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Research Article

Circular Pathways in Agriculture: Success Factors for Large-Scale Adoption of Mushroom Farming

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Abstract: The global food system faces a significant threat due to its substantial connections to greenhouse gas emissions, necessitating the exploration of sustainable alternatives. Amidst the prevalent realisation and responsiveness toward overcoming this adverse impact, mushroom farming (MF) has emerged as a promising solution for soil conservation, food security, and meeting sustainable environment goals. This study explores enablers to MF by reviewing the extant literature and conducting expert interviews. Further, the study employs Interpretive Structural Modelling (ISM) to capture the complex interdependencies among these enablers and understand potential strategies to leverage them as opportunities. Findings reveal that low technological requirements, flexibility in farming systems, nutritional security, and the versatile application of spent mushroom substrate are the most influential drivers of MF adoption. These insights provide a structured understanding of the multifaceted opportunities embedded in MF and highlight its potential to align with India's sustainability and food security goals.

Keywords: Mushroom farming, Sustainability, Interpretive Structural Modelling (ISM), Food security, Climate resilience

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Highlights:

- Uses ISM to analyse interdependencies among MF adoption drivers.
- Highlights key drivers advancing sustainable mushroom farming in India.
- Low technological requirements, flexibility in farming systems and nutritional security, are the most influential drivers.

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1. Introduction

Mushroom farming (MF) has become a viable agricultural practice to overcome issues related to food insecurity, soil health, and economic empowerment of local farmers. Mushrooms are a rich source of protein, essential amino acids, antioxidants, vitamins, and bioactive compounds, making them better plant-based protein alternatives (Ayimbila & Keawsompong, 2023; Boro et al., 2025; Sharma, 2015; Yuan et al., 2025). Additionally, they possess medicinal properties, including antimicrobial and anti-carcinogenic effects, contributing to human health and wellness (Boro et al., 2025; Tang et al., 2022). MF creates a sustainable food system that is nutritious, healthy, and culturally viable for the current generation without compromising the future generation's needs (Moxley et al., 2022). It offers promising solutions to combat the climate crisis by improving soil quality, decreasing greenhouse gas (GHG) emissions, managing agricultural waste, and ensuring nutritional security (Jayaraman et al., 2024).

MF requires minimal land and capital investment. It can be practiced in vertical or indoor systems, enabling participation by farmers with limited or no agricultural land while simultaneously preventing deforestation (Das & Bocken, 2024; Yuan et al., 2025). Varieties, namely Shiitake, white button, oyster, and paddy straw mushrooms, can easily be grown on decaying woods, hardwood trees, and rice straw beds (Sharma, 2015). Since mushroom farming can flourish on agricultural waste, it offers dual benefits of reducing soil and air pollution (Mishra & Shankar, 2025). Moreover, crop rotations involving mushrooms have demonstrated greater soil fertility and higher farm income than conventional rice–wheat systems (Hu et al., 2025). Further, protein extraction from mushrooms is more cost-effective and space-efficient than other plant and animal-based alternatives (Yuan et al., 2025).

Despite being perishable, mushrooms can be preserved through drying, freeze-drying, or processing into extracts, powders, and canned products, creating additional business opportunities and reducing food waste (Rorato et al., 2025; V. Sharma et al., 2024; Yang et al., 2025). Furthermore, mushrooms demonstrate remarkable versatility, with innovation and research enabling their use in sustainable applications such as building materials, biodegradable packaging, mycelium-based leather, biodegradable circuit boards, and platforms for textile engineering (Kniep et al., 2024; Sangeeta et al., 2024; Sharma, 2015).

Technological advancements further enhance the potential of MF. Recent developments such as Internet of Things-based monitoring systems allow farmers to regulate critical environmental parameters, including humidity, temperature, and ventilation, through automated systems (Aa et al., 2024; Chong et al., 2023; Rukhiran et al., 2023). These innovations improve productivity and quality while making MF accessible to small-scale and commercial producers.

The alignment of MF with the United Nations' Sustainable Development Goals (UNSDGs), notably zero hunger (SDG 2), responsible consumption and production (SDG12) and climate action (SDG 13) positions it well for leveraging progress toward sustainability in India and other agrarian economies (Aa et al., 2024; Mishra & Shankar, 2025b; X. Zhang et al., 2025).

Beyond dietary benefits, MF contributes to climate mitigation by reducing greenhouse gas emissions, supporting soil regeneration, and promoting sustainable waste management. These combined features make it a cost-effective pathway toward resilient food systems, environmental sustainability, and human well-being (Ayimbila & Keawsompong, 2023; Boro et al., 2025; Katsir et al., 2024; Khatun et al., 2015; Yuan et al., 2025).

