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REVIEW ARTICLE

Opportunities and challenges in the adoption of protected technologies in horticultural crops

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Abstract

Protected cultivation techniques have the potential to significantly enhance agricultural productivity and economic security, particularly for vegetable and flower growers in India. These techniques optimize environmental conditions, improving the quality and quantity of yields. However, their adoption is hindered by high initial setup costs, technical complexities and limited awareness and training. Personal factors such as age, education level, farming experience, household size along with social and economic factors like access to extension services, cosmopolitanism, credit availability and landholding size play a key role in adoption rates. The area under protected cultivation in India has expanded to approximately 70000 hectares, highlighting the significant potential for growth. Despite this expansion, adoption rates remain moderate, with many farmers failing to implement essential practices, such as soil solarization and climate control systems, particularly in regions like Tamil Nadu. Practical solutions such as comprehensive training programs, region-specific adaptable polyhouse designs and strengthened extension services are crucial to overcoming these barriers. In states like Rajasthan and Gujarat, where harsh climatic conditions prevail, customized polyhouse designs tailored to local environments have successfully improved productivity. Furthermore, financial support mechanisms, including increased subsidies and accessible credit, are necessary to encourage broader adoption. There is also a need for region-specific research to develop polyhouse designs that cater to the diverse climatic conditions across India. This study aims to enhance the understanding of agricultural innovation adoption and provide actionable insights into improving the adoption of protected cultivation technologies.

Keywords

adoption barriers; climate change; protected cultivation; strategies for adoption

Introduction

Climate change, characterized by shifts in temperature, precipitation and extreme weather events, significantly threatens agricultural productivity and food security (1, 2). An effective strategy to mitigate these adverse effects is the adoption of protected agriculture (PA), which involves using controlled micro-climates to influence plant growth and development (3, 4). This practice allows for regulating temperature, humidity, light and other factors to optimize crop production, leading to healthier and higher yields.

Protected cultivation is an advanced agricultural technology that uses polyhouses, low tunnels and plastic mulching to create optimal growing conditions. These techniques regulate temperature, humidity and light, enabling the production of off-season fruits, vegetables and flowers. Unlike traditional cultivation, which is highly dependent on open-field conditions and vulnerable to weather fluctuations, protected cultivation provides controlled environments to ensure better pest management, higher yields and improved quality (5). As of 2023, the global area under protected cultivation of horticultural crops was approximately 623302 hectares, with China contributing the largest share at 45 % (5, 6). The development of protected cultivation began in China and expanded significantly in the 20th century with commercial-scale greenhouses in the Netherlands (7).

In contrast, India's adoption of protected cultivation remains comparatively limited, estimated to cover approximately 0.5 % of the global area (8). India's foray into high-tech protected farming started with the Indo-Israel project on greenhouse cultivation at the Indian Agricultural Research Institute (IARI) in 1998. This collaboration established the Centre for Protected Cultivation Technology (CPCT) in 2004, advancing various protected structures and production technologies (9).

Despite its potential, the adoption rate in India is constrained by high initial investment costs, fragmented landholding patterns and limited awareness among farmers. However, Protected cultivation in India has shown promise, particularly in producing off-season vegetables, high-quality cut flowers, medicinal plants and nursery seedlings (10). The range of crops grown under protected cultivation includes flowers like Rose, Gerbera, Chrysanthemum and Carnation; vegetables such as tomato, capsicum, cucumber, broccoli, red cabbage, leafy vegetables and radish; fruits like strawberry; and various types of seedlings and nursery plants (11).

Climate control and cost categorize three main types of protected cultivation structures: high-tech polyhouses, semi-climate-controlled greenhouses and naturally ventilated greenhouses (8).

High-tech poly houses

Hi-Tech Polyhouses are advanced and cost-intensive structures equipped with automated irrigation, fertigation and climate control systems. They use components like evaporative cooling pads, exhaust fans, sensors and motorized plastic walls, all managed through computers. These structures are ideal for high-value crops like exotic vegetables and cut flowers. Despite high production efficiency, their adoption is limited due to the significant cost (6, 12). A detailed illustration of the fully controlled greenhouse is provided in Fig. 1.

Semi climate-controlled greenhouses

These greenhouses feature a galvanized iron frame, evaporative cooling pads, exhaust fans and poly film covering for climate regulation. Optional shading nets control light intensity. They are cost-effective and suited for vegetable cultivation in low- and mid-hill regions of North India, with installation costs at half of the fully climate-controlled greenhouses (13). A detailed illustration of the semi climate-controlled greenhouse is provided in Fig. 2.

Fig. 1. High-tech poly house.

