A study on adoption enablers of 3D printing technology for sustainable food supply chain

Abstract

Purpose

3D food printing technology is an emerging smart technology, which because of its inbuilt capabilities, has the potential to support a sustainable supply chain and environmental quality management. This new technology needs a supportive ecosystem, and thus, this paper identifies and models the enablers for adopting 3D printing technology toward a sustainable food supply chain.

Design/Methodology/Approach

The enablers were identified through an extensive literature review and verified by domain experts. The identified enablers were modelled through the hybrid total interpretive structural modelling approach (TISM) and the decision-making trial and evaluation laboratory (DEMATEL) approach.

Findings

It emerged that stakeholders need technical know-how about the 3D printing technology, well supported by a legal framework for clear intellectual property rights ownership. Also, the industry players must have focused and clear strategic planning, considering the need for sustainable supply chains. Moreover, required product innovation as per customer needs may enhance the stakeholders' readiness to adopt this technology.

Practical implications

The framework proposed in this research provides managers with a hierarchy and categorization of adoption enablers which will help them adopt 3D food printing technology and improve environmental quality.

Originality/Value

This research offers a framework for modelling the enablers for 3D food printing to develop a sustainable food supply chain using the TISM and DEMATEL techniques.

Keywords: 3D printing, sustainability, food supply chain, total interpretive structural modelling (TISM), decision-making trial and evaluation laboratory (DEMATEL), environmental quality

1. Introduction

A food supply chain involves several functionaries, from growers, producers, processors, and distributors to retailers (Mishra et al., 2021; Sid et al., 2018). These food networks must be safe and quick to ensure food safety and timely availability to end consumers (Todorovic et al., 2018). This is where the requirement for a short and sustainable supply chain in food emerges and in achieving sustainable development goals (Jarzębowski et al., 2020; do Canto et al., 2020). Currently, the agri-food supply chain aims to adopt practices for sustainable consumption and production goals to have fewer channels, fewer intermediaries, and more margins to achieve global optimization and environmental quality management (Mishra et al., 2022; Mor et al., 2021; Ben-Ner and Siemsen, 2017; Wamba, 2017). This also boosts economic, social and environmental performance (Siddh et al., 2020). In the present scenario, various IT-enabled technologies like RFID, cloud computing, and robotics enable the supply chain to become coordinated and robust (Singh and Gurtu, 2021; Irfan et al*.,* 2019). Recently, an emerging technology viz. 3D food printing technology can potentially convert conventional supply chains into sustainable ones (Verma et al., 2021). 3D printing can radically change supply chains (Oettmeier and Hofmann, 2016). It includes minimizing wastage, enhancing supply chain flexibility through product simplification & low volume, cost-effective manufacturing, and decreasing transit costs (Beltagui et al., 2020). Producing food through 3D food printers helps logistics and supply chain be more efficient by shifting from a push strategy to a pull strategy. Also, it eliminates a significant number of channels from the supply chain, thereby reducing lead time (Dadi et al., 2021; Jia et al*.,* 2016).

The global market for 3D food printing was valued at USD 87.2 million in 2021, and it is forecasted to grow at a CAGR of 48.60% (Quince market insights report, 2022). Baiano (2021) highlighted that the projected global market for ready-to-eat 3D printed food would be $44520 million by 2026. These figures reflect the enormous scope of 3D food printing for the food supply chain. Studies suggest that food supply chains can benefit from 3D food printing technology through shorter and faster supply chains to increase productivity and cost-effectiveness (Simon, 2018). 3D printing has been experimented with in food by various research institutes, big corporates, and start-ups worldwide. The major players in the 3D food business are "public and private R&D actors, who are testing and experimenting in collaboration mainly with small food companies, restaurants, chefs, and some larger food manufacturers" (EU report, 2016). Several big companies are actively adopting 3D food printing technology like Nestle, Mondelez, Hershey's, and Barilla

(Singhal et al., 2020; Udipi, 2017). In 2015, Hershey collaborated with 3D Systems to develop the "CocoJet 3D printer". Nestlé's R&D department (Nestle Institute of Health and Sciences) works on "Project Iron Man". It scans users, identifies deficient nutrients, and 3D prints the food with the nutrients they lack (Goulding, 2018). Israel-based food-tech firms like "SavorEat" and "Redefine Meat" have introduced plant-based meat using 3D printing technology (Reuters, 2021; David, 2021). Imaginarium is an Indian-based 3D printing company that has introduced the "Foodni Food 3D printer" created by Barcelona-based Natural Machines in 2021. It is an extrusion-based technology that can print different types of food (Sher, 2021). The research institutes like Manipal Institute of Technology, India, and the Indian Institute of Food Processing Technology, Thanjavur, are developing affordable 3D food printers to print 3D products (Rathore, 2021).

Although the food sector realizes the role and benefits of 3D food printers in food supply chains, their adoption does not show encouraging figures (Pereira et al., 2021). Although the Indian landscape is slowly showing expansion signals, like few licenses are in process for 3D bioprinters for food (Avinash et al., 2019), but the examples are limited. Very few studies have been conducted on 3D food printing technology (Ramachandraiah, 2021; Verma et al., 2022). Therefore, there is a need to identify the adoption enablers to enhance the 3D food printing technology adoption in developing nations (Palaniappan et al., 2020). Given the above, the research aims to answer the following research questions (RQ):

RQ1: What are the adoption enablers to 3D food printing technology to achieve a sustainable supply chain

RQ2: How to model these adoption enablers to develop a framework for a strategic ecosystem

This study has adopted a qualitative approach to analysis. The required information was sourced through literature screening and got validated by experts. The identified and validated enablers were modelled using the hybrid TISM and DEMATEL techniques. This study differentiated the identified enablers as drivers and dependent variables towards adopting 3D food printing technology. This study suggests a guiding framework for food processing companies, policymakers, technology providers, and other stakeholders develop a sustainable ecosystem where the industry can embrace 3D food printing technology. This highlights the managerial implications, stating the prospects of 3D food printing technology for the food industry towards shaping a sustainable supply chain.

The remainder of the paper is as follows; the next following section highlights recent developments in 3D printing technology. The following section explains the research methods adopted for the study, followed by an analysis and results. Section 5 highlights the discussion, followed by implications, limitations, and conclusion.

