

Additive Manufacturing in Edible Product Supply Chain: A Sustainable Perspective

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Abstract. As the quest for healthier lifestyles intensifies, there is a growing demand for customized nutritional options, challenging the traditional food supply chain with its perishable goods and unpredictable demand patterns. This paper explores the potential of additive manufacturing, or 3D printing, as an innovative solution to these challenges. We present a conceptual framework to assess the impact of AM on the supply chain of edible products, including food and medicine, through the lens of sustainability—encompassing environmental, social, and economic perspectives. Our systematic literature review identifies five key strategies through which AM can enhance supply chain sustainability: distributed localized manufacturing, in-house production, delayed production, mass customization, and on-demand production. This research contributes valuable insights for industry practitioners and policymakers, guiding them toward exploiting AM's potential to revolutionize the sustainable supply chain management of edible products. Our findings highlight the transformative capabilities of AM and set the stage for future research directions in the nexus of additive manufacturing and sustainable supply chain practices.

Keywords: Edible product, Supply chain, Sustainability, Additive manufacturing

1 Introduction

Have you ever tried customized food or medicine? Customized nutrition and medicine have become increasingly popular these years as people pursue healthier lifestyles. Customized nutrition and medicine offer a tailored approach to dietary planning that enhances health and wellness by addressing individual preferences, health conditions, and genetic predispositions [1], [2]. It optimizes nutrient intake, improves digestive health, and reduces the risk of chronic diseases by considering personal health data and the latest scientific research.

However, customization could be a challenge for traditional manufacturing in the edible product supply chain (SC) because it lacks economy of scale. In this case, additive manufacturing (AM) can be a good solution to this challenge. AM, also known as 3D printing, is a cutting-edge technology with immense potential to address the challenges

associated with personalized products and the variable demand inherent in edible product SCs [3], [4], [5]. The integration of AM can produce customized products and aligns with the growing sustainability movement in the edible product industry [6]. For example, 3D printing technology enables manufacturing closer to the consumer, which reduces the transportation distance and further decreases the carbon footprint and transportation costs [7]. Besides, AM's on-demand production capability can significantly reduce food waste as it reduces the inventory level in the SC [8], [9]. This approach enhances resource efficiency and diminishes the environmental footprint associated with product wastage, thereby making a substantial contribution to the establishment of more sustainable SCs [10].

Driven by the need to overcome challenges in the SC of edible products and inspired by the potential of AM to offer sustainable solutions, incorporating AM into these SCs presents a transformative opportunity. This adoption promises to revolutionize the production and distribution of edible goods, customizing them to individual tastes and nutritional requirements while also improving SC efficiency and reducing waste. Amidst global population growth, resource constraints, and increasing environmental issues, transforming the food SC sustainably is crucial. This study aims to explore AM's significant impact on edible product SCs, identifying how this innovative technology can introduce new opportunities and advantages, potentially transforming food management and contributing to a more sustainable culinary industry.

To guide our study, we formulate the following primary research question (RQ) and corresponding sub-questions:

RQ: How does AM integration support sustainability in edible product SCs?

2 Overview of AM for Edible Products

The first instances of 3D-printed food began to emerge around the early 2010s. One of the notable early examples was in 2013 when the company Natural Machines introduced Foodini, a 3D printer capable of printing various types of food [11]. Around the same time, NASA also started exploring 3D-printed food as a way to potentially feed astronauts on long space missions, awarding a contract in 2013 to Systems & Materials Research Corporation to study the feasibility of printing food in space [12]. These developments marked the beginning of 3D printed food technology, aiming to create edible items by layering ingredients with precision, which could customize nutrition, texture, and shape to meet specific dietary and aesthetic preferences [13]. Now, 3D printing technology can produce more food, such as pancakes, pasta, fruit-based snacks, cheese, chocolate, sugar, cookies, and bread [14], [15].

The first 3D-printed medicine approved by the U.S. Food and Drug Administration (FDA) was in August 2015. The medicine called Spritam (levetiracetam) is used to treat

seizures in people with epilepsy. It was produced by Aprelia Pharmaceuticals using their ZipDose Technology, which creates a more porous pill that dissolves rapidly in the mouth with a sip of liquid [16]. This milestone marked a significant advancement in pharmaceutical manufacturing, offering the potential for personalized medicine through customizable dosages based on patient needs. AM possesses the capability to produce specialized products like personalized nutrition solutions tailored to individuals with specific dietary needs, including those managing conditions like diabetes and hypertension [13]. Additionally, AM can address the dietary requirements of the elderly population, crafting food that caters to their unique nutritional needs [17].