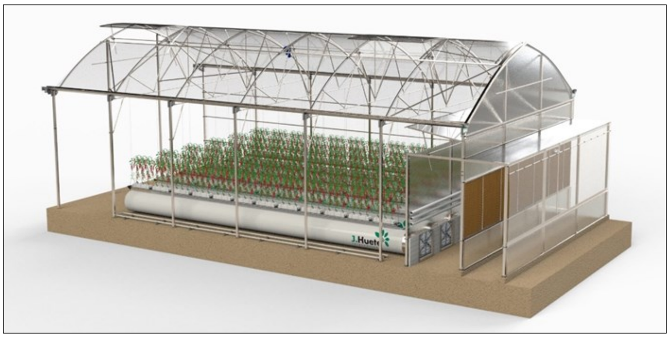

Fig. 2. Semi climate-controlled greenhouses.

Naturally ventilated greenhouses

Naturally ventilated greenhouses, the most common among Indian farmers, are simple, cost-effective structures with frames made of galvanized iron pipes, wooden logs, or steel pipes. They do not include heating or cooling systems but rely on natural airflow through side and roof vents for ventilation. The structure is covered with polyfilm and insect-proof netting may be used to protect crops. These greenhouses are affordable, with initial costs less than half that of semi-climate -controlled greenhouses (6,14,15). A detailed illustration of the naturally ventilated greenhouse is provided in Fig. 3.

To promote the adoption of advanced cultivation methods, the Government of India has implemented various schemes to support protected cultivation infrastructure and practices. The National Horticulture Board (NHB), established in 1984, has played a pivotal role in this endeavor. During 2022-23, NHB supported 201 projects focused on flowers and vegetables under protected conditions, providing a subsidy of ₹6,762.323 lakh and covering an area of 356.11 acres (16). The National Horticulture Mission (NHM), launched in 2005, has also achieved significant progress in protected cultivation. Between 2005-06 and 2017-18, NHM brought a total area of 2.19 lakh hectares under protected cultivation (17). The Mission for Integrated Development of Horticulture (MIDH), introduced in 2014, continues to strengthen the adoption of

Fig. 3. Naturally ventilated greenhouses.

protected cultivation across India. In Himachal Pradesh, MIDH and its predecessor, the Macro Management Scheme, brought 6.71 hectares under polyhouses by integrating protected cultivation into horticultural activities. Similarly, in Jammu & Kashmir, 19.33 hectares were covered under protected cultivation during 2015-16 with financial assistance of ₹477 lakhs. In Sikkim, the scheme covered 415.96 hectares under protected cultivation while training 48835 farmers in advanced horticultural techniques, highlighting its comprehensive capacity-building approach (18). The Rashtriya Krishi Vikas Yojana (RKVY), launched in 2007, has also significantly contributed to the development of protected cultivation. For instance, 7 polyhouses and 8 shade houses were erected in Karnataka, covering 12654 m^2 as demonstration units for high-value horticultural crops. Additionally, 689 training programs were conducted for farmers in 2017 (19). Despite these government initiatives and subsidies, the adoption rate of protected cultivation remains low due to challenges such as high initial investment costs, lack of technical guidance and insufficient awareness among farmers (20,21).

This review aims to assess the adoption levels, challenges, strategies for improving adoption and opportunities of protected vegetable and flower cultivation in India. It also provides a comprehensive understanding of protected cultivation practices and their potential for enhancing agricultural productivity and economic security.

Materials and Methods

A comprehensive literature synthesis was conducted by retrieving peer-reviewed publications, reports and newspaper articles from a wide-ranging database. The search strategy focused on identifying relevant literature about adoption, challenges, strategies and opportunities associated with protected cultivation, as well as climate-specific, crop-specific and area-specific structures, technologies, varieties and market requirements, including the benefit-cost ratio (B:C ratio). Web-based search engines such as Scopus and Google Scholar were utilized to procure literature encompassing studies, case reports and reviews published. Keyword combinations including 'Greenhouse' or 'Polyhouse', 'Protected Cultivation' and 'Adoption', 'Protected Cultivation' AND 'Impact', 'Protected Cultivation' and 'Challenges', 'Climate -specific Protected Cultivation' and 'Crop Varieties' and 'B: C ratio' were employed to ensure comprehensive coverage of the topics. 98 papers, reports, books, news articles, dissertations and websites were analyzed to support this review. Furthermore, for analysis, software such as NVIVO was used to create word clouds, Python programs were used to depict network maps and MS Excel was used to create charts.

