead to significant reductions in input costs and environmental impact, while also improving crop yields.
5. Implement crop modelling tools to simulate crop growth and development under different environmental conditions. This information can be used to optimize crop management practices and reduce risks.
6. • Develop and implement an integrated agricultural value chain that connects farmers with other stakeholders, such as processors, suppliers, and retailers. This can improve efficiency, reduce costs, and enhance the traceability of agricultural products.
7. Implement crop traceability systems to track the movement of agricultural products from farm to fork.This can help to ensure food safety and build consumer trust.
8. • Develop and deploy agricultural digital platforms to provide farmers and other stakeholders with access to information and services related to smart agriculture. This can help to accelerate the adoption of smart agriculture technologies and practices.
9. Implement agricultural risk awareness systems to help farmers identify and manage risks associated with climate change, pests, diseases, and other factors. This can enhance the resilience of the agricultural sector.
10. Explore and implement automated harvesting tools and disease detection tools to improve efficiency and reduce labor costs.

Figure 5.5: Roadmap for designing SA system.

6 TECHNOLOGY PROVIDER SELECTION FOR CONNECTIVITY IN SA

In this segment, a methodological approach, specifically the 2TLFFS-DEMATEL-VIKOR (VIseKriterijumska Optimizacija I Kompromisno Resenje), will be employed to discern the most suitable technology providers for CC, IoT, and Sensors within the context of SA. The criteria utilized herein are derived from a previously published article focusing on the selection of technology providers, emphasizing the foundational aspects discussed in preceding sections (Büyüközkan et al., 2023).

The antecedent chapters underscore the paramount significance of connectivity and the acquisition of data from agricultural fields as pivotal prerequisites for informed decision-making. Within this overarching framework, the inaugural step towards the establishment of an efficient SA system necessitates strategic investments in technologies facilitating comprehensive data acquisition from the field. Consequently, the proposed adoption of the 2TLFFS-DEMATEL-VIKOR framework is posited as a judicious and methodologically sound approach to guide the intricate process of technology provider selection.

This methodological framework aligns seamlessly with the outlined objectives, offering a structured and systematic means to evaluate and select technology providers for CC, IoT, and Sensors. As explicated in the preceding chapters, the efficiency and efficacy of a SA system hinge upon the adeptness of these technologies in facilitating robust data collection, analysis, and subsequent decision support.

6.1 Suggested Methodology for the Technology Provider Selection

In order to choose the most appropriate technology provider, their section suggests 2TLFFS-DEMATEL methodology to weight the criteria. The first chapter related to SWOT/PESTLE analysis presents the suggested 2TLFFS-DEMATEL methodology and the same steps are applied in this chapter as well for the criteria obtained from (Büyüközkan et al., 2023). The novel 2-TLFFS-VIKOR methodology is presented as follows:

Step 1: The DMs assess the technology provider alternatives according to the detected criteria. The evaluations of DMs are obtained with linguistic variables as in the previous sections. 2TLFFS linguistic variables are used for it.

Step 2: The weights of the DMs are defined based on their experience in years on the designated area. Here in this problem their experience about the digital technologies and digitalization will provide a basis to define their weights.

Step 3: The individual assessments of each DM are aggregated by using 2TLFFWHM operator as in Eq. (3.2.6).

Step 4: The entries of aggregated ultimate assessment matrix are converted to 2TL score values and the aggregated score values matrix can be obtained by using Eq. (5.2.2) as follows:

$$\mathcal{F} = \begin{pmatrix} f_{11} & f_{12} & \cdots & f_{1p} \\ f_{21} & f_{22} & \cdots & f_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ f_{s1} & f_{s2} & \cdots & f_{sp} \end{pmatrix}$$

Step 5: Based on the score values best and worst values of all criteria are selected. Let B and C are the benefit-type and cost-type criterion, then the best value f_v^+ and worst valur f_v^- of *vth* criterion are determined as follows:

$$f_v^+ = \begin{cases} \underset{1\le n\le s}{max}\, f_{nv}, & \text{if } \rfloor_v \in B, \\ \underset{1\le n\le s}{min}\, f_{nv}, & \text{if } \rfloor_v \in \text{C}. \end{cases}$$
$$f_v^- = \begin{cases} \underset{1\le n\le s}{min}\, f_{nv}, & \text{if } \rfloor_v \in \text{B}, \\ \underset{1\le n\le s}{max}\, f_{nv}, & \text{if } \rfloor_v \in \text{C}. \end{cases} \tag{6.1.1}$$