3 Methodology

In this study, we apply a Systematic Literature Review (SLR) methodology to synthesize and scrutinize prior research in our field, with the aim of developing frameworks to guide both practitioners and academics [18]. The SLR methodology unfolds in three critical stages: planning, execution, and dissemination. Initially, in the planning stage, the objective is to delineate the review's aims, formulate pertinent research questions, and devise a protocol for conducting the review [19]. Subsequently, the execution stage involves applying predefined inclusion and exclusion criteria to identify relevant studies, followed by the extraction, analysis, and synthesis of the data gathered. The culmination of this process is the dissemination stage, where the findings from the literature review are meticulously documented and presented in a report, offering a comprehensive overview of the insights gained [20].

4 Findings

4.1 Economic sustainability

AM has emerged as a transformative technology in various industries, including the edible products SC, by offering a myriad of economic benefits and sustainability, albeit with challenges and limitations.

Extended shelf life: 3D printing offers a transformative approach to the production and supply of edible products in the SC. By enabling on-demand production, it ensures that items, especially food, are produced and consumed fresh, minimizing the time they spend in storage and potentially extending their usable life [9], [21]. The technology's promotion of decentralized, localized production reduces transportation time, ensuring fresher products reach consumers [22]. The innovative concept of a "virtual warehouse" allows companies to maintain digital product design files, eliminating the need to store large quantities of perishables and ensuring fresh production upon demand [9]. Additionally, 3D printing's ability to repurpose viable leftovers from restaurants into customized food items reduces waste and promotes the consumption of fresh items [23].

Beyond the food industry, rapid prototyping in sectors like pharmaceuticals ensures timely production and delivery, potentially extending product shelf life [8].

Food waste reduction: 3D printing plays a pivotal role in reducing product spoilage within the SC. By facilitating on-demand production, it ensures that edible products, especially food, are manufactured only when required, minimizing overproduction and the associated risks of spoilage [9], [21]. The shift from traditional mass production to localized, decentralized manufacturing minimizes the time products spend in transit, reducing the chances of spoilage due to prolonged storage or transportation [22]. The concept of a "virtual warehouse" further supports this by eliminating the need to store large quantities of perishables, instead producing them fresh upon demand [9]. Additionally, 3D printing's capability to repurpose viable leftover food from restaurants into new, customized items ensures that food is consumed before it spoils, reducing waste [23]. In the pharmaceutical sector, on-demand production ensures the timely delivery of medicines, reducing the risk of spoilage due to expiration [8].

Water reduction: 3D food printing can indirectly contribute to water reduction in the edible product SC through various methods. Firstly, as [24] notes, 3D food printing is a highly efficient process that merges multiple steps into one, thereby minimizing resource usage, including water. This technology also ensures food is produced only upon order, which directly leads to a reduction in food waste. Since reducing food waste is crucial for conserving water in agriculture and food production[25], this aspect of 3D printing can substantially lower water usage. Additionally, the concept of distributed manufacturing, as discussed by [26] and [27], aligns with 3D food printing. By enabling local and regional food production, distributed systems, including 3D printing, can offer greater resilience against disruptions and potentially lead to more sustainable water use, depending on the specific practices and technologies employed. This approach not only contributes to water conservation but also enhances the overall sustainability of the food SC.

Decreased secondary packaging: 3D printing significantly contributes to decreasing packaging needs within the SC. Enabling on-demand and localized production reduces the necessity for extensive packaging typically required for long-term storage and long-distance transportation [9], [28]. The shift from centralized to decentralized manufacturing means products are produced closer to the point of consumption, minimizing the packaging layers traditionally used to protect goods during transit [28]. Furthermore, the "virtual warehouse" concept, where digital designs replace physical inventory, eliminates the need for packaging materials that would otherwise be used for warehousing purposes [9]. In the context of food, 3D printing's ability to produce items based on immediate demand ensures fresher products, reducing the reliance on packaging for extended shelf life [29].

Decreased complexity: AM revolutionizes economic sustainability by enabling localized, on-demand production, significantly reducing the need for extensive logistics and warehousing. This shift not only cuts down transportation costs but also optimizes cash

flow and financial efficiency by minimizing capital tied up in stock and storage [30]. 3D printing technology facilitates a reduction in the number of intermediaries in the SC, subsequently reducing costs and lead times [9], [31]. This necessitates new skills and competencies in SC management and the formation of new partnerships and collaborations among various SC actors [9].