India's policy commitment to sustainability was prominently showcased during the G20 Summit 2023 in New Delhi, where delegates were served sustainable food options—signalling a broader global emphasis on environmentally responsible practices. Effective mechanisms to promote MF locally could strengthen national economies while advancing global sustainability goals. Against this backdrop, the present study investigates the key success factors for MF in India using the Interpretive Structural Modelling (ISM) approach. ISM enables the analysis of interconnections among enablers, highlights hierarchical relationships, and supports strategy formulation for sustainable MF (Trivedi & Trivedi, 2018).

The remainder of this paper is organized as follows: Section 2 reviews the literature and identifies success factors, Section 3 details the methodology, and Section 4 presents analyses and discussions. Implications are reported in Section 5, while the last section concludes the study.

2. Literature Review

Mushroom cultivation has a rich history, with evidence of organized farming in China as early as 600 CE (Gu et al., 2019; Zhang et al., 2014). Over centuries, these practices spread to Europe, Asia, and the United States, marking their global presence (Moxley et al., 2022). In recent decades, MF has undergone a significant transformation, with a 70% increase in the production of speciality mushrooms (Jayaraman et al., 2024; C. Li & Xu, 2022; Y. Zhang et al., 2014). However, in India, the focus primarily remains on button mushrooms, a capital-intensive activity requiring many sophisticated processes (Chand & Singh, 2022; Ojha et al., 2025; Sharma et al., 2017).

Economic considerations are central to sustainable farming decisions, as financial viability directly affects every decision (Mohammed et al., 2023). In mushroom farming, the cost of production and ease of market access emerge as key factors guiding farming decisions (Chand & Singh, 2022; Schilla et al., 2025). Importantly, MF offers a dual advantage as it utilizes agricultural waste as substrate, thereby reducing the environmental burden of crop residue burning, while simultaneously ensuring a consistent income stream for farmers (Grimm et al., 2021; Grimm & Wösten, 2018; Jayaraman et al., 2024). Additionally, the by-product of mushroom cultivation, i.e., Spent Mushroom Substrate, can be repurposed as livestock feed or as carbon-rich soil amendment, reinforcing resource efficiency and supporting circular economy principles (Grimm & Wösten, 2018; Moxley et al., 2022).

From an environmental sustainability perspective, MF contributes positively to ecological health. Several studies reveal its role in soil regeneration, enhancement of soil quality, and reduction of greenhouse gas emissions compared to conventional cropping systems (Dorr et al., 2021; Jayaraman et al., 2024b; Patel et al., 2025). Life cycle assessment studies demonstrate that when circular economy strategies are practiced, MF exhibits a lower overall environmental impact than many conventional crops in terms of carbon footprints due to energy consumption and transportation (Dorr et al., 2021; Grimm & Wösten, 2018; Patel et al., 2025).

Beyond its economic and ecological contributions, MF is also recognized for its nutritional significance. Mushrooms are a valuable dietary component, rich in proteins, vitamins, and essential minerals, thereby enhancing food security and dietary diversity (Boro et al., 2025; Chand & Singh, 2022; Jayaraman et al., 2024; Schilla et al., 2025; Sharma et al., 2024). Additionally, studies also suggest that MF is particularly accessible to small-scale farmers, as it requires minimal capital and land, promises quick returns with income diversification opportunities (Chand & Singh, 2022; Koodagi et al., 2021; N. et al., 2024; Ojha et al., 2025). Supportive government policies, modular training programs, and structured market development initiatives, especially those encouraging women entrepreneurs, are pivotal for enhancing production capacity and fostering socio-economic empowerment among marginalized farming communities.

Despite MF's considerable potential, its large-scale adoption in India faces persistent constraints arising from technical, infrastructural, and financial challenges (Grimm et al., 2021; N. et al., 2024; Patel et al., 2025; Sharma et al., 2017; Wan Mahari et al., 2020). Recent studies emphasize the role of enablers such as digital innovation (e.g, Internet of Things), supportive policy frameworks, and circular waste management practices in advancing mushroom farming as a viable contributor to sustainable development (Grimm et al., 2021; Irwanto et al., 2024; Patel et al., 2025; Wan Mahari et al., 2020). Given the complex nature and interdependence of these factors, systematic approaches are increasingly employed to map hierarchical associations among the enablers and to inform targeted interventions (Irwanto et al., 2024; Patel et al., 2025; Trivedi et al., 2015; Trivedi & Trivedi, 2018; Yadav & Barve, 2015). Considering MF's urgency and potential benefits in India, evaluating these enablers becomes essential. Accordingly, the present research employs an ISM-based framework to identify success factors that can facilitate the sustainable expansion of mushroom farming in Indian contexts.