The maximum and minimum are derived by the formulation above. The next step is to calculate group utility ($\mathcal{S}_n$) measure and individual regret measure ($\mathcal{R}_n$) corresponding to the *nth* alternative.

$$\mathcal{S}_n = \sum_{v=1}^{p} w_v \left(\frac{f_v^+ - f_{nv}}{f_v^+ - f_v^-}\right),$$
$$\mathcal{R}_n = \underset{v=1}{\overset{p}{max}}\, w_v \left(\frac{f_v^+ - f_{nv}}{f_v^+ - f_v^-}\right). \tag{6.1.2}$$

The minimum and maximum values for group utility and individual regret are calculated as follows:

$$\mathcal{S}^* = \underset{n}{max}\, \mathcal{S}_n, \qquad \mathcal{S}' = \underset{n}{min}\, \mathcal{S}_n,$$
$$\mathcal{R}^* = \underset{n}{max}\, \mathcal{R}_n, \qquad \mathcal{R}' = \underset{n}{min}\, \mathcal{R}_n. \tag{6.1.3}$$

Finally the ranking measures of nth alternative can be calculated by using following equation:

$$Q_n = q\left(\frac{\mathcal{S}_n - \mathcal{S}'}{\mathcal{S}^* - \mathcal{S}'}\right) + (1-q)\left(\frac{\mathcal{R}_n - \mathcal{R}'}{\mathcal{R}^* - \mathcal{R}'}\right) \tag{6.1.4}$$

where the parameter q is known as the weight of strategy of the maximum group utility of the attribute and its value can be chosen from [0; 1] depend upon the MAGDM problem. Usually, q is considered as 0:5 in order to obtain the compromise solution that possesses maximum S and minimum R. For q = 1; compromise solution only emphasizes on R. Also, for q = 0; the compromise solution emphasizes to R.

Step 6: The alternatives are arranged in ascending order relative to *S, R and Q* values. The alternative having the minimum Q value is the most appropriate alternative than others.

Step 7: Let *A(1)* and *A(2)* ranked at the first and second place regarding Q respectively. The compromise solution will be *A(1)* if it satisfies the following conditions:

Condition 1: "Acceptable advantage"

$$Q\left(\text{Å}^{(2)}\right) - Q\left(\text{Å}^{(1)}\right) \geq DQ \tag{6.1.5}$$

where $DQ = \frac{1}{s-1}$ and s is the total number of alternatives.

Condition 2: "Acceptable stability in decision-making"

In case of one or both of these requirements do not obey then the set of compromise solution can be identified as follows:

A(1) and A(2) both are in the set of compromise solution, if only one condition is not satisfied.

If the first condition does not satisfy, then the set of compromise solution is originated by employing the following inequality:

$$Q\left(\mathbb{A}^{(p)}\right) - Q\left(\mathbb{A}^{(1)}\right) < DQ \tag{6.1.6}$$

6.2 Technology Provider Selection Criteria

The criteria are derived from the author's article (Büyüközkan et al., 2023). The following table (**Table 6.1**) provides the criteria list provided for the technology provider selection.

Table 6.1: CC, IoT and Sensor technology provider assessment dimensions and criteria.

Dimensions	Criteria	Criteria Definitions
A: Cloud Security	(CS1) Confidentiality	The focus is on protecting the confidentiality of transactional information, and carefully preserving and transporting customer information.
	(CS2) Integrity	Defines the avoidance of security risks from missing or corrupt data in order to ensure the integrity of imported data.
	(CS3) Availability	Defines whether computational resources are accessible and available for a certain period of time.
	(CS4) Auditability	In addition to accessing information about the security situation, it focuses on improving security.
	(CS5) Multi-tenant Trust	Explains whether the system provides the expected interaction.
B: Cost	(CO1) Investment Cost	Describes direct initial costs to obtain and locate the IT infrastructure.
	(CO2) Maintenance Cost	Describes constantly emerging costs of maintaining the IT infrastructure.
	(CO3) Integration Cost	Describes the cost of integrating the IT infrastructure into the processes of the organization.
	(CO4) Flexibility Cost	Describes further IT infrastructure that may increase the costs.
	(CO5) Support Cost	Describes the costs for help-desk support to be considered as part of the total costs.