2. Literature Review

Chuck Hull invented three-dimensional printing technology in 1986 in the USA (Lee, 2021). 3D printing technology is based on additive manufacturing (AM), used to make three-dimensional solid objects in layers from a digital file without a mould or cutting tool (Gu et al., 2020; Wamba, 2017). 3D printing is prominently used for fast prototyping by engineers, who can test the new designs with smaller inputs before putting them on large-scale production bases (Derossi et al., 2019; Lille et al., 2018). Expanding the material base will lead to the adoption of 3D printing in other industries and impact the way their supply chain functions (Chen, 2016). The majorly adopted technologies of AM in food printing are material extrusion (used for chocolate and pasta dough); binder jetting (used for protein powders and sugars); powder bed fusion (for sugars), and VAT Photopolymerization (for egg whites) (Javaid and Haleem, 2019). A few functional and successful 3D food printers stated in literature are Chefjet Pro, used in the UK primarily for chocolates (Baking Europe, 2016; Sun et al., 2015a); ChocEdge and Foodjet (Sun et al., 2015a; Sun et al., 2015b; Biozoon, Foodini; EU report, 2016). India's first 3D food printer, which successfully prints different chocolates, is named Chocobot, developed by Global 3D Labs (Rajput et al., 2019). Effective operations and managerial orientation towards sustainability enhance organisations' environmental performance (do Canto et al., 2020).

In the food industry, 3D printing "integrates additive manufacturing and digital gastronomy techniques to produce 3D custom-designed food objects without object-specific tooling, moulding, or human intervention" (Sun et al., 2015a). As per Godoi et al. (2016), the food material for 3D printing depends on printability, applicability, and post-processing. The food ingredients like sugar, chocolate, starch, mashed potatoes, and dough can easily be used in 3D food printers to create innovative shapes and designs (Dankar et al., 2018; Baiano, 2021). Any edible material which can be pureed or converted into a paste can be used for the 3D printing of food (Huang et al., 2020). However, it is challenging to 3D print traditional food items consumed daily, i.e., rice, vegetables, meat, etc., due to their nature (Palaniappan et al., 2020).

The emerging technology opens a plethora of possibilities for food supply chains. The traditional food production and supply chain might not entertain the consumer needs for food personalisation (Sun et al., 2018). The traditional food supply chains work on cost efficiency and are based on models that can support economies of scale. 3D food printing technology gives the freedom to customize and personalized meals according to the individual's nutritional requirement (Portanguen et al., 2022). It helps create novel food designs (Scheele et al., 2021). It is also suggested to minimize food wastage by recycling leftover food (Burke-shyne et al., 2020). Its application in the food supply chain enhances healthiness, quality, diversity, and sustainability (Zhang et al., 2021). These benefits point toward technology's ability to build a sustainable food supply chain (Rogers and Srivastava, 2021). It generates value from by-products, utilizing novel sources of protein such as insects and algae, and contributes to reducing the number of conventional food grains required for nutrition (Baiano, 2020; Burke-shyne et al., 2020; Keerthana et al., 2020; Lee, 2021; Varvara et al., 2021).

3D printing technology adoption faces challenges on various fronts, lacking research and practical attention. Most 3D food printing technology studies are carried out in raw material, the composition of products, and minimal in the context of 3D food printing technology and the food supply chain, where the research gaps for this study are realized.

Table 1. Enablers of 3D Printing Technology

Insert Table 1 approximately here

In the future, 3D food printing will encourage a sustainable production process, waste elimination, and reduced packaging (Rogers and Srivastava, 2021). Table 1 represents nine major 3D food printing technology enablers for short and sustainable supply chains identified through the literature review.

3. Methods

This study intends to identify the significant enablers for adopting 3D food printing technology for a sustainable food supply chain. A qualitative approach for analysis was adopted, and the necessary information, expert opinion, and literature screening were done for sourcing. The authors felt the need to introduce the hybrid TISM-DEMATEL technique in this study because the TISM model helps establish relationships between variables under study. To identify the intensity of these relationships, DEMATEL was used. DEMATEL identified the intensity of these relationships and the most influential variables impacting the subject under study. Further, The MICMAC analysis was used to determine each enabler's driving and dependence power, resulting in a four-quadrant clustered structure (Verma et al., 2022; Poonia et al., 2021; Lamba and Singh, 2018). The research framework adopted for the study is depicted in Figure 1.

Insert Figure 1 approximate here

Figure 1. Research framework

3.1 Data collection

A total of eleven domain experts were approached for validation of adoption enablers. One of the experts is the heading R&D at a multinational food company with working experience in India and Thailand. Two experts are working at the middle level in food companies; three are working at the middle level in the producer companies of 3D food printers; the rest five are active researchers cum academicians in 3D food printing technology. The experts were approached through emails and phone calls, and finally, discussion dates were finalized. The role of experts was to validate the identified variables and then suggest the directional relationship between the variables, as per the requirement of TISM and DEMATEL techniques. Firstly, the researchers gave them the list of identified variables, and all experts unanimously agreed. The researchers noted that the experts were then requested to share their opinions about the relationships between variables with logical reasoning in the second and third meetings. The identified and validated enablers were modelled using the TISM approach and DEMATEL technique, based on responses from the experts.

3.2 Total interpretive structural modelling (TISM)

TISM approach is a qualitative method for structuring the variables into a meaningful relational model based on the interrelationships between the identified variables. It is an extended version of Interpretive structural modelling (ISM) (Sindhu, 2022). TISM highlights the influence of one variable on another variable, helping identify the most significant variables affecting the problem statement. Following are the steps involved in the TISM approach and model development

(Deshmukh and Mohan, 2017; Jena et al*.,* 2017; Shankar et al*.,* 2019; Dwivedi and Madaan, 2020; Lianto et al*.,*2020; Dahiya et al., 2021):

i. The relevant variables impacting the topic under study are identified through literature review and validated by experts.
ii. Domain expert opinion defines the contextual relationship amongst the variables as a 'lead to' type of relationship. Experts are asked to provide logical reasoning for their views about the variables' contextual relationship.
iii. The interpretive logic-knowledge base is transformed into a binary matrix by converting the "i,j" entry of YES to "i,j" entry as 1 and the "i,j" entry of NO to "i,j" entry as 0 in the reachability matrix. The reachability matrix is then scrutinised for transitive links by following the formula:
iv. 'If variable 1 leads to variable 2, and variable 2 leads to variable 3, then variable 1 should also lead to variable 3', and wherever it is found, transitivities are included in the form of 1* in the reachability matrix.
v. The reachability set (horizontal) and antecedent (vertical) sets are identified for each variable, and their intersections are covered in the intersection set. Wherever the reachability set becomes equal to the intersection set, the level is allotted to that variable. Once a variable gets its level assigned, that variable is removed from further calculations. The process of iterations continues until all variables get their levels allotted.
vi. MICMAC analysis is carried out to club the variables into four groups based on their driving power and dependence and are called 'autonomous', 'dependent', 'linkage', and 'drivers' accordingly.
vii. Finally, the digraph/TISM model is prepared based on the levels achieved by each variable. The digraph represents the direction of influence of one variable on another graphically.

