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Review Article

A COMPREHENSIVE REVIEW OF LOW-COST POLYHOUSES: INNOVATIONS AND IMPACTS ON HORTICULTURAL PRODUCE

R R Mhade*, H T Jadhav and A N Malathi

AICRP-Plastic Engineering in Agriculture Structures and Environment Management (PEASEM)-Dapoli Center, College of Agricultural Engineering and Technology, Dr Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli-415 712, India

ABSTRACT

To reduce the initial costs associated with polyhouse construction and to foster protective cultivation among rural smallholder and marginal farmers, the development of low-cost polyhouses is imperative. A significant body of research has concentrated on enhancing the affordability of polyhouse structures through the use of bamboo and other locally sourced materials for their frameworks. Our analysis indicates that the construction costs of various naturally ventilated bamboo polyhouses are approximately 50% to 60% lower than those of conventional galvanized iron (GI) pipe polyhouses. This review provides a comprehensive examination of low-cost polyhouses employed for crop production, emphasizing their frame and cladding materials, environmental control mechanisms, and associated economic benefits.

Keywords: Bamboo polyhouse, Economic analysis, Naturally ventilated polyhouse, Smallholder farmer

Vegetables cultivated under open field conditions face numerous adverse natural events, including heavy rainfall, strong winds, hailstorms, and insect infestations, all of which significantly impact crop productivity and quality. Additionally, extreme environmental factors such as temperature, relative humidity, and light intensity can further diminish crop yields. Protective cultivation methods, particularly greenhouse cultivation, create optimal environmental conditions that enhance crop yield and quality, enabling year-round production essential for maintaining a consistent market supply (Singh *et al.*, 2003; Singh *et al.*, 2005). Among the various factors influencing plant growth within a greenhouse, carbon dioxide (CO_2) levels and photosynthetically active radiation (PAR) are two of the most critical variables.

Greenhouses can generally be categorized into two types based on their height: high-rise and low-rise. High-rise greenhouses are advantageous for natural ventilation, effectively maintaining the internal environment with minimal reliance on artificial mechanical systems. However, they are often challenging to manage and more costly to construct. Additionally, their design presents limitations in regions prone to strong winds. In contrast, low-rise polyhouses are more cost-effective and offer enhanced stability against high winds, making them particularly suitable for tropical areas. Nonetheless, maintaining the internal environment in low-rise structures can be challenging, especially when temperatures rise during the non-monsoon season. In hot and humid coastal regions, characterized by more uniform and less extreme climates, low-rise polyhouses can be effectively utilized for the cultivation of vegetables, leafy greens, and grafted plants, as well as for drying various agricultural products.

Low-rise and low-cost polyhouses present a viable alternative for protecting crops from severe climatic events. However, a specific definition for low-cost polyhouses is lacking in the existing literature. In this article, we define low-cost polyhouses as structures that utilize alternative cost-effective frame materials in place of traditional metal components. This review summarizes relevant literature with this definition in mind. According to NICRA (2024) and Jadhav and Rosentrater (2017a), low-cost polyhouses commonly employ locally sourced bamboo or wood as construction materials to reduce overall costs. Therefore, any polyhouse whose construction cost is lower than that of prevailing regional or traditional structures can be classified as a low-cost polyhouse. Typically, low-cost polyhouses do not incorporate mechanical systems for artificial environmental control. Consequently, during winter months, collapsible side curtains are fully closed at night to retain warmth, while in summer, these curtains are opened during the day to facilitate air circulation and lower internal temperatures.

Between the 15th and 19th centuries, wood and bamboo were the preferred materials for constructing greenhouse structural frames. However, these materials were later replaced by galvanized iron (GI) pipes and channels, which enhanced the durability of greenhouse

*Corresponding author: rushikeshmhade@gmail.com
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constructions but also significantly increased costs (Bhatnagar, 2014). Additionally, the incorporation of advanced environmental control systems further elevated the capital investment required for greenhouse operations. Consequently, one of the primary barriers to the widespread adoption of greenhouse technology among farmers is the high initial capital cost associated with both the greenhouse structure and the necessary environmental control systems. To address this issue, the construction of low-cost polyhouses is essential to facilitate protective cultivation for smallholder and marginal farmers. Once these farmers experience the advantages of protected cultivation, they may be encouraged to invest in more robust structures featuring GI pipe frames, which typically offer a longer lifespan of 20 to 25 years.

This article reviews low-cost naturally ventilated polyhouses that offer limited options for internal environmental control. For instance, bamboo frames in such polyhouses can have a lifespan of 15 to 25 years (Janssen, 2000). The primary objective of this review is to analyze existing literature in order to inform the development of improved low-rise bamboo polyhouses specifically designed for hot and humid regions, particularly in tropical coastal areas. The review encompasses available literature on low-cost greenhouses, focusing on frame materials, cladding options, environmental control measures, and their associated economic benefits.