C: Physical Property Part	(PP1) Communication	Defines the transfer of data/messages between internal services, or between an external client and the Cloud.
	(PP2) Computation	Describes the computing-intense data/job operating in the cloud.
	(PP3) Memory	Memory (Cache) represents rapid access to momentarily stored data.
	(PP4) Storage	Storage is used to perennially keep the data of customers until the data are extracted or while the services are delayed deliberately.
D: Capacity	(CP1) Transaction Speed	Describes how quickly transactions can be processed.
	(CP2) Availability	Explains whether a system will remain in operation.
	(CP3) Latency (Time)	Latency concerns the measure of time-delay for a particular job.
	(CP4) Reliability	Whether a system can fulfill its function appropriately.
E: Management Services	(MS1) Deployment	Design, manage, and deploy are the three processes of cloud application deployment which need to be automated to reduce the burden across cloud deployment.
	(MS2) Configuration	Automated configuration of computers from the policy definition is vital, especially for complex cloud environments.
	(MS3) Billing	Billing version for resource utilization is identified as pay-as-you-spend.
	(MS4) Reporting	Describes the system that provides reporting and produces the health report.
	(MS5) Monitoring	Describes monitoring cloud systems directly and easily using monitoring systems that register the resource usage (such as CPU, RAM, disk, bandwidth) on each node.

F: Service Quality	(SQ1) SLA Management	SLA is a component to negotiate and install resource agreements between resource customers and resource providers.
	(SQ2) Service Stability	Describes providing services to customers as expected or promised
	(SQ3) Enrich Content	Defines the quality aspects of cloud service content.
G: Vendor-related topics	(VR1) Vendor's Reputation	Vendor's reputation contains two elements: Number of clients/users and the brand value of vendor.
	(VR2) Experience in related products	Defines the vendor's experience in developing software products.
	(VR3) Quality of support service	The quality of support service necessitates the change and widening of several workflow system elements, also the development of extra modules.
	(VR4) Community support	The larger the community of a cloud service; the more support the firms can have.
	(VR5) R&D capability	Defines a quantitative feature whose initial value can be the R & D investment of cloud suppliers.

6.3 Application of the Suggested 2TLFFS-DEMATEL-VIKOR Methodology for Technology Provider Selection for SA.

To initiate the process, a decision-making group comprising five distinct experts is assembled. This identical group of experts will subsequently be employed to evaluate supplier alternatives. The assignment of weights to DMs is determined in accordance with their respective years of experience. Consequently, the initial phase of the 2TLFFS-DEMATEL application involves generating assessment matrices derived from the evaluations provided by the DMs.

Having identified the principal dimensions and criteria for supplier evaluation, the forthcoming application of the 2TLFFS-VIKOR methodology will focus exclusively on the elaboration of the first dimension. Subsequently, the supplier selection process will be meticulously executed, drawing upon the insights derived from the detailed examination of this primary dimension. This targeted approach ensures a comprehensive and nuanced assessment, allowing for a judicious and informed decision-making process based on the identified dimensions.

The following **Table 6.2** presents the assessment of each DM for the main dimensions.

Table 6.2: Each DMs assessment for main dimensions of technology provider selection.

DM1	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**
	CS		CO		PP		CP		MS		SQ	
CS	0	0	MLI	MHI	VHI	VLI	VHI	VLI	HI	LI	HI	LI
CO	MLI	MHI	0	0	HI	LI	HI	LI	VHI	VLI	MLI	MHI
PP	VLI	VHI	MLI	MHI	0	0	MLI	MHI	MLI	MHI	VLI	VHI
CP	MLI	MHI	MLI	MHI	MHI	MLI	0	0	MLI	MHI	MLI	MHI
MS	MLI	MHI	VLI	VHI	MLI	MHI	MLI	MHI	0	0	MLI	MHI
SQ	MLI	MHI	MLI	MHI	HI	LI	MLI	MHI	HI	LI	0	0

DM2	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**
	CS		CO		PP		CP		MS		SQ	
CS	0	0	MLI	MHI	EHI	ELI	VHI	VLI	HI	LI	HI	LI
CO	MLI	MHI	0	0	HI	LI	HI	LI	VHI	VLI	MLI	MHI
PP	VLI	VHI	MLI	MHI	0	0	MLI	MHI	MLI	MHI	VLI	VHI
CP	MLI	MHI	MLI	MHI	MHI	MLI	0	0	MLI	MHI	MLI	MHI
MS	MLI	MHI	VLI	VHI	MLI	MHI	MLI	MHI	0	0	MLI	MHI
SQ	MLI	MHI	MLI	MHI	HI	LI	MLI	MHI	HI	LI	0	0