3.3 Decision-making trial and evaluation laboratory (DEMATEL)

The DEMATEL is an inclusive approach for developing and interpreting a causal relationship model for complex and interlinked issues related to any subject (Lamba and Singh, 2018; Sindhu & Mor, 2021). Khan et al. (2020) and Susanty et al. (2020) list the steps involved in implementing the DEMATEL.

i. Identifying the decision objective and experts

As the first step in DEMATEL, the pair-wise relationship between the identified variables is established. To accomplish this, the experts are asked to evaluate all the pairs of variables on a scale of 0-4, where 0 reflects 'no influence' and 4 reflects 'extreme strong influence' of one variable on another.

ii. Direct relation matrix (A)

A non-negative matrix(n*n) for n variables is achieved for each expert. The average value is taken for the responses of all experts, and accordingly, the average matrix(M) is prepared, reflecting the initial direct relation of variables.

The formula followed for the same is: $M=\frac{1}{n}\sum_{k=1}^{n} M_{ij}^{k}$ (1)

iii. Normalized initial direct relation matrix (N)

The normalized initial direct relation matrix (N) is obtained by normalizing the average matrix (M) by using the formula:

$$N=M/k \quad (2)$$

Where, $k = \max_{i,j}\left(max_i \sum_{j=1}^{n} a_i, jmaxj \sum_{i=1}^{n} a_i, j\right)$, i,j=1,2,3……………..

iv. Total relation matrix (R)

The total relation matrix(R) reflects the way one variable influences the other variables and is obtained from the normalized matrix by using the formula:

$R=N(I-N)^{-1}$, where *I* represent the identity matrix. (3)

v. Developing the Causal diagram

The causal diagram is developed with the horizontal axis *(D+R)* named “Prominence”, which shows the relative significance of the particular variable in the system. Similarly, the vertical axis *(D-R)*, called “Relation”, indicates the type of relation between the variables. Based on the importance of (D-R), all the variables are differentiated between cause-and-effect groups. If the value of *(D-R)* is negative, the variable belongs to an effect group, whereas if *(D-R)* is positive, the variable belongs to the causal group.

4. Results

The following section describes the outcomes of data modelling through hybrid TISM - DEMATEL approaches.

4.1 TISM Modelling

The steps involved in the TISM approach are detailed in section 3.2, and the following outcomes are achieved by following the step-by-step TISM approach.

4.1.1. Identify and list the relevant variables, define the contextual relationship, and develop an Interpretive logic-knowledge base.

Literature screening was done on 3D printing technology in the food supply chain to identify the relevant enablers for the same. From the literature review, nine significant enablers were identified, listed, and discussed in section two. Selected enablers were verified by three domain experts, one from the industry and two from the research field of the food industry and 3D printing. The variables were screened to define the contextual relationships in the form of a 'lead to' type of relationship. The matrix thus formed is the Interpretive logic-knowledge base.

4.1.2. Developing a reachability matrix from the Interpretive logic-knowledge base and scrutinizing the matrix for transitivity.

The interpretive logic-knowledge base was transformed into a binary matrix using the rule mentioned in the methodology. The matrix thus obtained is known as the reachability matrix. The reachability matrix was then scrutinized for transitive links. Accordingly, the final reachability matrix was prepared and is placed in Table 2. Similarly, transitivity was included in the Interpretive logic-knowledge base by replacing NO with YES for that respective entry and writing the word 'transitive' in the respective column. Also, in the final reachability matrix, each variable shows the driving power (number of total 1s horizontally) and dependence (number of total 1s vertically).

Table 2. Final Reachability Matrix (Transitivity)

Insert Table 2 approximate here

4.1.3. Carrying out level partitioning of the reachability matrix

Each variable differs in its magnitude and direction to influence other variables. Level partitioning was done for each variable and allotted levels through stepwise iterations. In this study, four iterations were carried out to provide levels to each variable. The consolidated level-wise partition info is placed in Table 3.

Table 3. Consolidated Level of Variables

Insert Table 3 approximate here

4.1.4. MICMAC Analysis

Based on the driving power and dependence of each variable (Table 3), variables were divided into four clusters, namely autonomous, dependent, linkage, and independent variables (Agrawal et al., 2019; Jha et al., 2019; Poonia et al., 2021; Singh et al., 2017), presented in Figure 2 and as follows.

Cluster I: Autonomous Variables: The variables in this cluster have a weak driving power and weak dependence. These variables do not have any significant relation with other variables. In this study, no variable came into the autonomous variables group, which shows that all the variables under study are related.

Cluster II: Dependent Variables: The variables in this cluster have high dependence and weak driving power. These variables are significant for the system and decide the. The variables, viz. readiness to adopt technologies (V2) and costs of production (V8), got into this cluster.

Cluster III: Linkage Variables: The variables in this cluster have high driving power and high dependence. These variables are very unstable, and any changes in the system get reflected on these variables and other variables. In this study, a specific vision and action plan (V1), product features (V4), and customer acceptance (V7) emerged as linkage variables.

Cluster IV: Independent Variables: The variables in this cluster have high driving power and low dependence. These variables are strategic variables and can lead to achieving other variables. In this study, technical know-how (V5), clarity on intellectual property rights (V6), the need for the food industry (V3), and the required type of raw material and machine availability (V9) emerged in the cluster of independent variables.