2.1 Success Factors for MF in India

Achieving wider acceptance of MF as a sustainable food system is both a critical and complex endeavour, particularly in reducing GHG emissions and mitigating the climate crisis. Numerous enablers are indispensable for the successful enactment of MF in India. The present study identifies these enablers through an extensive literature review and consultations with five domain experts.

2.1.1 Low Technology and flexible cultivation system (LTF)

MF needs minimal land, leading to a high economic yield per unit area and unit time (Dey et al., 2020). Further, innovative farming techniques, such as vertical farming, further enhance productivity, offering viable livelihood opportunities for smallholder farmers and self-help groups with limited agricultural land (Jayaraman et al., 2024). Additionally, reduced dependence on extensive farmlands minimizes deforestation, prevents agricultural residue, and subsequently lowering GHG emissions (Youngerman & Gonzalez, 2024).

2.1.2 Stable Revenue Stream for Farmers (SRS)

MF presents an economically attractive option, as it can be practiced with limited land, labor, and capital resources. The edible biomass output from mushroom cultivation is considerably higher than that of many traditional crops, thereby increasing net returns for farmers (Moxley et al., 2022a). Moreover, the growing demand and premium pricing of specialty mushrooms make them economically rewarding. Additional revenue can be generated by valorizing agricultural by-products and leveraging their soil-regenerative properties, further reducing long-term input costs.

2.1.3 Self-reliance through localized food systems (LFS)

Localized food systems enable the local communities to be self-reliant on food supply. Only 29% of the rising demand for shiitake mushrooms, a popular variety, is fulfilled by local production (Youngerman & Gonzalez, 2024). Integrating small-scale mushroom farms into a local agriculture movement can help meet the demand while reducing GHG emissions by minimising the need for long-distance food transport.

2.1.4 Supportive government Policies (POL)

Favourable governmental policies and institutional support can enhance environmental and human well-being by incentivizing the MF. For instance, the National Institute of Food and Agriculture, U.S. Department of Agriculture, through the Northeast Sustainable Agriculture Research and Education program, has funded several specialty mushroom projects, exemplifying how policy support can accelerate the growth of this renewable food production system (Youngerman & Gonzalez, 2024).

2.1.5 Consumer acceptance as an alternative protein (CA)

Mushrooms are increasingly recognized for their nutritional value, containing significant protein levels alongside essential micronutrients, including vitamin D, magnesium, and potassium (Youngerman & Gonzalez, 2024). Further, their high digestibility has positioned them as a viable substitute for animal-based protein sources (Kalač, 2009). Rising consumer demand for meat alternatives with umami flavor and competitive nutrient profiles has further enhanced their acceptance, as they offer both health benefits and food security solutions at individual and community scales (Boro et al., 2025; Tang et al., 2022; Wang et al., 2021).

2.1.6 Low environmental impacts of production process (ENV)

Unlike conventional farming, mushroom cultivation does not require deforestation and can even be conducted in compact spaces (Youngerman & Gonzalez, 2024). By transforming low-quality agricultural waste into highly nutritious food, MF contributes to soil enrichment and environmental conservation (Jayaraman et al., 2024a). The incorporation of mushrooms into crop rotation systems (e.g., replacing rice–wheat cycles) improves soil fertility and reduces air pollution from residue burning, thereby advancing sustainable land-use practices (Berglund et al., 2024; Contato & Conte-Junior, 2025; Hu et al., 2025; F. Li et al., 2020; Nakatsuka et al., 2016; Tang et al., 2022).

2.1.7 Versatile applications of spent mushroom substrate (SMS)

Spent Mushroom Substrate, a by-product from mushroom cultivation, offers several environmental and economic benefits. It can be repurposed for multiple uses, including animal feed, biofuel production, compost, packaging material, and soil amendments (Jayaraman et al., 2024). Rich in calcium, nitrogen, and other nutrients, it improves soil fertility and structure, enhancing water retention, microbial activity, and thermal balance (Grimm & Wösten, 2018). Its non-toxic nature prevents open burning, thereby reducing air pollution and reinforcing the circular economy potential of mushroom farming.

2.1.8 Socio-cultural sustainability (SUS)

Mushrooms hold long-standing cultural and medicinal significance across different societies. For example, tiger milk mushrooms in Malaysia and wild mushrooms in the Khasi Hills of Meghalaya and the Western Ghats of India have been traditionally valued for their nutritional and therapeutic properties (Karun & Sridhar, 2017; Lau et al., 2015; Longvah & Deosthale, 1998). Further, their varieties, such as Astaeus, are known for their antimicrobial properties (Sridhar & Pavithra, 2021). Hence, the socio-cultural importance of MF underscores its potential as a sustainable solution for society.