DM3	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**
	CS		CO		PP		CP		MS		SQ	
CS	0	0	F	F	EHI	ELI	EHI	ELI	HI	LI	HI	LI
CO	F	F	0	0	HI	LI	HI	LI	EHI	ELI	F	F
PP	VLI	VHI	VLI	VHI	0	0	F	F	VLI	VHI	VLI	VHI
CP	VLI	VHI	F	F	HI	LI	0	0	VLI	VHI	F	F
MS	VLI	VHI	VLI	VHI	F	F	F	F	0	0	F	F
SQ	VLI	VHI	F	F	HI	LI	HI	LI	HI	LI	0	0

DM4	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**
	CS		CO		PP		CP		MS		SQ	
CS	0	0	F	F	EHI	ELI	EHI	ELI	HI	LI	HI	LI
CO	F	F	0	0	HI	LI	HI	LI	EHI	ELI	F	F
PP	VLI	VHI	VLI	VHI	0	F	F	F	VLI	VHI	VLI	VHI
CP	VLI	VHI	F	F	HI	0	0	0	VLI	VHI	F	F
MS	VLI	VHI	VLI	VHI	F	F	F	F	0	0	F	F
SQ	VLI	VHI	F	F	HI	LI	HI	LI	HI	LI	0	0

DM5	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**	**N**	**NM**
	CS		CO		PP		CP		MS		SQ	
CS	0	0	VLI	VHI	HI	LI	HI	LI	HI	LI	HI	LI
CO	VLI	VHI	0	0	HI	LI	HI	LI	HI	LI	VLI	VHI
PP	VLI	VHI	VLI	HI	0	0	VLI	VHI	VLI	VHI	VLI	VHI
CP	VLI	VHI	VLI	VHI	HI	LI	0	0	VLI	VHI	VLI	VHI
MS	VLI	VHI	VLI	VHI	HI	LI	HI	LI	0		VLI	VHI
SQ	VLI	VHI	HI	LI	HI	LI	HI	LI	HI	LI	0	0

By following the 2-TLFFS-DEMATEL steps we obtain the aggregated total direct/indirect influence matrix. The following **Table 6.3** gives the matrix with relevant *(D+R)* and *(D-R)* values.

Table 6.3: Total influence matrix for technology provider selection.

	CS	CO	PP	CP	MS	SQ	D	R	D+R	D-R	Weight	C/E
CS	0.030	0.088	0.414	0.335	0.311	0.158	0.215	1.336	1.55	-1.12	1.914	E
CO	0.062	0.023	0.176	0.162	0.229	0.075	0.300	0.727	1.03	-0.43	1.112	E
PP	0.018	0.032	0.021	0.060	0.041	0.022	0.991	0.193	1.18	0.80	1.428	C
CP	0.034	0.057	0.132	0.030	0.056	0.059	0.787	0.367	1.15	0.42	1.228	C
MS	0.032	0.025	0.090	0.082	0.024	0.058	0.809	0.311	1.12	0.50	1.226	C
SQ	0.039	0.075	0.159	0.117	0.148	0.022	0.394	0.561	0.95	-0.17	0.969	E