Insert Figure 2 approximate here

Figure 2. MICMAC Analysis

4.1.4. TISM Model

The TISM model/digraph graphically represents the levels of different enablers as per their dependence and driving powers. The model was created per the level partitions achieved and mentioned in Table 3. Nine enablers got partitioned into four levels, where level 4 represents the most significantly impacting enabler, and level 1 shows the most strategic enabler. The arrows in the model always point upwards or horizontally (for same-level variables), showing the 'lead to' relationship amongst the variables. The dashed line in the model reflects the indirect 'lead to' relation between the variables. The TISM model so generated is placed in Figure 3.

Insert Figure 3 approximate here

Figure 3. TISM Model

4.2 DEMATEL Modelling

As per the steps mentioned in section 3.3, the DEMATEL technique was applied to the variables, and stage-wise results may be shown as follows.

Step 1: Direct relation matrix (A)

The pair-wise relationship between the identified enablers was identified using the equation (1), and accordingly, a direct relation matrix (A) was formed, as mentioned in Table 4.

Table 4. Direct Relation Matrix

Insert Table 4 approximate here

Step 2: Normalized initial direct relation matrix (X)

The normalized initial direct relation matrix (X) was obtained by normalizing the initial direct relation matrix (A) using the equation (2). Accordingly, the matrix obtained is mentioned in Table 5.

Table 5. Normalized initial direct relation matrix (X)

Insert Table 5 approximate here

Step 3: Total Relation Matrix

The total relation matrix (T) was obtained using equation (3), and the matrix obtained is placed in Table 6.

Table 6. Total relation matrix

Insert Table 6 approximate here

Step 4: Developing the Causal Diagram

The values of (D+R) and (D-R), i.e., the sum of influences given to enablers and received by enablers, were calculated and shown from the total relation matrix in Table 7.

Table 7. Sum of influences (given and received) on enablers of 3D printing

Insert Table 7 approximate here

Values of (D+R), reflecting the relative importance of the variable and the degree of the relation, are ranked and summarized in Table 8.

Table 8. Relationship strength rankings

Insert Table 8 approximate here

Similarly, values of (D-R) that reflect the relation between the variables were also calculated and summarised in Table 9, where positive values of (D-R) reflect that the indicator belongs to the cause group and negative values of (D-R) reflect that the indicator belongs to the effect group.

Table 9. Relation type and relative rankings

Insert Table 9 approximate here

Finally, the values of (D+R) and (D-R) were plotted to obtain the causal diagram and are shown in Figure 4.

Insert Figure 4 approximate here

Figure 4. The Causal diagram

5. Discussion

As per the TISM model, the *need of the food industry* (V3), *technical know-how (*V5), and *clarity of intellectual property rights* (V6) emerged as the three most significant drivers for other enablers. The food industry needs a solution for high costs, longer lead times, and inefficient production, which can be addressed by 3D printing. Similarly, technical know-how about the technology and the process can only make 3D printing technology successful in the food industry. Also, the food industry seeks clarity for the ownership of intellectual rights, especially for the design and products, as product design innovation is fast and straightforward in the case of 3D printed food, thereby making the designs and products vulnerable to copying and using competitors. These three driving forces then support the factors on the next level, viz., *specific vision and action plan* (V1) and *required type of raw material and machine availability* (V9). As 3D printing technology is entirely new for the food sector in developing nations, companies in the food industry need to have a specific vision and action plan for adopting 3D printing technology; only then can other enablers support the adoption. Also, 3D printing of food needs specially designed raw materials/ingredients and customized equipment types. It can lead to adopting 3D technology if both the ingredients and equipment are assured. As per the model, if the previous level driving forces are enacted, then they support achieving the following level forces, viz., *product features* (V4), *customer acceptance* (V7), *and costs of production* (V8). For 3D-printed food to succeed in the market, it needs to be accepted by the consumers. Consumer acceptance requires special features in the product, designed customized as per their requirements, and these forces support stakeholders' readiness to adopt the technology (V2).

As per the Causal diagram drawn through the DEMATEL approach and Table 7, values of (D+R) and (D-R) are drawn for each variable. The *product features (V4)* score the highest value of (D+R), followed by *customer acceptance (V7), readiness to adopt new technologies (V2), needs of the food industry (V3), costs of production (V8), specific vision and action plan (V1), technical know-how (V5), clarity on Intellectual property rights (V6),* and lastly*, the required type of raw material and machine availability (V9),* respectively. The higher the value of (D+R), the higher its prominence in the system.

Similarly, values of (D-R) for each variable were drawn, where the positive value of (D-R) makes the particular variable to be categorized into the cause group, and the negative value of (D-R) puts the variable into the effect group. In this study, out of five variables that got into the cause group, the *technical know-how* (V5) variable got the highest positive (D-R) value, reflecting that this variable has a very high impact on other variables. However, it has a low (D+R) value, which may be attributed to its least value of 'R'. Similarly, *clarity on intellectual property rights* (V6), follows the same suit, with a very high positive value of (D-R) and low value of (D+R), due to the least value of 'R'.The following variable, i.e., the *required type of raw material and machine availability*

(V9*)*, has a moderate positive value of (D-R) and 'D', with the least value of (D+R) and 'R'. This shows that the required raw material has a moderate impact on other variables, with significantly less significance for the system. Another variable, i.e., the *need of the food industry* (V3*)*, has a moderate positive value of (D-R) with a strong value of 'D', making this variable impact other variables. Also, the (D+R) values are moderate for this variable due to the low 'R' value. Lastly, *customer acceptance* (V7), with a positive (D-R) value and very high (D+R) and 'D' values, and moderate 'R' value, makes this variable significant for the system, with a high impact on other variables.

Further, in this study, four variables emerged with negative values of (D-R) and are categorized as the effect group. Where *readiness to adopt new technologies* (V2*)* emerged as the variable with the highest negative value of (D-R), and strong values of (D+R) and 'R', makes this variable getting profoundly impacted by other variables while being strategic for the system. The variable, *product features* (V4), has a negative value of (D-R), with the highest value of (D+R) and 'R', which shows that product features are getting impacted by other variables and is very significant for the system. Similarly, *specific vision and action plan* (V1*)* got moderate values of negative (D-R) as well as (D+R) and 'R', which shows that specific vision and action plan is moderately significant with a moderate receiving relation. Lastly, *costs of production (V8)* with negative (D-R) value and high 'R' with medium (D+R) value reflect that cost of production is impacted by other variables to a great extent and is significant for the system.