2.1.9 Training & Development programs (TDP)

Adequate training and development programs are essential to equip farmers with the technical expertise required for efficient mushroom cultivation. For instance, knowledge dissemination on using rice straw for composting not only enhances farm profitability but also promotes environmental benefits by reducing residue burning (Singh & Arya, 2021). Similarly, awareness of the advantages of mushroom-based crop rotations can enable farmers to achieve higher economic returns while contributing to ecological sustainability (Hu et al., 2025).

2.1.10 Nutritional Security (NFS)

Mushrooms contribute significantly to nutritional security due to their high protein content, bioactive compounds, and essential vitamins such as riboflavin and niacin, while remaining low in fats and calories (Singh & Arya, 2021). Their umami flavour profile and vitamin D enrichment make them a strong substitute for animal meat, aligning with global efforts to achieve UNSDG #2—Zero Hunger (Boro et al., 2025). Moreover, mushrooms have been consumed for medicinal and dietary purposes by many indigenous communities (Jayaraman et al., 2024; Konietzko et al., 2023; Wang et al., 2021). Varieties including Shiitake, oyster, paddy straw, and white button mushrooms are widely grown and consumed in Asia, whereas white and brown button mushrooms dominate in European and North American diets (K. Sharma, 2015). Table 1 provides the success factors for MF in India and their literary sources.

Table 1: Success factors and sources

Enabler	Sources
Low Technology and Flexible Cultivation System (LTF)	(Aa et al., 2024; Chong et al., 2023; A. Dey et al., 2020; B. Dey et al., 2024; Grimm & Wösten, 2018; Hendinata & Fikri, 2023; Longvah & Deosthale, 1998; Moxley et al., 2022; Rukhiran et al., 2023b; Sangeeta et al., 2024; Sharma, 2015; United Nations- Nations Unies, 2008; Yang et al., 2025; Zhang et al., 2025)
Stable Revenue Stream for Farmers (SRS)	(B. Dey et al., 2024; Hu et al., 2025; Koodagi et al., 2021; Moxley et al., 2022)
Self-reliance on Food Supply via Localized Food System (LFS)	(Hu et al., 2025; Pokhrel, 2016; Tesfaw et al., 2015; Youngerman & Gonzalez, 2024)
Supportive government Policies (GOV)	(Niti Aayog, 2022; United Nations- Nations Unies, 2008; Youngerman & Gonzalez, 2024)
Wide Consumer Acceptance as Alternative Protein (CA)	(Contato & Conte-Junior, 2025; Kalač, 2009; Youngerman & Gonzalez, 2024)
Low Environmental Impacts (ENV)	(Ayimbila & Keawsompong, 2023; Boro et al., 2025; Katsir et al., 2024; Khatun et al., 2015; Yuan et al., 2025)
Versatile applications of Spent Mushroom Substrate (SMS)	(Berglund et al., 2024; Grimm & Wösten, 2018; Hu et al., 2025; Kang et al., 2020; Nakatsuka et al., 2016)
Sociocultural Sustainability (SUS)	(Karun & Sridhar, 2017; Lau et al., 2015b; Longvah & Deosthale, 1998; Sridhar & Pavithra, 2021)
Training & Development programs (TDP)	(Hu et al., 2025; Koodagi et al., 2021; Niti Aayog, 2022; Singh & Arya, 2021; United Nations- Nations Unies, 2008)
Nutritional Security (NFS)	(Ayimbila & Keawsompong, 2023; Boro et al., 2025; Contato & Conte-Junior, 2025; Escobar-Sáez et al., 2022; Estell et al., 2021; Kalač, 2009; Khatun et al., 2015; Lau et al., 2015; Longvah & Deosthale, 1998; Mishra & Shankar, 2025; Shireen & Wright, 2024; Singh & Arya, 2021; Xie et al., 2024; Yuan et al., 2025; Zhang et al., 2025)

3. Methodology

Interpretive Structural Modeling (ISM) technique offers a structured approach for analysis when the factors in a system are interrelated, making it complex. Proposed by Warfield, ISM transforms ambiguous mental models into systematic visual representations (Ahmad & Qahmash, 2021; Malone, 1975; Sushil, 2012; Warfield, 1974). It enables the identification of relationships among factors, organizes them hierarchically, and distinguishes their direct and indirect linkages. ISM is particularly effective in analysing systems involving driving and dependent factors (Attri et al., 2013; Xu & Zou, 2020). It is a step-by-step process of identifying critical factors, establishing intercontextual association among them, followed by generating the Structural self-interaction matrix (SSIM), Reachability matrix, and finally, generating the hierarchical model (Hughes et al., 2016; Trivedi et al., 2015; Trivedi & Trivedi, 2018). Being interpretive in nature, ISM relies on expert judgments to map complex relationships (Muduli et al., 2013) and facilitate theory building in areas where the availability of empirical datasets is very limited, highlighting the need of a structural interpretation. Since mushroom farming research in Indian contexts is still at a nascent stage, it places special emphasis on capturing hierarchical relationships among the factors rather than estimating causal intensity among them.