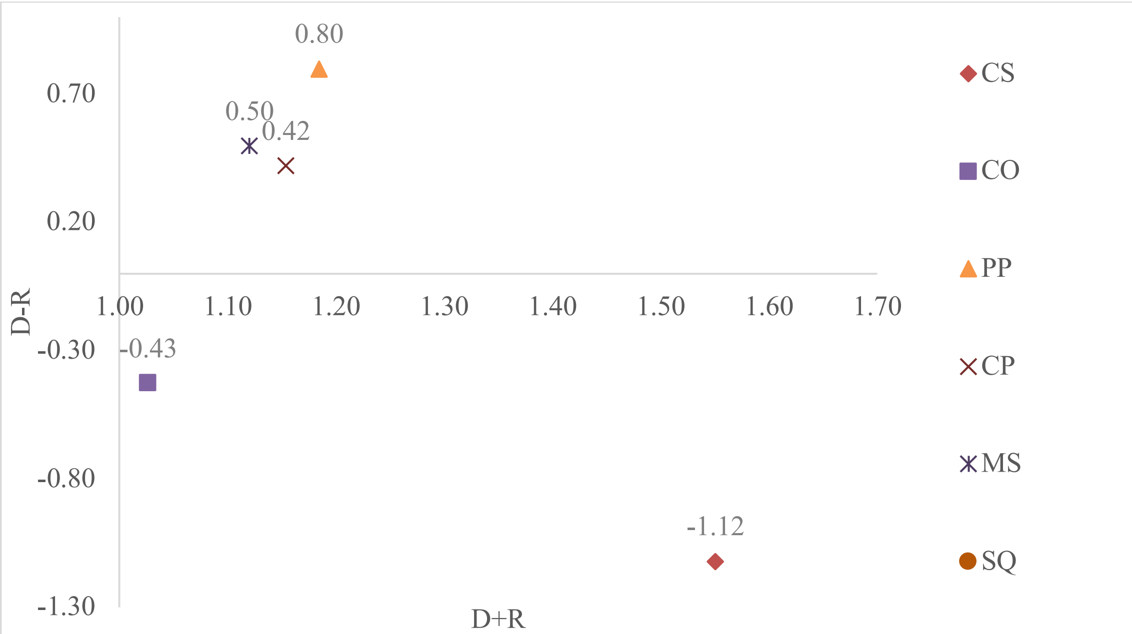

Figure 6.1: Cause effect diagrams for technology provider selection dimensions.

The graph (**Figure 6.1**) above shows the cause effect diversion for the main dimensions. Followingly 2TLFFS-VIKOR is applied to choose the most appropriate supplier from the six different alternatives. By following the 2TLFFS-VIKOR steps provided at the beginning of this chapter we obtain an aggregated assessment matrix with score values. The following **Table 6.4** provides the aggregated assessment matrix with dimension weights derived from the 2TLFFS-DEMATEL application.

Table 6.4: Ultimate aggregated assessment matrix for 2TLFFS-VIKOR.

Weights	0.222	0.147	0.169	0.165	0.160	0.137
	CS	**CO**	**PP**	**CP**	**MS**	**SQ**
Alternatives	**Benefit**	**Cost**	**Benefit**	**Benefit**	**Benefit**	**Benefit**
Supplier 1	1.0526	1.0526	7.2961	6.0209	5.6287	2.5885
Supplier 2	1.0526	0.5786	2.5885	2.5885	4.3461	1.0526
Supplier 3	0.2992	0.5786	2.5885	1.0526	0.5786	0.2992
Supplier 4	0.5786	1.0526	2.2806	1.0526	0.5786	1.0526
Supplier 5	0.5786	0.2992	1.3726	1.3726	2.5885	1.0526
Supplier 6	0.5786	1.3726	2.5885	1.8048	2.5885	1.0526
F*	1.0526	0.2992	7.2961	6.0209	5.6287	2.5885
F-	0.2992	1.3726	1.3726	1.0526	0.5786	0.2992

6.3.1 Results for the Technology Provider Evaluation

After normalization and the weighting of the assessment matrix, S, R and Q values for each supplier is obtained. The values are presented in the following **Table 6.5**.

Table 6.5: *S, R, and Q* values for technology provider alternatives.

	Si	**Ri**	**Qi (q=0.5)**	**Rank**
Supplier 1	0.103	0.103	0.000	1
Supplier 2	0.419	0.135	0.343	2
Supplier 3	0.857	0.222	1.000	6
Supplier 4	0.803	0.165	0.725	5
Supplier 5	0.652	0.169	0.643	4
Supplier 6	0.749	0.147	0.613	3

In the VIKOR method, the parameter q serves as a critical tuning knob, influencing the balance between proximity to the ideal solution *(Si)* and distance from the negative ideal solution *(Ri)* when determining the compromise solution *(Qi)* for each alternative. By adjusting q, we can prioritize either performance maximization or risk minimization, tailoring the analysis to your specific decision priorities. Conducting a sensitivity analysis through varying q values reveals the stability of the ranking and sheds light on potential shifts in preferred options. Ultimately, the optimal q value depends on risk tolerance, degree of uncertainty in the data, and expert judgment, ensuring your decision aligns with your intended goals.

In this selection process we have chosen q=0.5 since it is the most common value used in VIKOR analysis. It gives equal importance to both *Si* and *Ri*, leading to a balanced compromise solution.