Results and Discussion

Adoption of protected cultivation technologies in India

Adoption is a decision to continue the full use of innovation(22, 23). The adoption of protected cultivation has expanded significantly, with the number of participating states and union territories increasing from 9 to 30 between 2007-08 and 2012-13. This growth can be attributed to the phased implementation strategy employed nationwide. The area devoted to protected cultivation in India presently stands at approximately 70000 hectares (8). Notably Andhra Pradesh, Gujarat, Maharashtra, Haryana, Punjab, Tamil Nadu and West Bengal emerged as consistent contributors to the expansion of protected cultivation between 2007 and 2012. Maharashtra and Gujarat, in particular, recorded substantial cumulative areas of 5730.23 hectares and 4720.72 hectares, respectively, by 2012, (4). According to the Ministry of Agriculture and Farmers' Welfare (2021), Andhra Pradesh ranks first in the area under protected cultivation with 5142 hectares, followed by Karnataka (4152 hectares), Chhattisgarh (3666 hectares) and Gujarat (3075 hectares), among others. Detailed state-wise data on the area covered under protected cultivation during 2020-2021 is presented in Fig. 4.

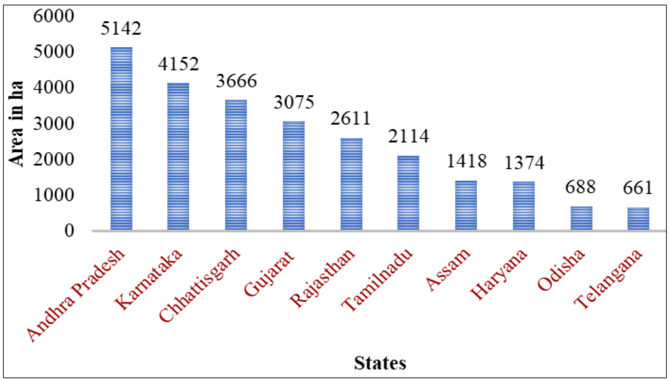

Fig. 4. State-wise details of the area covered under protected cultivation under MIDH during 2020-2021. (98).

Numerous studies have observed that most farmers exhibited a medium level of adoption regarding protected cultivation practices. For instance, it was found that all the farmers adopted the micro irrigation components of the protected cultivation technology, but all the farmers did not adopt other components (24). Comparable trends were also observed in another study (25). The probable reason for this medium level of adoption may be attributed to the farmers' limited knowledge regarding the different technologies involved in protected cultivation. Another investigation found that most respondents belonged to the partial adoption category regarding the cultivation practices of tomato and capsicum under shade net, with no farmers adopting the recommended tomato cultivar (26). These studies collectively highlighted the utmost importance of designing more extension activities, such as demonstrations, study tours and exposure visits, to convince farmers to fully adopt the recommended practices of protected cultivation technology.

There are significant gaps in the adoption of technology -protected cultivation practices. In Punjab, capsicum and cucumber growers did not follow soil solarization practices, which are important for controlling pests and improving soil health (27). Additionally, many capsicum, tomato and cucumber growers did not adopt recommended sowing practices, reducing crop productivity (27). Farmers in Krishnagiri, Tamil Nadu, did not adopt necessary climate control practices in greenhouses, which are crucial for maintaining optimal growing conditions (28). Similarly, in Maharashtra, many greenhouse operators failed to install essential systems like exhaust fans, mist cooling systems and hygrometers for humidity control, which are critical for ensuring healthy crops and good yields (29). To address these issues, it is important to promote awareness and training on recommended practices, enhance access to affordable technology and provide financial support to facilitate the adoption of necessary systems. The lack of adoption of such practices could be attributed to various factors.

Factors influencing the adoption of protected cultivation practices

In recent years, innovative technologies have been developed worldwide, offering solutions for almost every field. It remains uncertain whether the innovations will reach all communities. Even at a high level of awareness, there are different reactions to different technologies. The adoption time varies vastly and is influenced by numerous factors, including the technology's characteristics and those of the adopter. Numerous studies have utilized various models to analyze how and why the different factors influence adoption (30, 31). Over the years, several theories and models have been developed to explain the factors influencing technology adoption, as summarized in Table 1.

By synthesizing all these theories and models, (30) the factors affecting technology adoption were categorized into four groups: Personal attribute-related factors, social factors, economic factors and technology-related factors. Factors influencing the adoption of protected cultivation practices are given in Table 2.

In accordance with Fig. 5, among the 18 authors, the majority (55.6 %) cited annual income as a crucial component in implementing protected farming techniques, followed by age and education (50 %), household size and access to credit (44.4 %). These results highlighted the main factors influencing adoption: household size, age, education, annual income and credit availability. Factors including achievement motivation, managerial ability, marital status, technical training and cost of technology (5.6 % each) that were less commonly explored points for research gaps. To better understand the adoption dynamics in protected cultivation, future research must consider elements like technological complexity, environmental sustainability, cultural preferences, environmental influences and technology attributes.