Reduced inventory: AM's flexibility allows for on-demand production, significantly reducing the need for large inventories and enabling customization and localization of products. This approach minimizes inventory carrying costs, enhances responsiveness to market demands, and reduces waste and overproduction [32].

Decreased energy consumption: AM significantly reduces energy consumption in SCs, primarily through its material-efficient processes and the ability to localize production. This efficiency in AM leads to a substantial reduction in the energy required for material processing, handling, and transportation. By minimizing reliance on traditional, energy-intensive manufacturing processes, AM not only streamlines production but also lessens the environmental impact of manufacturing. The shortened SCs inherent in AM mean less energy is consumed in logistics, further contributing to energy savings. This approach aligns with the increasing global focus on reducing energy consumption and carbon emissions in industrial processes. Economically, AM contributes to sustainability by lowering production and logistics costs, enhancing productivity, and offering greater flexibility in manufacturing. The rapid prototyping and production capabilities of AM accelerate time-to-market, improving business competitiveness. Additionally, AM's support for on-demand production minimizes the need for large inventories, optimizing cash flow and financial efficiency [33].

Waste reduction: AM enables efficient, on-demand production, which eliminates the need for large-scale production runs and reduces overproduction. This approach minimizes waste by producing only what is needed when it is needed. Additionally, the concept of a virtual warehouse, where digital files replace physical inventories, further reduces waste associated with storage and material degradation. AM's ability to produce customized items in small series also plays a crucial role in minimizing waste, as it avoids the unnecessary production of standardized parts that may not be utilized. Economically, these practices contribute to sustainability by reducing costs associated with storage, material handling, and production inefficiencies. The shift to on-demand production lowers the expenses related to maintaining large inventories and the waste generated from unsold or obsolete products. This streamlined approach enhances overall production efficiency, leading to cost savings and improved financial performance [9].

Reduced transportation: AM's impact on economic sustainability through DLM is multifaceted. By localizing production closer to the point of consumption, AM reduces the need for long-haul transportation of goods. This shift not only cuts down on transportation costs but also minimizes the dependency on complex logistics networks, leading to a more streamlined and cost-effective SC. Reduced transportation requirements

also mean lower risks associated with shipping delays and global SC disruptions, enhancing the reliability and responsiveness of the SC [34].

Decreased lead time: AM, particularly through 3D food printing technology, significantly reduces lead time in the SC, thereby enhancing economic sustainability. This reduction is achieved by shifting from a traditional push strategy to a more responsive pull strategy, aligning production closely with real-time demand and minimizing intermediary steps. This streamlined process not only reduces inventory and storage costs by enabling on-demand production but also allows for rapid customization and prototyping, leading to quicker market responsiveness [31].

4.2 Environmental sustainability

AM, alongside postponement strategies, has been recognized for its potential to enhance environmental sustainability in various sectors, including food and pharmaceuticals. These technologies and strategies can significantly impact waste reduction, resource optimization, and carbon footprint minimization across SCs.

Surplus food recycling: AM can minimize waste production by utilizing only the necessary materials during the manufacturing process, potentially reducing the environmental impact associated with waste generation [35], [36]. The technology can convert waste or by-products from the food processing industry into a dried powder form, which can be added to the printing material supply, allowing for direct processing and reuse in food product development [37].

Decreased secondary packaging: 3D printing promotes on-demand and localized production, which inherently reduces the need for extensive packaging that's typically associated with long-distance transportation and prolonged storage [9], [28]. When products are manufactured only as required, there's a diminished necessity for bulk packaging [31]. Moreover, the precision of 3D printing allows for products to be designed in ways that optimize packaging efficiency, minimizing wasted space and consequently reducing the amount of packaging material needed [8]. By decreasing the reliance on packaging material, 3D printing not only reduces waste but also cuts down on the energy and resources traditionally used in the production of packaging materials [31]. This shift in production and distribution dynamics, facilitated by 3D printing, directly contributes to environmental sustainability by minimizing waste, conserving resources, and reducing the carbon footprint associated with packaging production and disposal [8], [28].