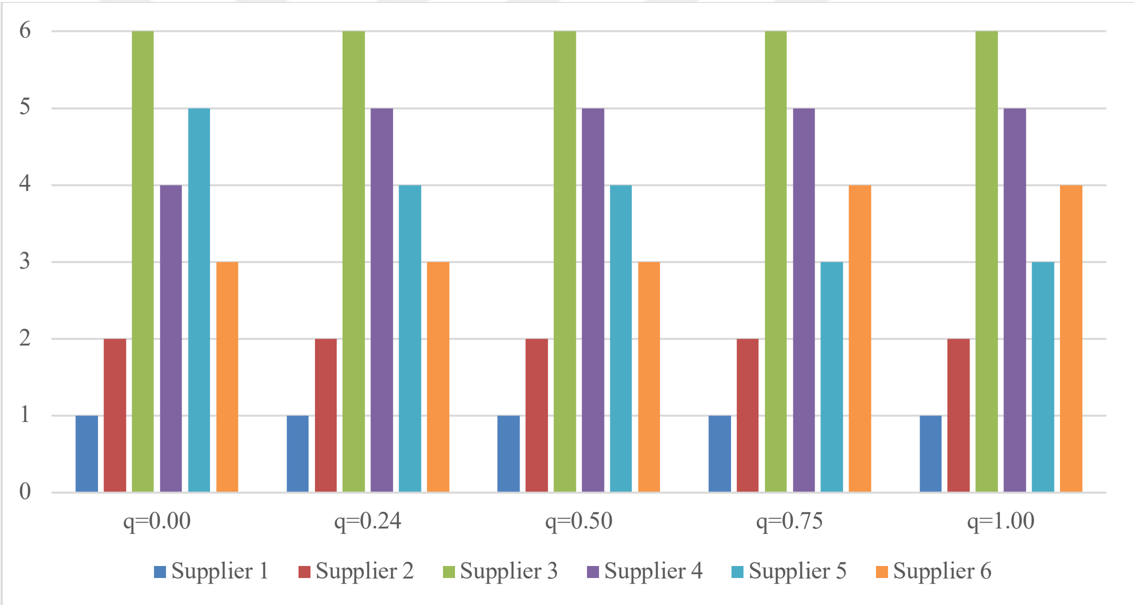

Figure 6.2: The sensitivity analysis for 2TLFFS-VIKOR.

Based on the figure above, it seems that the ranking of the suppliers is relatively stable under different q values. Supplier 1 remains ranked first across all q values, while Supplier 6 remains ranked third. However, there are some minor changes in the ranking of the other suppliers, with Supplier 4 and 5 swapping places for q = 0.1 and q = 0.9.

This suggests that the ranking of the suppliers is not highly sensitive to the q value, indicating that the overall performance of the suppliers is relatively well-defined. Accordingly:

- Supplier 1 is consistently ranked first across all q values, suggesting that it is the most robustly performing supplier.
- Supplier 6 is also consistently ranked in the top three, making it a reliable choice as well.

This chapter explored supplier selection using a novel 2TLFFS-DEMATEL-VIKOR methodology. This approach effectively handled the uncertainties inherent in both the supplier performance data and the decision-making process. DEMATEL facilitated the identification of key dimensions and their interrelationships, while VIKOR provided a robust ranking of suppliers based on their performance across multiple criteria. This integrated approach proved valuable for supplier selection by offering a comprehensive and transparent decision-making framework. By leveraging the strengths of both DEMATEL and VIKOR, this methodology facilitated informed and reliable supplier selection, ensuring the long-term success and competitiveness of the organization.

6.3.2 Comparative Analysis

The novel suggested model is compared with the 2TL-VIKOR methodology. The following Figure represents the comparative results from two applications of the same problem.

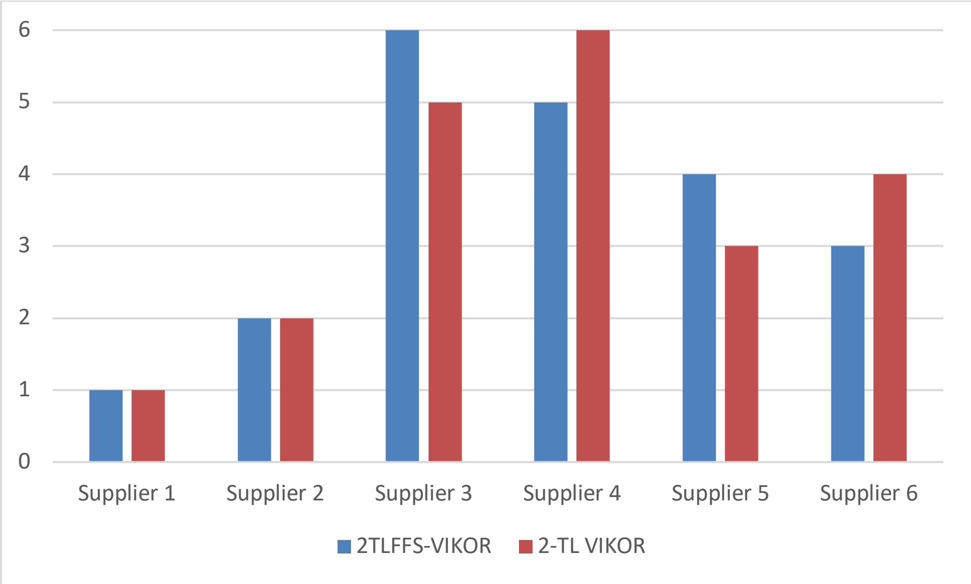

Figure 6.3: Comparative analysis for 2TLFFS-VIKOR.