ISM has been widely applied in various fields of study, including e-commerce, sustainable transportation, such as inland waterways, sustainable energy sources such as ocean energy, circular economy, and brand experience in retailing (Khan & Rahman, 2015a; A. Trivedi et al., 2021a, 2023; V. Trivedi & Trivedi, 2018a; Zhou et al., 2019).

To complement ISM, this study also uses MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) analysis, which assesses the driving power and dependence of factors derived from the reachability matrix. MICMAC analysis helps in addressing the issue of binary structuring in ISM through driving-dependence categorization, offering better interpretation of influence and robustness of the analysis. It classifies factors into four categories: independent, dependent, autonomous, and linkage factors. Due to wide employability of this combined approach, it has been used extensively in diverse fields including inland waterways (A. Trivedi et al., 2021b), hydrogen energy storage (Wu et al., 2022), e-commerce (V. Trivedi & Trivedi, 2018b), waste management (A. Kumar & Dixit, 2018; A. Trivedi et al., 2015), flood risk assessment (Li et al., 2023), supplier selection (Mandal & Deshmukh, 1994), building energy performance (Xu & Zou, 2020), sustainability (Kumar & Goel, 2022), brand experience in retailing (Khan & Rahman, 2015b), humanitarian supply chains (Yadav & Barve, 2015), and information system project failure (Hughes et al., 2016).

Since ISM and MICMAC are qualitative approaches that involve expert judgments, significant emphasis has been made to ensure their methodological credibility through a diverse pool of experts and consensus aggregation. In light of its broad applicability, the present study adopts ISM, supported by MICMAC analysis, to develop a clear hierarchical framework for examining the enablers to MF in India.

4. Results

For the present study, data were collected from a panel of twenty experts representing industry and academia. All respondents had at least ten years of relevant professional or research experience. Among them, thirteen were industry experts, including practitioners and agribusiness consultants from the food industry. The academic experts included professors and senior researchers specializing in sustainability and food systems. This diverse pool of experts was intentionally created to ensure the minimization of individual cognitive bias and group-level opinions. Their judgments were aggregated, and the ISM technique was subsequently applied. The stepwise procedure is detailed below.

Step 1: The experts provided judgments that established the contextual relationships among the identified success factors of MF. The research team constructed a Structural Self-Interaction Matrix (SSIM) to represent the pairwise associations between factors, listed in rows i and columns j, according to the following rules:

V= Variable i will lead to variable j
A= Variable j will lead to variable i
X= Variable i and j will lead to each other
O= Variable i and j are unrelated

The study applied the modal measure to determine the relationship between each pair of factors, selecting the response that occurred most frequently among the experts. The most frequently occurring judgment across experts are captured through modal aggregation, thereby minimizing extreme or outlying responses. Table 2 presents the aggregated SSIM.

Table 2: Structural Self-Interaction Matrix (SSIM)

	SRS	**LFS**	**GOV**	**CA**	**ENV**	**SMS**	**SUS**	**TDP**	**NFS**
LTF	V	V	X	O	V	A	V	A	V
NFS	V	O	V	O	O	X	V	V	
TDP	V	V	X	X	X	V	X		
SUS	X	A	X	X	A	X			
SMS	V	V	V	V	X				
ENV	V	X	X	X					
CA	V	X	X						
GOV	X	X							
LFS	X								

Step 2: A Reachability Matrix (RM) is derived from the SSIM by transforming the symbolic entries into binary values (0 and 1) according to defined rules. Specifically:

- If (i,j) entry in the SSIM is V, then, (i,j)=1, and (j,i)= 0.
- If (i,j) entry in the SSIM is A, then, (i,j)=0, and (j,i)= 1.
- If (i,j) entry the SSIM is X, then, (i,j)=1, and (j,i)= 1.
- If (i,j) entry the SSIM is O, then, (i,j)=0, and (j,i)= 0.

The reachability matrix obtained from the SSIM is presented in Table 3.