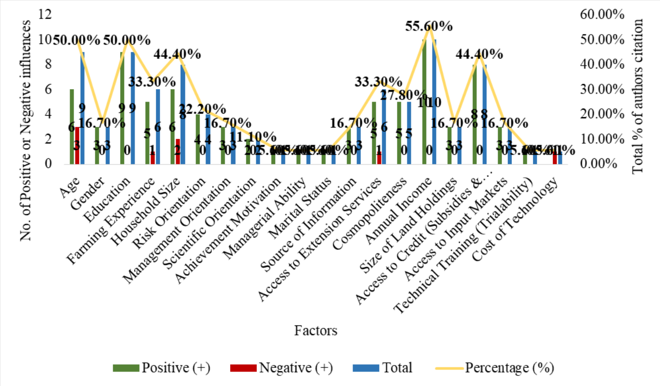

Fig. 5. Factors influencing the adoption of protected cultivation practices.

Challenges in protected cultivation practices

Protected cultivation, while offering numerous advantages, also imposes significant constraints on farmers.

Fig. 6 presents a network diagram illustrating the collaborative networks among authors and the constraints associated with protected cultivation. The diagram visualizes the number of authors who have discussed each challenge,

Table 1. Adoption models formulated to clarify technology uptake

S. No.	Theories & Models	Reference
1.	**The theory of Reasoned Action** holds that a person's behavioral intention is led by their attitude toward technology, belief about outcomes and subjective norms from others.	(63)
2.	**The theory of Interpersonal Behaviour** suggests that personal emotions, habits and situational factors constitute human behavior, highlighting how perceptions and social influences impact behavioral intent and change in three stages.	(64)
3.	**The Innovation-Decision Process** is divided into five stages of knowledge, persuasion, decision, implementation and confirmation stages that lead an individual from awareness to reinforcing their choice to adopt or reject an innovation.	(22)
4.	**The Technology Acceptance Model (TAM)** combines the Theory of Reasoned Action toward elaborating how technology characteristics influence the acceptance of information technologies within individuals.	(65)
5.	**Social Cognitive Theory (SCT)** highlights the interaction of personal factors, cognitive abilities and environmental influences in behavioral change, especially in technology use.	(66)
6.	**The Theory of Planned Behaviour (TPB)** indicates that behavioral intention is affected through attitude, subjective norms and perceived control, which influence adoption in agriculture, health and education.	(67)
7.	**The Decomposed Theory of Planned Behavior (DTPB)** refine TPB by explaining how attitude, subjective norms and perceived behavioral control affect behavioral intention and adoption.	(68)
8.	**Diffusion of Innovation** theory outlines adoption stages (understanding, persuasion, decision, implementation, confirmation). It classifies adopters (innovators, early adopters, early majority, late majority, laggards) in an S-shaped curve, illustrating innovation spread in a social system over time.	(69)
9.	**The Final Version of Technology Acceptance Model** includes external factors affecting perceived usefulness's behavioral intention and ease of use.	(70)
10.	**TAM 2** extends the model based on user perceptions of technology's usefulness that go through three stages of adoption, concentrating on task-technology fit and both voluntary and mandatory contexts.	(71)
12.	**The Unified Theory of Acceptance and Use of Technology** identifies four key factors, performance expectancy, effort expectancy, social influence and facilitating conditions, influencing technology adoption behavior.	(72)
11.	**Technology Readiness** explains consumers can be placed into five categories based on their responses to the questionnaire: explorers, pioneers, skeptics, paranoids and laggards.	(73)
13.	**The Expectancy Livelihood Model (ELM)** applies the livelihood approach to technology adoption, focusing on vulnerability and five capital sources that inform strategies related to rural development.	(74)
14.	**Perceived Characteristics of Innovating Theory (PCIT)** contribute to the diffusion of the innovation model through voluntariness, image and behavior and underline how observability and demonstrability affect adoption rates.	(75)
15.	**Compatibility UTAUT (C-UTAUT)** combines compatibility beliefs within the UTAUT model and this model further emphasizes that work style, practices, experience and values influence technology adoption.	(76)
16.	**The Basic Model of Human Behaviour with Technologies** integrates users, technologies, activities and effects to explain technology adoption.	(77)