Low cost greenhouses

The naturally ventilated bamboo polyhouse (Fig. 1) was developed to reduce the capital costs associated with galvanized iron (GI) greenhouses in the hot and humid climate of the Konkan region in India. It has been reported that the construction cost of the bamboo polyhouse is approximately 72% that of the GI polyhouse (Jadhav and Rosentrater, 2017a). The Konkan landscape is characterized by hilly terrain, uneven surfaces, and irregular shapes (Bhattacharyya *et al.*, 2021), compounded by small landholdings and poor socio-economic conditions among farmers. These factors pose significant challenges to the construction of large-area polyhouses. Consequently, naturally ventilated polyhouse structures ranging from 50 m^2 to 100 m^2 have been adopted by progressive farmers in this region for vegetable cultivation and graft nursery production, even under challenging weather conditions marked by high rainfall and humidity. Several researchers have focused on making these structures more cost-effective for the specific agro-climatic conditions of Konkan. For instance, Sanap *et al.* (2022) constructed a bamboo polyhouse (Fig. 2) with an area of 128 m^2 as an entrepreneurship model for a nutri-garden in the Palghar district of the Konkan region, Maharashtra. The construction cost of this bamboo polyhouse, including drip irrigation installation, was ₹ 704 per m^2, while the prevailing cost of a GI polyhouse was ₹ 2,885 per m^2—nearly four times higher than that of the bamboo alternative.

Furthermore, Das *et al.* (2016) developed a low-cost polyhouse for the hillock region of Assam specifically for tomato production, achieving a setup cost that was 45.68% lower than the local price of metal polyhouses. Similarly, Gopi *et al.* (2019) designed a cost-effective polyhouse (Fig. 3) for the semi-arid tropics of Telangana, aimed at reducing installation costs and facilitating polyhouse cultivation among rural smallholder and marginal farmers. Their polyhouse construction cost was reduced by 52.4% compared to traditional metal polyhouses of similar sizes. Numerous researchers have also explored low-cost solar greenhouses tailored for hilly and cold arid climatic conditions. These cold arid regions are typically located at high altitudes, experiencing cool summers and extremely cold winters. In India, such areas fall under the trans-

Fig. 1. Naturally ventilated bamboo polyhouse constructed at Dapoli (Konkan region, India) (Source: Jadhav and Rosentrater, 2017a).

Fig. 2. Bamboo polyhouse constructed at Palghar, Maharashtra (Source: Sanap *et al.*, 2022)

Himalayan zone, including Ladakh (J&K), Lahaul & Spiti (HP), and certain remote regions of Uttarakhand (Niti and Garhwal). High-tech greenhouses are rarely found in Ladakh due to the region's severe electricity shortages (Wani *et al.*, 2011). The lean-type Ladakhi polyhouse, a common greenhouse design (Fig. 4), measures approximately 10 m × 5 m, with a back wall height of 2 m. Its structure typically comprises mud-brick walls on three sides (two end walls and one side wall), with polyethylene film supported by wooden or bamboo poles (Singh *et al.*, 2000). Another economical option is the trench-type greenhouse (Fig. 5), which is particularly suitable for high-altitude hilly regions. This underground structure has the lowest cost among greenhouse types, exhibiting low heat loss and high temperature retention (Singh and Dhaulakhandi, 1998). Additionally, low plastic tunnels are utilized to enhance crop production in regions facing semi-severe winters (Fig. 6). Reddy and Reddy (2016) also noted that shade houses equipped with high-density polyethylene (HDPE) shade nets, providing shading effects between 25% and 90%, serve as an alternative low-cost crop production method. While shade nets do not offer rain protection, shade houses can effectively safeguard crops from hailstorms depending on their design. Moreover, a naturally ventilated low-cost greenhouse constructed with bamboo and local wood materials was utilized for the production of cut flowers, such as gerbera and carnation, in the North-Western Himalayan ranges. Ranjan *et al.* (2013) reported that flowers produced in these low-cost greenhouses exhibited superior quality compared to those grown in open field conditions.

To reduce polyhouse costs, Edke (2001) developed various bamboo-based low-cost greenhouses, with the construction cost of an Edke-type bamboo polyhouse being approximately 50% that of a galvanized iron (GI) polyhouse. These greenhouses are designed to withstand wind velocities of up to 120 km/h. Additionally, Edke secured patents for his innovative bamboo-based greenhouse design from both the Indian and Chinese governments. Arupratan (2014) further advanced this field by creating an eco-friendly, energy-efficient, and low-cost naturally ventilated polyhouse using bamboo. It has been reported that bamboo polyhouses are comparable to traditional GI greenhouses in terms of cleanliness, durability (approximately 10 years), and overall functionality, requiring only slightly more maintenance.