Food waste reduction: 3D printing is a transformative technology that significantly reduces food waste in the SC, thereby contributing to environmental sustainability [21], [38]. By employing a produce-on-demand strategy, 3D printing ensures that food items are fabricated only when there's a specific need, minimizing overproduction and the subsequent disposal of unsold or expired products [21], [29]. Additionally, 3D food printing can repurpose leftover but still viable food from restaurants, converting it into

customized food items in an extruded 3D printed form, which further reduces wastage [23]. This technology also allows for the precise use of raw materials, ensuring that only the required amount is used in the production process, leading to minimal wastage [29]. By minimizing food waste, 3D printing not only conserves valuable resources but also reduces the environmental impact associated with the decomposition of organic waste, such as greenhouse gas emissions. Thus, the integration of 3D printing in the food SC aligns with the principles of environmental sustainability by promoting efficient resource utilization and minimizing ecological footprints [38], [39].

Decreased energy consumption: AM supports a circular economy through efficient material use and the potential for material recycling and reuse. The reduction in waste and lower CO₂ emissions from AM processes contribute to environmental sustainability, making it a favorable choice for industries looking to balance economic growth with environmental responsibility [33].

Waste reduction: AM's precision and material efficiency significantly reduce material waste, aligning with sustainable manufacturing practices. The trend towards using more environmentally friendly materials in AM further enhances its environmental sustainability [9].

Reduced transportation: From an environmental perspective, the reduction in transportation facilitated by AM and DLM has profound implications. Fewer transportation requirements mean a significant decrease in greenhouse gas emissions and fossil fuel consumption, directly contributing to a reduction in the carbon footprint of the SC [34].

Decreased carbon emissions: AM significantly reduces the carbon footprint and contributes to environmental sustainability through several key mechanisms. Firstly, AM minimizes raw material requirements throughout the SC, thereby reducing the need for mining and refining basic material ores. This leads to a significant decrease in carbon emissions associated with material extraction and processing. Secondly, AM enables the creation of products with improved operational efficiency, which translates to more resource-efficient usage over their lifecycle. These factors collectively contribute to a substantial reduction in the overall carbon footprint of manufacturing processes, aligning with the goals of environmental sustainability by minimizing resource depletion and mitigating the impact of global warming [33].

4.3 Social sustainability

The integration of AM in edible products SC can contribute to social sustainability by allowing people to customize their products and increasing the freshness, etc.

Customized nutrition and medicine: 3D printing offers unparalleled capabilities in customizing nutrition and medicine, catering directly to individual needs and preferences [38], [40]. In the realm of food, 3D printing allows for the creation of meals tailored to specific dietary requirements, ensuring that individuals receive the precise

nutrients they need [6], [21]. This not only addresses health concerns but also cultural and personal preferences, fostering inclusivity and well-being [39]. In the medical sector, 3D printing enables the production of personalized medicines, ensuring that patients receive dosages and drug combinations tailored to their unique health profiles [41]. This level of customization can lead to more effective treatments, fewer side effects, and improved patient adherence to medication regimens [40]. By addressing individual needs so precisely, 3D printing enhances the quality of life and well-being of individuals, directly contributing to social sustainability. Furthermore, the ability to produce on-demand reduces waste associated with mass production and minimizes the risk of overmedication or nutritional imbalances, promoting a more responsible and sustainable approach to health and nutrition in the SC [21], [38].

Increase freshness: 3D printing plays a pivotal role in enhancing the freshness of products within the SC, particularly in the food sector [6], [21]. By adopting a produce-on-demand approach, 3D printing ensures that food items are created only when required, minimizing the time they spend in storage and ensuring they reach consumers in their freshest state [21], [29]. This not only guarantees better taste and quality but also reduces the risk of foodborne illnesses associated with stale or spoiled products [39]. Furthermore, the ability to print food on the spot based on user requirements means that consumers consistently have access to fresh meals, enhancing their overall dining experience and well-being [21]. By delivering fresher, higher-quality products, 3D printing directly contributes to improving consumer health and satisfaction, which are key components of social sustainability. Additionally, the reduction in food waste due to the timely production of fresh products aligns with sustainable practices, ensuring resources are used efficiently and responsibly in the SC [38].

Accessibility to edible products: 3DP can potentially improve food security and access to healthy foods by providing customized meals for people with specific dietary needs or preferences [8], [24]. The technology can also address issues like malnutrition and improve food scarcity by creating new value chains [42]. Localized food systems can also forge new connections between consumers and their food, enhancing social value and potentially improving food security, especially in areas with high poverty rates [27].