Table 2. Factors influencing the adoption of protected cultivation practices

S. no.	Factors	Influence (+/-)	Hypothesis	Reference
		Personal Factors		
1	Age	Positive	Age influences the adoption of protected cultivation in a dual manner. Older farmers may adopt it positively due to accumulated wealth, greater landholdings and the financial stability to invest in high-cost technologies. On the other hand, younger farmers are often more likely to adopt these practices due to their openness to innovation, better access to technical education and a higher willingness to take risks.	(26)
		Positive		(78)
		Positive		(79)
		Negative		(80)
		Negative		(81)
		Positive		(24)
		Positive		(82)
		Positive		(83)
		Negative		(84)
2.	Gender	Male > Female	Male farmers are more likely to adopt protection cultivation than females since they are better endowed with resources and networks.	(85)
		Male > Female		(55)
		Male > Female		(81)
3.	Education	Positive	Education enhances the adoption of protected cultivation practices by helping farmers understand and implement advanced technologies. It also enables farmers to align their cultivation methods with market demand, improving profitability and sustainability through informed decisions on crop selection, production and marketing.	(86)
		Positive		(87)
		Positive		(29)
		Positive		(26)
		Positive		(88)
		Positive		(89)
		Positive		(24)
		Positive		(83)
		Positive		(90)
4.	Farming experience	Positive	Farmers with longer years of experience in farming have more chances of adopting the protected cultivation practices.	(86)
		Positive		(31)
		Positive		(26)
		Positive		(88)
		Positive		(81)
		Negative		(84)
5.	Household size	Positive	Most authors found that larger household sizes enhance the adoption of protected cultivation by providing essential labour. However, Binuomote (2021) (47) and Dias *et.al.,* (2020) (43) reported a negative influence, as larger households may perceive greenhouse investments as risky, potentially affecting family welfare.	(22)
		Positive		(78)
		Positive		(88)
		Positive		(80)
		Positive		(81)
		Positive		(24)
		Positive		(84)
		Negative		(82)
6.	Risk orientation	Positive	Farmers who have a greater ability to take on risks are likely to adopt protected cultivation due to their willingness to try new things.	(26)
		Positive		(87)
		Positive		(55)
		Positive		(90)
7.	Management orientation	Positive	Management orientation influences adoption positively as it steers Strategic decision and provision of new technologies to be used in agricultural practices.	(87)
		Positive		(26)
		Positive		(88)
8.	Scientific orientation	Positive	Scientific orientation drives adoption by prioritizing evidence-based decision-making and integrating	(26)
		Positive		(88)
9.	Achievement motivation	Positive	Achievement motivation propels farmers towards successful adoption of protected cultivation due to their drive for excellence.	(88)
10.	Managerial ability	Positive	Farmers possessing strong managerial skills are more inclined to implement protected cultivation, as these skills facilitate planning, resource allocation and informed decision-making.	(87)
11.	Marital status	Positive	Marital status positively influences the adoption of protected cultivation, as married farmers pursue stable income to ensure family welfare.	(84)
		Social factors		
12.	Source of information	Positive	Information sources significantly enhance the adoption of protected cultivation, since access to diverse information channels facilitates technology implementation.	(87)
		Positive		(29)
13.	Access to extension services	Positive	Access to extension services was determined to have positive effects on the adoption of protected cultivation by most authors. However, a negative effect was noted because farmers mostly depend on private organizations to implement protected cultivation practices (46).	(26)
		Positive		(91)
		Positive		(26)
		Positive		(88)
		Positive		(80)
		Positive		(89)
14.	Cosmopoliteness	Positive	Cosmopoliteness has a positive effect on the adoption of protected cultivation, as persons with larger external contacts receive various knowledge and experiences, increasing their likelihood of adopting new practices.	(87)
		Positive		(91)
		Positive		(29)
		Positive		(84)
		Positive		(26)

Economic Factors				
15.	Annual income	Positive Positive Positive Positive Positive Positive Positive Positive Positive Positive	Higher annual income fosters adoption of protected cultivation by enabling investment in infrastructure and technology, enhancing overall technology adoption in agriculture.	(87) (29) (26) (78) (88) (89) (24) (83) (90) (82)
16.	Size of land holdings	Positive Positive Positive Positive Positive	Adoption of protected cultivation is positively impacted by larger land holdings since they give farmers greater resources and flexibility, as well as the ability to finance initial expenditures in protected buildings.	(86) (81) (83) (85) (55)
17.	Access to credit (Subsidies & loans)	Positive Positive Positive Positive Positive Positive	Access to credit, including subsidies and loans, enables farmers to invest in protected cultivation by alleviating financial constraints, thus promoting sustainable growth.	(26) (80) (89) (83) (90) (82)
Technological factors				
18.	Access to input Markets (Protected cultivation materials)	Positive Positive Positive	Access to input markets for protected cultivation materials facilitates the adoption of protected cultivation by providing essential supplies, overcoming logistical barriers and reducing costs, thereby enhancing productivity.	(85) (80) (83)
19.	Technical training	Positive	The adoption of protected cultivation is strongly impacted by technical training because it increases farmers' trust in the technology through practical application.	(55)
20.	Cost of technology	Negative	The high cost of technology limits adoption since it may discourage farmers with little financial resources from investing in protected cultivation.	(55)