Many researchers have focused on developing cost-effective greenhouses tailored to African agro-climatic conditions, aiming to alleviate food insecurity and malnutrition. Thipe *et al.* (2017) noted that in southern Africa, two popular greenhouse configurations

Fig. 3. Developed bamboo polyhouse for Telangana semi-arid tropics (Source: Gopi *et al.*, 2019)

Fig. 4. Ladkhi greenhouse (Source: www.thebetter india.com)

Fig. 5. Trench type greenhouse (ideal trench size: 10 m x 3 m x 1 m) (Source: Singh *et al.*, 1998)

Fig. 6. Low plastic tunnels (Source: Singh *et al.*, 1998)

have emerged: the affordable and energy-efficient naturally ventilated structures, which are limited in their ability to manage heat loads in arid or semi-arid climates, and the more expensive fan-pad evaporatively cooled greenhouses. In East Africa, the first low-cost greenhouse prototype was constructed in Nyeri, Kenya, in 2010. Following this, two distinct affordable greenhouse designs were field-tested in Tanzania, and an additional two prototypes were built in Nairobi in 2012. These prototypes were constructed using Polypropylene Random Copolymer Type 3 (PPR) pipes, significantly enhancing affordability (Pack and Mehta, 2012).

The low-cost polyhouses discussed above also have certain limitations. Notably, these structures are generally not designed or analyzed for specific windstorm conditions, with the exception of the work by Sanap *et al.* (2022). To enhance their robustness, it is essential that polyhouses be designed with local wind patterns in mind. Additionally, the overall strength of these low-cost polyhouses depends significantly on the methods used to join structural members. The joints of alternative materials, such as wood and bamboo, should be standardized and carefully designed to accommodate the forces experienced by the structure. Moreover, the lifespan of alternative framing materials in low-cost polyhouses is often shorter than that of metal counterparts. This lifespan can be further diminished if the framing material is not chosen according to established guidelines. For instance, in the case of bamboo, selecting mature bamboo aged 3 to 4 years, along with appropriate chemical treatments (IS 15912, 2018), is crucial for ensuring longevity and durability.

Structural and claddings details for the low-cost polyhouses

1. Frame material

The construction cost of polyhouses is primarily influenced by the materials used for their frames and the climate control systems employed (Bhatnagar, 2014). To develop a low-cost polyhouse, it is essential that the structural components of the frame are inexpensive, readily available locally, and easy to work with during construction. Many researchers have explored the use of bamboo as a framing material for low-cost polyhouses. Rather than purchasing commercially treated bamboo, sourcing mature bamboo (approximately 3 years old) directly from producers and then chemically treating it can enhance its longevity and overall quality. However, the selected bamboo varieties must also be sufficiently robust to withstand high wind pressures, as well as resist corrosion, weathering, and dampness associated with the local climate. Consequently, utilizing these specific bamboo varieties as an alternative to costly galvanized iron (GI) framing can effectively reduce greenhouse costs (Sanap *et al.*, 2022; Bhatnagar, 2014; Das *et al.*, 2016; Jadhav and Rosentrater, 2017a).

Jadhav and Rosentrater (2017a) developed a low-cost polyhouse structure utilizing locally available bamboo. To protect the bamboo columns from ground dampness, they placed annular PVC pipe shells around the bases where the columns made contact with the foundation concrete. The gap between the bamboo and the PVC shell was subsequently filled with fine sand-cement mortar. For assembly, they employed nut bolts and flat metal strips to secure the structural bamboo frame. In a similar vein, Gopi *et al.* (2019) applied coal tar to the lower sections of wooden columns to shield them from soil dampness and prevent decay. These coal tar-coated columns were then wrapped with 1000-gauge black LDPE film, secured using polypropylene ropes. Additionally, they utilized welded GI pipes and nut bolts to connect the various members of the bamboo polyhouse. For their greenhouse columns, Sanap *et al.* (2022) selected bamboo of the variety-*P. Madhavi*, with a diameter of 55 ± 3 mm and a wall thickness of 15 mm. For the other structural components, such as rafters, purlins, and the bottom chord, they chose bamboo with a diameter of 49 ± 3 mm and a minimum thickness of 12 mm.

A critical consideration regarding alternative frame materials for low-cost greenhouses is their lifespan. Treated bamboo frames can last between 15 to 25 years (Janssen, 2000), making them a viable option for sustainable greenhouse construction.