7 CONCLUSION AND PERSPECTIVES

In this concluding chapter, the thesis provides a synthesis of key conclusions and discussions derived from the study. Limitations affecting the findings are outlined, and the various influences impacting the study are elucidated. Additionally, future research avenues are proposed, drawing upon the insights gleaned from the findings and the constraints encountered during the course of this research endeavor.

7.1 Conclusion

This thesis targets to answer some questions which stem for a need to better understand the SA and its components. This thesis aims to create a roadmap to design agrarian systems for a smooth transition to SA.

The initial chapter of this thesis conducts a comprehensive review of existing SA literature, offering a detailed examination of the predominant technologies embedded within SA systems. This exhaustive analysis serves a dual purpose: firstly, to identify prevalent technologies, and secondly, to discern existing gaps and illuminate future trajectories in the realm of SA. The synthesis of insights from this literature review further facilitates a nuanced understanding of the sustainability-digitalization conundrum inherent in SA. Moreover, the review illuminates the benefits and challenges inherent in the adoption of SA technologies.

The discerned knowledge from the SA literature review serves as a foundational pillar for the thesis, shaping a contextual understanding of the intricate interplay between sustainability and digitalization within the SA domain. Significantly, the review underscores the imperative for a comprehensive approach in the design and implementation of SA systems.

By unveiling the existing landscape, this chapter not only contributes to the academic discourse but also lays the groundwork for subsequent chapters, which delve into specific dimensions of technology selection and system development within the SA framework.

Based on the results of the literature review, in this thesis, an initial stage involves conducting a SWOT/PESTLE analysis specifically tailored for Turkish agriculture. The rationale behind undertaking a detailed analysis is to gain insights into the current state before designing the transition to SA. Through this analysis, the strengths, weaknesses, risks, and opportunities of Turkish agriculture are elucidated. To enhance the effectiveness of the SWOT/PESTLE analysis and prioritize analysis factors when formulating strategies, the DEMATEL method is employed. By focusing on independent factors (causal factors) using the DEMATEL method, strategies are developed with key themes for the transition to SA.

The compiled strategies, particularly emphasizing sustainability alongside digitization, pose a crucial question for the next chapter: How should we design SA systems to incorporate both digitization and sustainability features? Additionally, to obtain a comprehensive approach identified in the literature review, the fourth chapter employs a two-stage QFD method to strive for a roadmap meeting the requirements of both sustainability and digitization for SA systems. At the conclusion of this application, 10 steps for transitioning to SA are identified. At the forefront of these steps is the investment in information-gathering technologies for agricultural systems.

Building upon this requirement, the final chapter proposes a provider selection methodology for essential CC, IoT, and sensor technologies crucial for connectivity and data collection. This methodology comprises the 2TLFFS-DEMATEL-VIKOR techniques.

Conventional MCDM methodologies predominantly rely on crisp values, which may not be suitable for addressing real-world problems characterized by uncertainty, vagueness, ambiguity, and imprecision. Recognizing this limitation, efforts have been made to extend these methodologies to more comprehensive environments (Büyüközkan & Göçer, 2018a). In this thesis, the extension of FFS known as 2TL is employed to tackle such challenges.

Various mathematical constructs have been introduced to represent uncertain information in the objective world, including FS, IFS, PFS, and FFSs. While classical Fuzzy Sets express membership degrees only, IFSs, introduced by K.T. Atanassov in 1986, generalize this concept by considering both membership and non-membership degrees for all objects in the universe, ensuring their sum falls within the range of [0, 1] (Atanassov, 2012). An enhancement to IFS is the PFS, devised by Yager in 2013, allowing the sum of the squares of membership and non-membership degrees to fall within [0, 1]. PFS thus encompasses IFS, demonstrating its broader applicability (X. Zhang & Xu, 2014).

Senapati and Yager (2020) conducted an insightful analysis of the relationships between FFS, IFS, and PFS. They concluded that IFS is a specific instance or special case within the broader framework of PFS, while FFS is an extension or generalization of PFS. Furthermore, the concept of FFS was expanded by Senapati and Yager (2020) to include the cubic sum of membership and non-membership values within the range of [0, 1].