Table 3. Reachability Matrix

	LTF	**SRS**	**LFS**	**GOV**	**CA**	**ENV**	**SMS**	**SUS**	**TDP**	**NFS**
LTF	1	1	1	1	0	1	0	1	0	1
SRS	0	1	1	1	0	0	0	1	0	0
LFS	0	1	1	1	1	1	0	1	0	0
GOV	1	1	1	1	1	1	0	1	1	0
CA	0	1	1	1	1	1	0	1	1	0
ENV	0	1	1	1	1	1	1	1	1	0
SMS	1	1	1	1	1	1	1	1	0	1
SUS	0	1	0	1	1	0	1	1	1	0
TDP	1	1	1	0	1	1	1	1	1	0
NFS	0	1	0	1	1	0	0	1	1	1

Step 3: Level partitioning is done in the third step. The following rules are applicable while carrying out the level partitioning. For each factor, reachability and antecedent sets are produced based on the data from the reachability matrix. The two sets are then utilised to create an intersection set representing the common elements between both sets. If, in a particular case, for a factor, the intersection set matches the reachability set, that factor is considered to be a top-level variable within the hierarchy of association. Subsequently, the factor is separated from the others, and the level partitioning is repeated. These iterations continue to reach a stage where all factors finally achieve their particular levels within the hierarchy.

The level partitioning was carried out based on the reachability matrix, as explained in Step 3. Tables 4-8 represent the five levels created, which were later used to develop the interpretive model shown in Figure 1.

Table 4. Level Partitioning- Stage I

	Reachability Set	Antecedent Set	Intersection Set	Level
LTF(1)	1,2,3,4,6,8	1,4,7,9	1,4	
SRS(2)	2,3,4,8	1,2,3,4,5,6,7,8,9,10	2,3,4,8	I
LFS(3)	2,3,4,5,6,8	1,2,3,4,5,6,7,9	2,3,4,5,6	
GOV(4)	2,3,4,5,6,8,9	1,2,3,4,5,6,7,8,10	2,3,4,5,6,8	
CA(5)	2,3,4,5,6,8,9	3,4,5,6,7,8,9,10	3,4,5,6,8,9	
ENV (6)	2,3,4,5,6,7,8,9	1,3,4,5,6,7,9	3,4,5,6,7,9	
SMS(7)	1,2,3,4,5,6,7,8,10	6,7,8,9	6,7,8	
SUS (8)	2,4,5,7,8,9	1,2,3,4,5,6,7,8,9,10	2,4,5,7,8,9	
TDP (9)	1,2,3,5,6,7,8,9	4,5,6,8,9, 10	5,6,8,9	
NFS(10)	2,4,5,8,9,10	1,7,10	10	

Table 5. Level Partitioning- Stage II

	Reachability Set	Antecedent Set	Intersection Set	Level
LTF(1)	1,3,4,6,8	1,4,7,9	1,4	
LFS(3)	3,4,5,6,8	1,3,4,5,6,7,9	3,4,5,6	
GOV(4)	3,4,5,6,8,9	1,3,4,5,6,7,8,10	3,4,5,6,8	
CA(5)	3,4,5,6,8,9	3,4,5,6,7,8,9,10	3,4,5,6,8,9	II
ENV (6)	3,4,5,6,7,8,9	1,3,4,5,6,7,9	3,4,5,6,7,9	
SMS(7)	1,3,4,5,6,7,8,10	6,7,8,9	6,7,8	
SUS (8)	4,5,7,8,9	1,3,4,5,6,7,8,9,10	4,5,7,8,9	II
TDP (9)	1,3,5,6,7,8,9	4,5,6,8,9, 10	5,6,8,9	
NFS (10)	4,5,8,9,10	1,7,10	10	

Table 6. Level Partitioning- Stage III

	Reachability Set	Antecedent Set	Intersection Set	Level
LTF(1)	1,3,4,6,	1,4,7,9	1,4	
LFS(3)	3,4,6	1,3,4,6,7,9	3,4,6	III
GOV(4)	3,4,6,9	1,3,4,6,7,10	3,4,6	
ENV (6)	3,4,6,7,9	1,3,4,6,7,9	3,4,6,7,9	III
SMS(7)	1,3,4,6,7,10	6,7,9	6,7	
TDP (9)	1,3,6,7,9	4,6,9, 10	6,9	
NFS (10)	4,9,10	1,7,10	10	

Table 7. Level Partitioning- Stage IV

	Reachability Set	Antecedent Set	Intersection Set	Level
LTF(1)	1,4,	1,4,7,9	1,4	IV
GOV(4)	4,9	1,4,7,10	4	
SMS(7)	1,4,7,10	7,9	7	
TDP (9)	1,7,9	4,9, 10	9	
NFS (10)	4,9,10	1,7,10	10	

Table 8. Level Partitioning- Stages V

	Reachability Set	Antecedent Set	Intersection Set	Level
GOV(4)	4,9	4,7,10	4	V
SMS(7)	4,7,10	7,9	7	V
TDP (9)	7,9	4,9, 10	9	V
NFS (10)	4,9,10	7,10	10	V