The variable, *technical know-how* (V5), emerged as one of the most significant drivers per TISM and emerged as an influential cause variable per DEMATEL. This signifies that food industry stakeholders need to have technical know-how about 3D printing technology. In turn, well-aware individuals will help achieve the other underlying enablers identified for the system. The variable identified as a significant driver and cause factor is *clarity on intellectual property rights* (V6). This study reflects that stakeholders in the food industry seek clarity about ownership of different intellectual property rights, w.r.t product design, data, and product type, which decides the fate of other enablers and eventually decides the objective's achievement. Similarly, the *need for the food industry* (V3) also emerged as a strong driving force per TISM and a substantial cause factor per DEMATEL. This signifies that stakeholders will accept this technology if 3D printing can provide solutions to the food industry's needs.

Further, the model highlights that the driving forces or the cause factors, with the support of other linkage variables, lead to the achievement of the most dependent variable as per TISM, which is identified as the strong effect factor as well through DEMATEL, viz. *readiness to adopt new technologies* (V2). This is true otherwise also because the ultimate success of the model depends on the willingness of stakeholders to adopt new technologies.

6. Implications

The study provides vital suggestions for managers, researchers, and practitioners to adopt 3D food printing technology for a sustainable food supply chain. Adopting 3D food printing technology can reduce lead time, distribution, and packaging costs. More product variants are possible at less cost and less time, with fewer wastages and efficient use of by-products, making the supply chain more sustainable to market needs, and thus improving environmental performance. 3D printing has potential advantages and applications in the food sector, simplifying the food supply chain. The results revealed a need for organizations to provide employees with technical know-how about applying the technology. The appropriate technical know-how should be provided to the industry professionals, leading to more penetration and acceptance of the technology in the food supply chain.

The clarity on intellectual copyrights has also emerged as a significant enabler for adopting 3D food printing in the food supply chain. Currently, there are various issues related to intellectual property rights in 3D food printing, i.e., lack of guidelines and regulations (Verma et al., 2022). An increased clarity among managers on IPRs in context to 3D files, designs, policies, and regulations, may open a plethora of opportunities for more innovations at the industry level (Halassi et al., 2019).

The proposed modelling provides managers with a hierarchy and categorization of adoption enablers to assist managers in quantifying, monitoring, and managing risks in adopting 3D food printing technology for a sustainable food supply chain. 3D food printing can incentivise its players to acquire the extensive and trustworthy data required to develop a sustainable food supply chain structure and environmental quality.

7. Conclusion

The current research is focused on identifying and modelling the adoption enablers of 3D food printing technology in the Indian scenario for a sustainable food supply chain. In order to answer the research question, the study identified adoption enablers of 3D food printing for a sustainable food supply chain through a literature review. Domain experts verified the identified enablers and were further tested using data collected through a questionnaire survey approach. Further, the enablers were modelled through the hybrid TISM and DEMATEL approaches. TISM helped establish the relationships between adoption enablers. The DEMATEL approach identified the intensity of that relationship and the most influential variables impacting the subject under study. The MICMAC analysis determined each enabler's driving and dependence power, resulting in a four-quadrant clustered structure. Based on the outcomes of the tools, this study highlights the importance of technical know-how for the food supply chain participants to understand and accept the 3D printing technology. The regulatory bodies need to develop clear policy guidelines regarding the users' intellectual property rights for 3D printing technology. Moreover, required product innovation as per customer needs may enhance the stakeholders' readiness to adopt this technology. Therefore, as reflected in the study findings, the industry must consider the following adoption enablers when adopting the 3D food printing technology for a sustainable supply chain. 3D food printing technology seems to have a promising role in the sustainable food supply chain and improved environmental performance, with supportive policies and stakeholders' orientation. Future research may find coherence between consumer perception and industry orientation towards 3D printed food. This study is in the context of the processed food sector; future studies may be carried out in other food sectors. Future research may also focus on identifying and modelling the benefits of 3D printing in the food sector and adopting other qualitative analyses and statistical modelling to strengthen the research domain.

References

Agrawal, P., Narain, R., & Ullah, I. (2019). Analysis of barriers in implementation of digital transformation of supply chain using interpretive structural modelling approach. *Journal of Modelling in Management*, *15*(1), 297–317. https://doi.org/10.1108/jm2-03-2019-0066.

Baiano, A. (2020). 3D Printed Foods: A Comprehensive Review on Technologies, Nutritional Value, Safety, Consumer Attitude, Regulatory Framework, and Economic and Sustainability Issues. *Food Reviews International*, *38*(5), 986–1016. https://doi.org/10.1080/87559129.2020.1762091.

Baking Europe, (2016), 3D Printing. Finnovation PD, available at http://www.bakingeurope.eu/previews/2016/BakingEurope-Spring-2016.pdf (Accessed on: 24.5.2020).

Beltagui, A., Kunz, N., & Gold, S. (2020). The role of 3D printing and open design on adoption of socially sustainable supply chain innovation. *International Journal of Production Economics*, *221*, 107462. https://doi.org/10.1016/j.ijpe.2019.07.035.

Ben-David, R. (2021, November 21). Israel's Redefine Meat to serve 3D-printed, plant-based meat at eateries in Europe. Times of Israel. https://www.timesofisrael.com/israels-redefine-meat-to-serve-3d-printed-plant-based-meat-at-eateries-in-europe/ (Accessed on: 24.5.2020).

Biswas, P. (2017). Modeling reconfigurability in supply chains using total interpretive structural modeling. *Journal of Advances in Management Research*, *14*(2), 194–221. https://doi.org/10.1108/jamr-09-2016-0071.

Burke-Shyne, S., Gallegos, D., & Williams, T. (2020). 3D food printing: nutrition opportunities and challenges. *British Food Journal*, *123*(2), 649–663. https://doi.org/10.1108/bfj-05-2020-0441.

Chen, Z. (2016). Research on the Impact of 3D Printing on the International Supply Chain. *Advances in Materials Science and Engineering*, *2016*, 1–16. https://doi.org/10.1155/2016/4173873.