In the context of FFS theory, it is noteworthy that FFS plays a pivotal role in various fields due to its advantageous and powerful nature in dealing with uncertain information (D. Liu, Liu, & Chen, 2019). This thesis leverages the 2TL extension of FFSs to address the challenges posed by uncertain and imprecise information, providing a robust foundation for addressing multiple-choice problems in a more realistic and encompassing manner.

The journey of designing and implementing a successful SA system necessitates a nuanced and multifaceted approach. This thesis navigates this complexity by presenting a series of interconnected chapters, each contributing a unique piece to the puzzle of building a sustainable and digitalized SA system.

By intricately weaving together these diverse chapters, this thesis presents a compelling narrative that transcends mere summarization. Each chapter builds upon the previous one, progressively delving deeper into the complexities of SA system design while offering concrete solutions and actionable strategies. This interconnected approach ensures a comprehensive understanding of the multifaceted considerations involved in crafting a successful SA system, providing valuable insights for researchers and practitioners alike.

7.2 Limitations and Future Research Areas

This thesis represents a cutting-edge contribution to the field of SA, offering innovative models and designs for SA systems while critically examining the digitalization of agricultural practices. However, like any research endeavor, this study is not exempt from limitations, and several areas of potential constraint are acknowledged:

- Methodological Limitations: The study is subject to methodological limitations stemming from the subjective nature of the analysis. The linguistic judgments provided by experts rely on their past knowledge, experiences, and subjective assessments, introducing a level of inherent bias. Furthermore, experts' assumptions and subjective evaluations may influence results, particularly in descriptive interpretations. The efficacy of the QFD framework, although valuable, is contingent on meticulous implementation, where chosen translation methods and accuracy in assigning weights during the QFD process significantly impact the final roadmap. The inherent subjectivity and reliance on qualitative judgments within the SWOT/PESTLE analysis introduce potential variability in interpretations, affecting the conclusions.

- Context-Specific Nature: The research is situated within the specific context of the Turkish agricultural landscape, limiting the generalizability of findings to other regions or countries. The transferability of results may require additional analysis and adjustments to accommodate local contexts and specificities. Additionally, the dynamic nature of the SA field, marked by constant technological advancements, may render certain aspects of the research outdated, potentially affecting its relevance and applicability in the future.

Despite these acknowledged limitations, the study provides valuable insights, and future research in the domain of SA can build upon this groundwork and past experiences. The following future research trends are proposed:

- While technologies such as the IoT, CC, and sensors prominently feature in this thesis for data collection, the processing of future data through ML algorithms emerges as a crucial area of exploration for accurate decision-making in SA systems. Consequently, there is a compelling need to delve into the processing of data acquired in the future through ML algorithms, paving the way for more sophisticated automation in agriculture.

- Furthermore, the automation introduced poses significant challenges, particularly in the context of sustainability and food security, which are critical considerations in the broader agricultural landscape. Addressing these challenges through automation aligns with the overarching objectives of sustainable agriculture practices and ensuring food security. Therefore, these aspects should be prioritized in future research endeavors.

- Additionally, the strategies and roadmaps proposed within this thesis should be tested and adapted for application in diverse developing countries. Conducting experiments in different developing nations is essential to gauge the universality and effectiveness of the suggested approaches.

- Finally, in the domain of technology provider selection outlined in this thesis, delving into the examination of the sub-dimensions of the identified criteria and selecting suppliers based on these sub-dimensions holds significance for future research. Investigating the nuances within the criteria and sub-dimensions, as well as aligning supplier selection with these specific parameters, becomes imperative for the advancement of future studies in this field.

Despite its immense promise, SA is yet to fully realize its potential. This research highlights several areas demanding immediate attention if SA is to fulfill its transformative potential. In today's rapidly evolving and competitive agricultural landscape, businesses that fail to embrace and implement sound SA practices risk losing ground to their more proactive counterparts.

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BIOGRAPHICAL SKETCH

Born on [redacted], in [redacted], Turkey, **Deniz Uztürk** is an accomplished professional with a diverse academic background. She attended İstanbul Saint Joseph French High School for her secondary education from 2002 to 2008. Following her graduation, she pursued her undergraduate studies in Mining Engineering at Istanbul Technical University, completing her degree in 2014. Building on this foundation, she transitioned to the field of Industrial Engineering, earning her graduate degree from Galatasaray University in 2017. After gaining practical experience at Mavi Consultance, where she contributed to the development of Climate Change and Air Quality Action Plans for Istanbul, Deniz embarked on a Ph.D. journey in Industrial Engineering at Galatasaray University. Simultaneously, she assumed the role of research assistant in the Management Department at Galatasaray University's Faculty of Economics and Administrative Sciences.

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