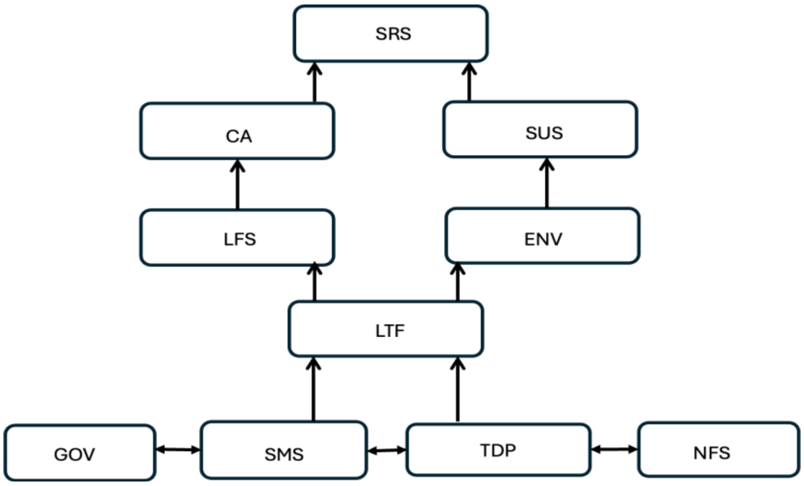

Figure 1. Interpretive Structural Model

A MICMAC (Matrice d'Impacts Crois'es Multiplication Appliqu'ee 'a un Classement) analysis was carried out to examine the driving power and dependencies among the identified elements. The MICMAC analysis functions around the concept of multiplication, i.e., if factor A affects factor B, and factor B influences factor C, then factor A is inferred to indirectly influence factor C. Based on their relative driving and dependency powers, the factors are classified into four quadrants. Autonomous factors exhibit both low driving power and low dependency. Dependent factors are characterized by low driving power but high dependency. In contrast, linkage factors demonstrate both high driving power and high dependency, while independent factors display high driving power with low dependency. The outcomes of this classification, as revealed through the MICMAC analysis, are illustrated in Figure 2.

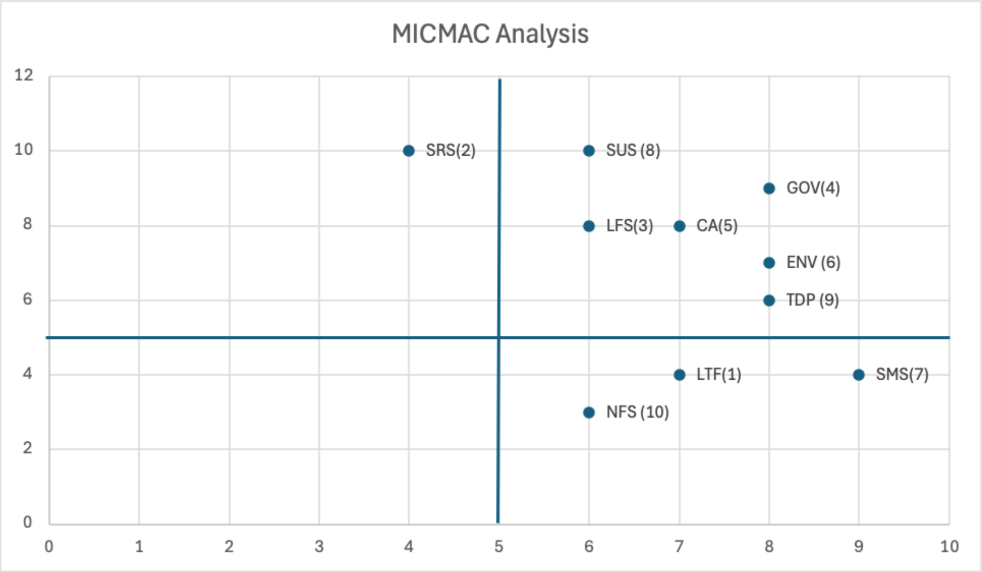

Figure 2. MICMAC Analysis

The analysis of the interpretive structural model reveals that government policies (GOV), the versatility of Spent mushroom substrate (SMS), training and development programs (TDP), and nutritional food security (NFS) emerge as the most significant enablers of MF adoption in India. They are capable of enhancing the MF adoption ecosystem through their enabling farmer training, demand-side acceptance, and by-product value addition. These factors substantially influence other enablers, particularly the low technology and flexible cultivation system (LTF), which is positioned at the second level of the hierarchy, underscoring its pivotal role. The presence of favorable policies, economic incentives, and training provisions can encourage the adoption of adaptable MF systems accessible to small-scale farmers. The localized food system (LFS) and the reduced environmental impact of the production process (ENV) occupy the third tier, reflecting their supportive but comparatively less dominant influence. The ecological and societal benefits these factors offer can be realized only when higher level factors are effectively implemented.