Chirico Scheele, S., Hartmann, C., Siegrist, M., Binks, M., & Egan, P. F. (2021). Consumer Assessment of 3D-Printed Food Shape, Taste, and Fidelity Using Chocolate and Marzipan Materials. *3D Printing and Additive Manufacturing*. https://doi.org/10.1089/3dp.2020.0271.

Dadi, V., Nikhil, S. R., Mor, R. S., Agarwal, T., & Arora, S. (2021). Agri-Food 4.0 and Innovations: Revamping the Supply Chain Operations. *Production Engineering Archives,* 27(2), 75-89, https://doi.org/10.30657/pea.2021.27.10.

Dahiya, S., Panghal, A., Sindhu, S., & Siwach, P. (2021). Organic food women entrepreneurs-TISM approach for challenges. *Journal of Enterprising Communities: People and Places in the Global Economy*, *15*(1), 114–136. https://doi.org/10.1108/jec-04-2020-0068.

Dankar, I., Haddarah, A., Omar, F. E., Sepulcre, F., & Pujolà, M. (2018). 3D printing technology: The new era for food customization and elaboration. *Trends in Food Science & Technology*, *75*, 231–242. https://doi.org/10.1016/j.tifs.2018.03.018.

Derossi, A., Caporizzi, R., Ricci, I., & Severini, C. (2019). Critical Variables in 3D Food Printing. *Fundamentals of 3D Food Printing and Applications*, 41–91. https://doi.org/10.1016/b978-0-12-814564-7.00003-1.

Deshmukh, A. K., & Mohan, A. (2017). Analysis of Indian retail demand chain using total interpretive modeling. *Journal of Modelling in Management*, *12*(3), 322–348. https://doi.org/10.1108/jm2-12-2015-0101.

do Canto, N. R., Bossle, M. B., Vieira, L. M., & de Barcellos, M. D. (2020). Supply chain collaboration for sustainability: a qualitative investigation of food supply chains in Brazil. *Management of Environmental Quality: An International Journal*, *32*(6), 1210–1232. https://doi.org/10.1108/meq-12-2019-0275.

Dwivedi, A., & Madaan, J. (2020). A hybrid approach for modeling the key performance indicators of information facilitated product recovery system. *Journal of Modelling in Management*, *15*(3), 933–965. https://doi.org/10.1108/jm2-01-2019-0003.

EU Report, (2016), "Identifying current and future application areas, existing industrial value chains and missing competences in the EU, in the area of additive manufacturing (3D-printing)", available at https://ec.europa.eu/growth/content/report-3d-printing-current-and-future-application-areas-existing-industrial-value-chains-0_en. (Accessed on: 28.04.2020).

Godoi, F. C., Prakash, S., & Bhandari, B. R. (2016). 3d printing technologies applied for food design: Status and prospects. *Journal of Food Engineering*, *179*, 44–54. https://doi.org/10.1016/j.jfoodeng.2016.01.025.

Goulding, S. (2021, October 18). R&D Aspects of 3D Printing Chocolate. 3DPrint.Com | The Voice of 3D Printing / Additive Manufacturing. Retrieved February 8, 2022, from https://3dprint.com/213896/rd-3d-printing-chocolate/ (Accessed on: 08.2.2022).

Groot, S. (2018), Effect of perceived risks, naturalness, usefulness and ease of use on the consumer acceptance of 3D food printing. Bachelor thesis, Wageningen. (Accessed on: 08.2.2022).

Gupta, V. (2016), 3D Printing–An Emerging Issue in Copyright Law, available at: https://www.wipo.int/wipo_magazine/en/2017/01/article_0006.html (Accessed on: 29.05.2020).

Gu, Z., Fu, J., Lin, H., & He, Y. (2020). Development of 3D bioprinting: From printing methods to biomedical applications. *Asian Journal of Pharmaceutical Sciences*, *15*(5), 529–557. https://doi.org/10.1016/j.ajps.2019.11.003.

Halassi, S., Semeijn, J., & Kiratli, N. (2019). From consumer to prosumer: a supply chain revolution in 3D printing. *International Journal of Physical Distribution & Logistics Management*, *49*(2), 200–216. https://doi.org/10.1108/ijpdlm-03-2018-0139.

Huang, M., Zhang, M., & Guo, C. (2020). 3D printability of brown rice gel modified by some food hydrocolloids. *Journal of Food Processing and Preservation*, *44*(7). https://doi.org/10.1111/jfpp.14502.

Irfan, M., Wang, M., & Akhtar, N. (2019). Impact of IT capabilities on supply chain capabilities and organizational agility: a dynamic capability view. *Operations Management Research*, *12*(3–4), 113–128. https://doi.org/10.1007/s12063-019-00142-y.

Jarzębowski, S., Bourlakis, M., & Bezat-Jarzębowska, A. (2020). Short Food Supply Chains (SFSC) as Local and Sustainable Systems. *Sustainability*, *12*(11), 4715. https://doi.org/10.3390/su12114715.

Javaid, M., & Haleem, A. (2019). Using additive manufacturing applications for design and development of food and agricultural equipments. *International Journal of Materials and Product Technology*, *58*(2/3), 225. https://doi.org/10.1504/ijmpt.2019.10018137.

Jena, J., Sidharth, S., Thakur, L. S., Kumar Pathak, D., & Pandey, V. (2017). Total Interpretive Structural Modeling (TISM): approach and application. *Journal of Advances in Management Research*, *14*(2), 162–181. https://doi.org/10.1108/jamr-10-2016-0087.

Jha, P., Aggarwal, R., & Singh, S. P. (2019). Studying the interrelationship between third party logistic service provider enablers using ISM methodology. *Journal of Modelling in Management*, *15*(1), 182–200. https://doi.org/10.1108/jm2-09-2018-0132.

Jia, F., Wang, X., Mustafee, N., & Hao, L. (2016). Investigating the feasibility of supply chain-centric business models in 3D chocolate printing: A simulation study. *Technological Forecasting and Social Change*, *102*, 202–213. https://doi.org/10.1016/j.techfore.2015.07.026.

Jiang, Q., Zhang, M., & Mujumdar, A. S. (2021). Novel evaluation technology for the demand characteristics of 3D food printing materials: a review. *Critical Reviews in Food Science and Nutrition*, 1–16. https://doi.org/10.1080/10408398.2021.1878099.