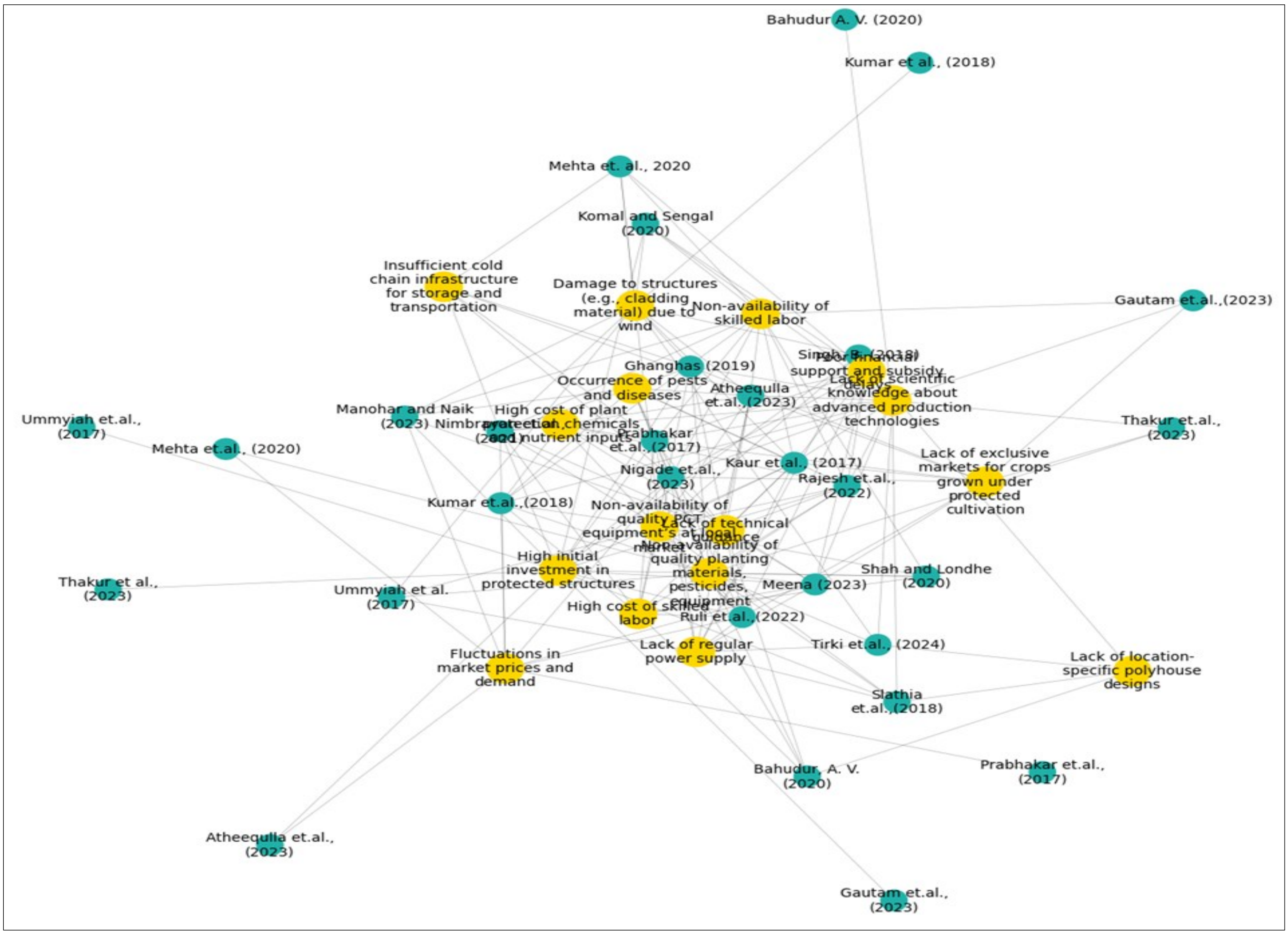

Fig. 6. Network map of major constraints and authors.

with the intensity of each issue represented by the number of connections. A higher number of connections indicates a more significant number of authors citing the particular problem. This network involves 20 authors who have highlighted various challenges in protected cultivation. Among these, the most frequently discussed issue is a high initial investment in protected structures, identified by 17 authors (32-34). High upfront costs can be particularly burdensome in regions where the market demand for protected crops is uncertain or fluctuating. 9 authors (33, 34) noted market price and demand fluctuations, further compounding the challenge of justifying the high investment. This is followed by a lack of scientific knowledge about advanced production technologies, highlighted by 15 authors (37-39) and the non-availability of quality planting materials, pesticides and equipment, also discussed by 15 authors (35, 40, 41).