Increased product safety: 3D printing has emerged as a transformative technology that significantly enhances food safety and quality within the SC, contributing to the broader objectives of social sustainability [21], [38]. By allowing precise control over the production process, 3D printing ensures that food products are manufactured to exact specifications, reducing the risk of contamination and ensuring consistent quality [39]. The technology's ability to produce food on demand ensures that products are always fresh, further elevating their quality [21]. Moreover, 3D printing can be integrated with advanced monitoring and tracking systems, ensuring that any deviations from set quality standards are immediately detected and addressed [22]. This not only ensures the safety and quality of the food but also builds trust among consumers, as they can be confident about the products they consume. By prioritizing food safety and

quality, 3D printing plays a pivotal role in safeguarding public health and well-being, aligning with the principles of social sustainability and ensuring that the needs of the community are met without compromising future generations [38], [43].

Increased flexibility: AM significantly increases the flexibility of the SC, especially in response to pandemics. This flexibility is achieved through the rapid and cost-effective production of personalized medical devices and drug delivery systems, directly addressing urgent healthcare needs. By enabling on-site manufacturing in hospitals or research labs, AM circumvents traditional SC delays, ensuring timely access to essential medical supplies like protective equipment and customized medication. This strategy contributes to social sustainability by enhancing healthcare responsiveness and accessibility, particularly in crisis situations. It ensures that medical resources are readily available and adaptable to the evolving health needs of the population, thereby supporting public health resilience and community well-being during challenging times like pandemics [41].

5 Conceptual framework

The utilization of the Antecedent, Decision, and Outcome (ADO) framework as a systematic approach in the context of SLRs. By offering a structured approach, the ADO framework facilitates the analysis of the "why" (antecedent in the ADO framework) and "how" (decision in the ADO framework) aspects in a systematic manner [44].

In our framework, we embrace the ADO approach, where the antecedent (A) relates to the existing challenges in the SC of edible products that AM aims to address. These challenges may encompass customization requirements in food and medicine products, issues with food waste, and inefficiencies in production and distribution, among others. Decisions (D) encompass the SC strategies enabled by AM. SC strategy is defined as the approach and processes a company adopts to manage the flow of goods, information, and finances related to a product or service, from the acquisition of raw materials to the delivery to the end consumer. SC strategy in this research includes DLM, in-house production, delayed production, mass customization, and on-demand production, which are derived as the themes and summarized in the thematic analysis. The outcomes (O) are tied to the three pillars of sustainability.