Keerthana, K., Anukiruthika, T., Moses, J., & Anandharamakrishnan, C. (2020). Development of fiber-enriched 3D printed snacks from alternative foods: A study on button mushroom. *Journal of Food Engineering*, *287*, 110116. https://doi.org/10.1016/j.jfoodeng.2020.110116.

Khan, S., Haleem, A., & Khan, M. I. (2020). Risk management in Halal supply chain: an integrated fuzzy Delphi and DEMATEL approach. *Journal of Modelling in Management*, *16*(1), 172–214. https://doi.org/10.1108/jm2-09-2019-0228.

Kubáč, L., & Kodym, O. (2017). The Impact of 3D Printing Technology on Supply Chain. *MATEC Web of Conferences*, *134*, 00027. https://doi.org/10.1051/matecconf/201713400027.

Kumar, P., Shankar, R., & Yadav, S. S. (2008). Flexibility in global supply chain: modeling the enablers. *Journal of Modelling in Management*, *3*(3), 277–297. https://doi.org/10.1108/17465660810920609.

Lamba, K., & Singh, S. P. (2018). Modeling big data enablers for operations and supply chain management. *The International Journal of Logistics Management*, *29*(2), 629–658. https://doi.org/10.1108/ijlm-07-2017-0183.

Lee, J. (2021). A 3D Food Printing Process for the New Normal Era: A Review. *Processes*, *9*(9), 1495. https://doi.org/10.3390/pr9091495.

Lianto, B., Dachyar, M., & Soemardi, T. P. (2020). Modelling the continuous innovation capability enablers in Indonesia's manufacturing industry. *Journal of Modelling in Management*, *17*(1), 66–99. https://doi.org/10.1108/jm2-04-2020-0103.

Lille, M., Nurmela, A., Nordlund, E., Metsä-Kortelainen, S., & Sozer, N. (2018). Applicability of protein and fiber-rich food materials in extrusion-based 3D printing. *Journal of Food Engineering*, *220*, 20–27. https://doi.org/10.1016/j.jfoodeng.2017.04.034.

Mishra, R., Singh, R. K., & Rana, N. P. (2022). Developing environmental collaboration among supply chain partners for sustainable consumption & production: Insights from an auto sector supply chain. *Journal of Cleaner Production*, *338*, 130619. https://doi.org/10.1016/j.jclepro.2022.130619.

Mishra, R., Singh, R. K., & Subramanian, N. (2021). Impact of disruptions in agri-food supply chain due to COVID-19 pandemic: contextualised resilience framework to achieve operational excellence. *The International Journal of Logistics Management*. https://doi.org/10.1108/ijlm-01-2021-0043.

Mohr, S., & Khan, O. (2015). 3D Printing and Its Disruptive Impacts on Supply Chains of the Future. *Technology Innovation Management Review*, *5*(11), 20–25. https://doi.org/10.22215/timreview/942.

Mor, R. S., Bhardwaj, A., Singh, S., & Khan, S. A. R. (2021). Modelling the distribution performance in dairy industry: a predictive analysis. *LogForum: Scientific Journal of Logistics*, 17(3), 425-440, https://doi.org/10.17270/J.LOG.2021.609.

Nachal, N., Moses, J. A., Karthik, P., & Anandharamakrishnan, C. (2019). Applications of 3D Printing in Food Processing. *Food Engineering Reviews*, *11*(3), 123–141. https://doi.org/10.1007/s12393-019-09199-8.

Oettmeier, K., & Hofmann, E. (2016). Impact of additive manufacturing technology adoption on supply chain management processes and components. *Journal of Manufacturing Technology Management*, *27*(7), 944–968. https://doi.org/10.1108/jmtm-12-2015-0113.

Palaniappan, A., Vinodh, S., & Ranganathan, R. (2020). Analysis of factors influencing AM application in food sector using ISM. *Journal of Modelling in Management*, *15*(3), 919–932. https://doi.org/10.1108/jm2-11-2018-0190.

Pereira, T., Barroso, S., & Gil, M. M. (2021). Food Texture Design by 3D Printing: A Review. *Foods*, *10*(2), 320. https://doi.org/10.3390/foods10020320.

Poonia, A., Sindhu, S., Arya, V., & Panghal, A. (2021). Analysis of drivers for anti-food waste behaviour - TISM and MICMAC approach. *Journal of Indian Business Research*, *14*(2), 186–212. https://doi.org/10.1108/jibr-02-2021-0069.

Portanguen, S., Tournayre, P., Sicard, J., Astruc, T., & Mirade, P. S. (2022). 3D food printing: Genesis, trends and prospects. *Future Foods*, 627–644. https://doi.org/10.1016/b978-0-323-91001-9.00008-6.

Quince Market Insights. (2022, January 7). 3D Food Printing Market is Estimated to Grow at a CAGR Of 48.60% During the Estimated Time Frame from 2021 to 2030; Quince Market Insights. GlobeNewswire News Room. Retrieved February 8, 2022, from https://www.globenewswire.com/en/news-release/2022/01/07/2363161/0/en/3D-Food-Printing-Market-is-Estimated-to-Grow-at-a-CAGR-Of-48-60-During-the-Estimated-Time-Frame-from-2021-to-2030-Quince-Market-Insights.html (Accessed on: 08.02.2022).

Rajput, H., Goswami, D., Nigam, S., Rani, R. and Srivastav, P. (2019), 3D Printing: Advancement in Food Formulation. In: Recent Trends & Advances in Food Science & Post Harvest Technology Ed. Chakraborty, I., Ilahy, R., Vikram, B. and Mani, M.A., pp 232-251.

Ramachandraiah, K. (2021). Potential Development of Sustainable 3D-Printed Meat Analogues: A Review. *Sustainability*, *13*(2), 938. https://doi.org/10.3390/su13020938.

Rathor, S. (2021, February 15). Tech Tadka: Soon you can 3D print food in your kitchen. The Times of India. https://timesofindia.indiatimes.com/city/hyderabad/tech-tadka-soon-you-can-3d-print-food-in-your-kitchen/articleshow/80914732.cms (Accessed on: 08.02.2022).