Additionally, 12 authors (36, 42, 43) reported the non-availability of skilled labor, while 12 authors (44, 45) also mentioned the non-availability of quality-protected cultivation equipment in local markets. Other significant constraints include the high cost of skilled labor, noted by 11 authors (46, 47) and damage to structures (e.g., cladding material) due to wind, discussed by 11 authors (48, 49). Furthermore, a lack of technical guidance was identified by 11 authors (50, 51). Ten authors (35, 44) discussed the lack of regular power supply and the occurrence of pests and diseases. Only four authors highlighted the lack of location-specific polyhouse designs (38, 52), underscoring the need for more studies on polyhouse construction tailored to local environmental and climatic conditions.

Strategies to improve the adoption of protected cultivation

Various strategies have been identified to enhance the adoption of protected cultivation technologies that address farmers' multifaceted challenges. However, it is crucial to recognize that the practical implementation of these strategies on the ground without ensuring market demand may face limitations. Strategies to improve adoption include improving farmer training, developing cost-effective and climate-specific techniques, strengthening extension services and ensuring timely access to quality inputs and financial support. A flexible price policy mechanism should also address fluctuating market demand, ensuring that farmers are compensated fairly even when demand is low or unstable. It is also essential to align these efforts with market needs to make the technologies viable and sustainable. Emphasizing energy efficiency, mechanization and site-specific planning further bolsters the sustainability and profitability of protected cultivation. Additionally, targeted measures such as specialized insurance schemes, flexible pricing policies and direct marketing avenues can create a more favorable environment for farmers to adopt and benefit from these technologies. A detailed summary of these strategies is presented in Table 3.

NVivo's text analysis tools, such as word frequency and word cloud visualizations, are used to analyze the strategies used by different authors to enhance the adoption of protected cultivation practices. These tools provide essential insights into the significance and prevalence of specific terms or concepts, thereby improving the comprehension of the data (53).

From Fig. 7, the word cloud highlights the essential strategies to increase the uptake of protected cultivation practices. Conducting technical training programs on protected cultivation is an important approach (54), 76.7 % of adopters in Punjab benefited from training by institutions like Punjab Agricultural University and the Centre of Excellence at Kartarpur Sahib. Similarly, a report highlighted that technical training-built trust and practical skills in Kenya, enabling farmers to confidently implement these methods, leading to increased output and reduced maintenance costs (55). The development of cost-effective, climate-specific structures improves sustainability and profitability by maximizing yields in various weather situations and reducing energy costs. Expanding protected agriculture subsidies promotes the adoption of polyhouse technology by lowering its price and increasing farmer productivity and income. Farmers' confidence will be strengthened by introducing insurance programs tailored to protected agriculture, particularly for cladding material vulnerable to weather extremes like wind and hailstorms. Transparent loan and subsidy administration will increase public confidence in government programs. Providing high-quality, locally accessible planting materials for protected agriculture lessens reliance on outside resources. Furthermore, enhancing the produce's direct marketing channels enables farmers to secure larger profit margins and build enduring, direct connections with customers, which boosts income and

Fig. 7. (Word Cloud) Depiction of Strategies to improve the adoption of protected cultivation.

stabilizes the market.

Opportunities in Protected cultivation

Fig.8 clearly illustrates that Protected cultivation addresses various agricultural challenges, such as high temperatures, water scarcity, low soil fertility and excessive solar radiation, while also mitigating the risks associated with climate variability. For instance, protected cultivation enables year-round production by creating favorable microclimates in hot, arid regions like Rajasthan and Gujarat, where open-field vegetable farming yields poor-quality produce (56). It facilitates off-season and year-round cultivation, significantly increasing the production of high-value crops such as vegetables, fruits and flowers (49, 57). The controlled environment minimizes pest and disease occurrences, reduces water usage due to lower evaporation rates and enhances production quality through optimal conditions such as regulated sunlight, temperature and humidity (58, 59). In areas like the central