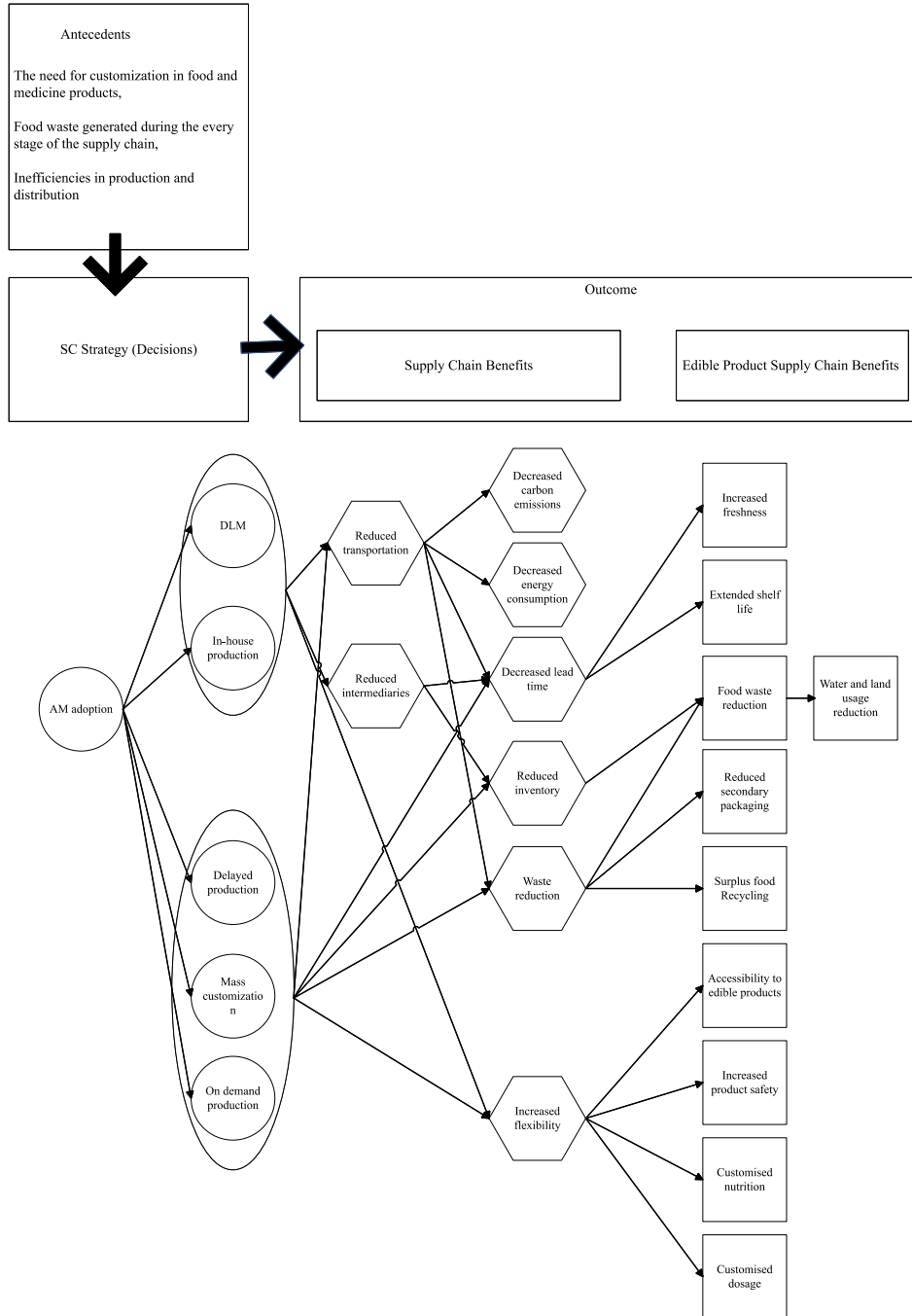


Fig. 1. Conceptual framework of integrating AM in edible product SC.

Within Figure 1, a distinction is drawn between general and specific outcomes for SCs. Generic outcomes applicable across various sectors, such as aerospace, clothing, and others, and are represented in hexagon shapes, while outcomes specific to edible product SCs are presented in square shapes. For example, although decreased lead time is a generic outcome, its impact on edible product SC is specifically associated with increased freshness and extended shelf life.

AM seeks to tackle present challenges by facilitating various SC strategies: DLM, in-house production, delayed production, mass customization, and on-demand production. Among these, DLM and in-house production yield similar results. Both strategies focus on minimizing intermediaries and bringing production closer to consumers, which simplifies the SC and reduces transportation. Consequently, this reduces lead time, carbon emissions, as well as inventory levels and waste within the SC. These outcomes specifically contribute to increased freshness, extended shelf life, increased transparency, reduced edible product waste, decreased water and land usage, minimized secondary packaging, and the promotion of surplus food recycling.

Delayed production, mass customization, and on-demand production share common benefits, contributing to the reduction of inventory, waste, and energy use while enhancing overall flexibility. From the perspective of edible product SCs, these strategies play a crucial role in minimizing spoilage, prolonging shelf life, enhancing transparency, and decreasing product wastage. As mentioned previously, the reduction in edible product waste also contributes to the overall reduction of water and land usage.

Figure 1 also delineates the relationship between these SC strategies applied by AM adoption and their outcomes, particularly within the context of the edible product SC. For example, the integration of AM can enhance product freshness by supporting DLM and in-house production, resulting in decreased transportation and shorter lead times in the SC. The utilization of AM also extends the shelf life of edible products in the SC by reducing lead time and inventory levels through the amalgamation of those all strategies.

6 Conclusion

In recent years, AM has become increasingly significant in the food and medicine industry, and the COVID-19 pandemic has further highlighted its potential to address SC disruptions by enabling the relocation of manufacturing facilities closer to end customers. This adaptability allows for a more responsive approach to unpredictable demand while maintaining reduced inventory levels, which can be critical in both food and medicine field.

Following a meticulous SLR, we identify five pivotal channels through which AM can reshape the perishable edible product SC: DLM, in-house production, delayed production, mass customization, and on-demand production. Employing the ADO theoretical framework, we scrutinize our discoveries to delineate the connections between antecedents, decisions, and outcomes.

The findings of this study have benefits for the food and medicine industry, AM industry, and researchers. The food and medicine industry can consider leveraging 3D printing to produce customized products to address fluctuating demands effectively. The AM industry can promote the use of 3D printing technology in other sectors by highlighting its ability to enhance SC performance. For researchers, this study provides valuable insights and directions for further research.

Overall, the integration of 3D printing technology in the food and medicine industry and its effects on the SC have the potential to revolutionize production processes, improve SC performance, and deliver more responsive and sustainable solutions.

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