Reuters. (2021, December 29). Israel's SavorEat Begins Selling Personalised 3D-Printed Vegan Burgers. NDTV Gadgets 360. Retrieved February 8, 2022, from https://gadgets.ndtv.com/science/news/3d-printed-vegan-burgers-savoreat-custom-protein-fat-content-launch-2677785 (Accessed on: 10.02.2022).

Rogers, H., & Srivastava, M. (2021). Emerging Sustainable Supply Chain Models for 3D Food Printing. *Sustainability*, *13*(21), 12085. https://doi.org/10.3390/su132112085.

Rylands, Brogan; Bohme, Tillman; Gorkin III, Robert A.; Fan, Joshua P.; and Birtchnell, Thomas, "3D Printing - To print or not to print? Aspects to consider before adoption - A supply chain perspective" (2015). Australian Institute for Innovative Materials - Papers. 1761. https://ro.uow.edu.au/aiimpapers/1761.

Sid, S., Mor, R. S., Panghal, A., Kumar, D., & Gahlawat, V. K. (2021). Agri-food supply chain and disruptions due to COVID-19: Effects and Strategies. *Brazilian Journal of Operations & Production Management*, *18*(2), 1–14. https://doi.org/10.14488/bjopm.2021.031.

Siddh, M. M., Soni, G., Jain, R., Sharma, M. K., & Yadav, V. (2020). A framework for managing the agri-fresh food supply chain quality in Indian industry. *Management of Environmental Quality*, 32(2), 436-451. https://doi.org/10.1108/MEQ-05-2020-0085.

Sindhu, S. (2020). Cause-related marketing — an interpretive structural model approach. *Journal of Nonprofit & Public Sector Marketing*, *34*(1), 102–128. https://doi.org/10.1080/10495142.2020.1798851.

Sindhu, S., & Mor, R. S. (2021). Modelling the Enablers for Branded Content as a Strategic Marketing Tool in the COVID-19 Era. *Systems*, *9*(3), 64. https://doi.org/10.3390/systems9030064.

Singh, R. K., & Gurtu, A. (2021). Embracing advanced manufacturing technologies for performance improvement: an empirical study. *Benchmarking: An International Journal*. https://doi.org/10.1108/bij-02-2021-0110.

Singh, R. K., Koul, S., & Kumar, P. (2017). Analyzing the interaction of factors for flexibility in supply chains. *Journal of Modelling in Management*, *12*(4), 671–689. https://doi.org/10.1108/jm2-04-2016-0039.

Singhal, S., Rasane, P., Kaur, S., Garba, U., Bankar, A., Singh, J., & Gupta, N. (2020). 3D food printing: paving way towards novel foods. *Anais Da Academia Brasileira de Ciências*, *92*(3). https://doi.org/10.1590/0001-3765202020180737.

Shankar, R., Pathak, D. K., & Choudhary, D. (2019). Decarbonizing freight transportation: An integrated EFA-TISM approach to model enablers of dedicated freight corridors. *Technological Forecasting and Social Change*, *143*, 85–100. https://doi.org/10.1016/j.techfore.2019.03.010.

Sher, D. (2021, December 2). Imaginarium brings Foodini food 3D printer to India. 3D Printing Media Network - The Pulse of the AM Industry. Retrieved February 8, 2022, from https://www.3dprintingmedia.network/imaginarium-brings-foodini-food-3d-printer-to-india/ (Accessed on: 12.02.2022).

Sun, J., Peng, Z., Yan, L., Fuh, J., & Hong, G. S. (2015). 3D food printing—An innovative way of mass customization in food fabrication. *International Journal of Bioprinting*, *1*(1). https://doi.org/10.18063/ijb.2015.01.006.

Sun, J., Peng, Z., Zhou, W., Fuh, J. Y., Hong, G. S., & Chiu, A. (2015). A Review on 3D Printing for Customized Food Fabrication. *Procedia Manufacturing*, 1, 308–319. https://doi.org/10.1016/j.promfg.2015.09.057.

Sun, J., Zhou, W., Huang, D., Fuh, J. Y. H., & Hong, G. S. (2015). An Overview of 3D Printing Technologies for Food Fabrication. *Food and Bioprocess Technology*, *8*(8), 1605–1615. https://doi.org/10.1007/s11947-015-1528-6.

Sun, J., Zhou, W., Huang, D., & Yan, L. (2018). 3D Food Printing: Perspectives. *Polymers for Food Applications*, 725–755. https://doi.org/10.1007/978-3-319-94625-2_26.

Susanty, A., Puspitasari, N. B., Prastawa, H., & Renaldi, S. V. (2020). Exploring the best policy scenario plan for the dairy supply chain: a DEMATEL approach. *Journal of Modelling in Management*, *16*(1), 240–266. https://doi.org/10.1108/jm2-08-2019-0185.

Todorovic, V., Maslaric, M., Bojic, S., Jokic, M., Mircetic, D., & Nikolicic, S. (2018). Solutions for More Sustainable Distribution in the Short Food Supply Chains. *Sustainability*, *10*(10), 3481. https://doi.org/10.3390/su10103481.

Udipi, SA. (2017), 3D Printing: PFNDAI Bulletin. pp.3-7. Available at: http://www.pfndai.org/Document/BulletIn/2017/03.Mar2017_Bulletin_Web.pdf. (Accessed on: 21.05.2020).

Varvara, R. A., Szabo, K., & Vodnar, D. C. (2021). 3D Food Printing: Principles of Obtaining Digitally-Designed Nourishment. *Nutrients*, *13*(10), 3617. https://doi.org/10.3390/nu13103617.

Verma, V. K., Kamble, S. S., Ganapathy, L., Belhadi, A., & Gupta, S. (2022). 3D Printing for sustainable food supply chains: modelling the implementation barriers. *International Journal of Logistics Research and Applications*, 1–27. https://doi.org/10.1080/13675567.2022.2037125.

Wamba, SF. (2017), 3D printing and supply chain management: a literature review and research agenda. 5th International Conference on Mechanical Engineering (Meche), Dubai, UAE.

Zhang, J. Y., Pandya, J. K., McClements, D. J., Lu, J., & Kinchla, A. J. (2021). Advancements in 3D food printing: a comprehensive overview of properties and opportunities. *Critical Reviews in Food Science and Nutrition*, 1–18. https://doi.org/10.1080/10408398.2021.1878103.