The output from the MICMAC analysis also supports the results from ISM. It reveals that low technology requirements, a flexible farming system, high nutritional food security, and versatile usage of spent mushroom substrate are the most critical enablers influencing all other success factors. These are known as the independent factors. Further, SUS, LFS, CA, ENV, GOV, and TDP are the linkage factors in Figure 2. Linkages in the middle order are strongly influenced by independent factors. These factors have high interactions and mutual influence. Though the above MICMAC classifications are based on experts' perceptions, they offer significant analytical value as they facilitate revealing influential patterns among enablers instead of exact empirical magnitudes.

5. Implications

5.1 Practical Implications

The results highlight the critical role of government policies in facilitating large-scale adoption of mushroom farming (MF). The establishment of clear regulatory frameworks, the provision of incentives and subsidies, and the implementation of training programs and R&D initiatives are strongly recommended to promote MF as a means to achieve both economic and climate objectives. Training programs should be developed to enhance farmers' skills and capacity to extract maximum economic benefits from mushrooms and their by-products. Such interventions could address farmers' perishability risks, that impede MF adoption by promoting knowledge transfer through evidence-based practices.

Another essential part of the training module should include the versatility of spent mushroom substrate and its circular applications. Innovative packaging materials, construction materials, and other circular economy business models can be promising entrepreneurial opportunities branching out from MF, opening new economic opportunities. As reported by earlier studies, MF offers significant environmental benefits such as mitigating air pollution by reducing agricultural waste burning, and improving soil fertility (Hu et al., 2025; F. Li et al., 2020). Further, the localized production and distribution of mushrooms has the potential to minimize transportation-related greenhouse gas (GHG) emissions, further enhancing its climate mitigation benefits. Beyond environmental outcomes, mushrooms contribute to economic resilience, nutrition security, and human health, reinforcing their status as a sustainable farming choice (Ayimbila & Keawsompong, 2023). These implications pinpoint that MF is not only an agricultural innovation but a diverse strategic choice to promote sustainable livelihoods, circularity, and environmental sustainability.

5.1 Theoretical Implications

The study also offers several theoretical contributions. First, it furthers the extant literature on sustainable food systems by positioning mushroom farming as a viable option that collectively includes the environmental, social, and economic dimensions. It delineates all the enablers to MF adoption and reports the critical factors. It also demonstrates the applicability of the ISM approach in sustainable food systems. Another contribution of the study is integrating the circular economy and sustainable farming practices. It also provides a theoretical bridge between sustainability transitions literature and agri-food system innovation.

6. Concluding Remarks

The present study aims to raise awareness among policymakers, farmers, researchers, and other stakeholders about the environmental degradation caused by unsustainable farming practices. By employing the ISM-MICMAC approach, the paper identified and structured the critical success factors influencing MF adoption in India, offering a deeper analysis of their hierarchical interrelationships.

The findings highlight the significance of government policies, training and developmental programs, nutritional food security, and the versatile usage of spent mushroom substrate for meeting UNSDGs #2 (Zero hunger), #12 (Responsible Consumption and Production), and #13 (Climate Action). It also reveals the contributions of MF toward a sustainable living environment, improved soil health, and soil regeneration.

The contributions of this paper are twofold. First, it maps the complex interrelationships among the enablers through an ISM–MICMAC based framework. It provides recommendations on how targeted interventions can accelerate MF adoption. Second, it highlights how by-products from MF can be utilized by various sectors, extending its value beyond food production.

Despite promising several contributions, this study also has a few limitations. The findings are based on expert judgments that may have associated subjectivity. Furthermore, the analysis is confined to Indian contexts as the expert pool was from India, potentially limiting its generalizability to other regions with different economic, topographical, and environmental settings. Further, the methodological approach offers only a static view of interrelationships among the barriers and does not capture the time-varying dynamics associated with macroeconomic and environmental factors.

Future research can address these limitations by employing quantitative validation methods to statistically test the interdependencies identified in this study. Future studies may utilize longitudinal data to capture temporal evolution of the relationships. Further, hybrid approaches involving DEMATEL (Decision Making Trial and Evaluation Laboratory) may also be adopted to measure the strength of relationships. Experimental designs could also be developed to evaluate the practical effectiveness of MF adoption. Additionally, real-world Indian case studies can be explored to uncover context-specific barriers and best practices, while cross-country comparative studies could broaden the generalizability of findings.

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