Table 3. Strategies to improve the adoption of protected cultivation

S. No.	Strategies	Benefits	Reference
1.	Implement comprehensive training programs for farmers of polyhouse technology and crop management.	Enhances farmers' skills, leading to higher productivity and reduced maintenance costs.	(92), (93), (48)
2.	Develop and validate cost-effective, climate-specific agro-techniques and low-cost structures for greenhouse farming, incorporating efficient microclimate management measures.	Increases sustainability and profitability by reducing energy costs and optimizing crop yields under varying weather conditions.	(92), (44), (50), (35)
3.	Develop and Implement energy-efficient, cost-effective agro-techniques tailored for diverse crops in greenhouse management.	Reduces operational costs and enhances sustainability, making greenhouse farming more profitable and eco-friendlier.	(94), (36)
4.	Create training and certification for polyhouse manufacturers to improve professionalism and skills.	Enhances the quality and reliability of polyhouse structures, fostering trust among farmers and promoting the adoption of protected cultivation technologies.	(52)
5.	Enhance agricultural extension services with appropriate materials to promote adopting polyhouse farming practices.	Facilitates access to relevant information for farmers, improving their understanding and implementation of Polyhouse techniques, leading to increased adoption and success.	(78), (86)
6.	Introduce a specialized insurance scheme covering crops cultivated under protection and polyhouse structures, particularly addressing vulnerabilities in cladding materials and wind and hail storms.	Protects investments in both crops and infrastructure, mitigating risks associated with weather-related damages and promoting confidence in adopting protected cultivation practices.	(50), (35), (36)
7.	Implement a flexible price policy mechanism for crops cultivated under protected cultivation.	Promotes market equilibrium by encouraging increased production during scarcity and curbing price volatility, which benefits both farmers and consumers.	(36), (44)
8.	Ensure timely access to high-quality, protected cultivation planting material sourced locally.	Facilitates efficient farming practices, enhances crop quality and reduces dependency on external sources, promoting agricultural self-sufficiency.	(36), (47)
9.	Boost subsidies for protected cultivation in polyhouses, leveraging locally sourced materials to lower initial investment and installment costs.	Boosting subsidies can encourage adoption among farmers. However, it may lead to long-term dependency on government support and unequal distribution of subsidies, benefiting wealthier farmers more than resource-poor ones, which could widen the adoption gap.	(36), (47), (45), (44)
10.	Promote direct and forward marketing of protected cultivation produce.	Enables farmers to bypass intermediaries, capture higher profit margins and establish direct consumer relationships, fostering market stability and increased revenue.	(36), (45)
11.	Ensure appropriate selection of location and site for polyhouse installation.	Optimizes environmental conditions for crop growth, maximizes resource efficiency and minimizes risks such as extreme weather events, enhancing protected cultivation's overall success and sustainability.	(36), (47)
12.	Implement loans and subsidies efficiently and transparently for beneficiary farmers.	Ensures fair access to financial support, reduces bureaucratic hurdles and fosters trust in government initiatives, thereby facilitating the adoption of agricultural technologies and practices like protected cultivation.	(36)
13.	Introduce mechanization and automation to tackle labor scarcity while conducting capacity development programs to enhance laborer skills.	Increases efficiency and productivity in agricultural operations mitigates labor shortages and ensures a skilled workforce capable of effectively utilizing advanced technologies, ultimately leading to improved agricultural output and profitability.	(35)

Fig. 8. Opportunities in protected cultivation.

Himalayas, productivity increases have been reported, ranging from 15.85 % to 932.20 % compared to open-field conditions. For example, semi-permanent structures in Nepal achieved a productivity of 218.87 mt/ha/year (60, 61). Crops grown under protected cultivation also command higher market prices, with capsicum and roses fetching 2-3 times more revenue than open-field conditions. Farmers in Karnataka reported a 78.40 % increase in income after adopting this technology (62). Additionally, protected cultivation creates significant employment opportunities, with labor requirements 85.45 % higher than open-field systems due to the intensive management of protected structures (32). Overall, protected cultivation not only enhances productivity and income but also ensures food and livelihood security while improving the nutritional status of rural communities.

Conclusion

This study highlights the significant opportunities and challenges associated with adopting protected cultivation in India, particularly among resource-poor farmers. While protected cultivation optimizes temperature, humidity and light conditions to improve yield quality and quantity, its adoption remains limited due to barriers such as high initial setup costs, technical complexities and a lack of awareness and training among farmers. Unlike previous studies, this review emphasizes the influence of socio-economic and regional factors on adoption rates and underscores the need for region-specific, climate-resilient solutions. The findings reveal that hands-on, practical training programs, the development of low-cost and locally adaptable structures and strengthened agricultural extension services are crucial for improving adoption rates. Financial support mechanisms, including enhanced subsidies, accessible credit facilities and targeted insurance schemes, are essential to mitigate financial constraints.

To further enhance adoption and sustainability, future research should explore integrating sustainable energy solutions, such as solar power and using automation to improve efficiency in protected cultivation systems. Moreover, developing cost-effective greenhouse designs and microclimate management techniques tailored to India's diverse agro-climatic zones will ensure long-term sustainability. By focusing on these actionable recommendations, the adoption and sustainability of protected cultivation can be significantly improved, leading to improved farmer livelihoods, increased food security and greater resilience to climate change.

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Authors' contributions

MS Conducted the primary literature review, synthesized findings and drafted the manuscript. ND Supervised the study, provided guidance in framing the article and reviewed the manuscript critically for intellectual content. RP Assisted in the collection and organization of relevant literature. SKA Provided inputs on technical aspects of protected cultivation. GD Provided technical inputs and contributed to refining the manuscript. GV helped in editing and assisted in final manuscript review.

Compliance with ethical standards

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