2. Cladding material

The efficiency and productivity of a greenhouse are significantly influenced by the choice of covering material. Key factors to consider when selecting a covering material include cost, durability (lifespan), weight, ease of repair or replacement, light transmission, and insulation properties. Standard materials used for greenhouse covers encompass fiberglass, glass, plastic sheets and films, as well as single or double layers of polyethylene films (Reddy and Reddy, 2016). Fiberglass cladding materials present recycling challenges and have the lowest light transmissivity among greenhouse coverings. Nonetheless, they are often employed in hot and arid regions to minimize energy transmission and maintain a cooler internal climate (Bakochristou *et al.*, 2019). While glass greenhouses excel in temperature retention, their high initial costs and installation complexities limit their adoption for profitable commercial crop production, particularly in developing countries. In response to these challenges, polyhouses—greenhouses utilizing polyethylene as cladding material—have emerged as a viable alternative to glass greenhouses, offering reduced installation costs and ease of use (Jadhav and Rosentrater, 2017b).

In recent decades, the adoption of low-cost plastic greenhouses has surged globally, significantly surpassing the use of glasshouses. This trend can be attributed to the lower cost of plastic compared to other greenhouse cladding materials (Castilla *et al.*, 2004). Von Elsner *et al.* (2000) reported that in Mediterranean European Union countries, which fall within the temperate zone, the prevalence of plastic-covered greenhouses (including high tunnels) exceeds 95%—with figures reaching 99% in Spain, 98% in Portugal, 95% in Greece, and 91% in Italy. In contrast, the adoption rate in Northern European Union countries is notably low, with only 2% in the Netherlands and Denmark, 5% in Belgium, and 10% in Germany. Considering other significant temperate zones, Japan, which was a global leader in greenhouse area, had 40,259 hectares in 1983, increasing to 52,571 hectares by 1997, with 96% of this total greenhouse area covered in plastic (Ito, 1999). In China, the area dedicated to greenhouses grew dramatically from nearly nonexistent in 1980 to approximately 177,000 hectares of mainly lean-to-type greenhouses and 186,000 hectares of high tunnels by 1996, while the area under glasshouses remained minimal at just 60 hectares (Zhibin, 1999). In summary, the types of cladding materials used across various climate zones are detailed in Table 2.

Covering materials for greenhouses must be transparent to allow sufficient photosynthetically active radiation (PAR) to reach plants, while also trapping heat during colder weather and shielding plants from external environmental conditions. Additionally, multilayer plastic sheets offer enhanced mechanical properties; however, their thickness can impact PAR transmittance (Guan *et al.*, 2017). The optical and energy characteristics (Table 1) of greenhouse covering materials are crucial as they influence heat transfer, infrared (IR) and ultraviolet (UV) absorbance or transmittance, and radiation control (Oz *et al.*, 2017; Zhang *et al.*, 2017; Alkitab *et al.*, 2019). Beyond the inherent properties of the cladding materials, several factors influence the selection of covering materials, including the energy requirements of the plants, resistance to photo-oxidation (Hao and Papadopoulos, 1999; Kittas *et al.*, 2006; Anton *et al.*, 2014), budget constraints, and greenhouse design considerations—such as the type of greenhouse based on shape and specific climatic conditions (Bakochristou *et al.*, 2019; Subin *et al.*, 2019). Furthermore, environmental sustainability plays a vital role in the decision-making process (Rorrer *et al.*, 2019; La Mantia, 2010).

In the modern history of greenhouse development, Dr. Emery M. Emmert has made significant contributions toward reducing greenhouse costs. In 1948, he successfully constructed a greenhouse using plastic as the covering material, replacing traditional glass (Bhatnagar, 2014). Since then, numerous researchers have adopted 200-micron polyethylene sheets as the covering material for low-cost polyhouses (Sanap *et al.,* 2022; Jadhav and Rosentrater, 2017a; Bhatnagar, 2014; Das *et al.*, 2016; Gopi *et al.*, 2019). Additionally, Singh and Dhaulakhandi (1998) reported the use of double layers of polyethylene films to cover trench-type greenhouses in the Ladakh region, effectively preventing heat loss during winter nights.

Hao and Papadopoulos (1999) conducted a comparative analysis of various greenhouse covering materials, including D-poly, acrylic, and glass, concluding that glass is the most suitable covering for cultivating cucumbers. On the other hand, Kittas *et al.* (2006) found that eggplants exhibited the fastest growth and developed the most robust canopies in greenhouses covered with 0% UV plastic sheets. Over time, greenhouse covering materials can accumulate dirt and deteriorate, leading to a reduction in light penetration. The accumulation of dust and algal growth on plastic films further diminishes radiation

Table 1. Optical and energy properties of greenhouse covering materials (Kittas and Baille, 1998)

Type of material	τPAR (%)	ρPAR (%)	αPAR (%)	τNIR (%)	ρNIR (%)	αNIR (%)	Q (%)
Glass	84	6	10	73	7	20	83
Low-density polyethylene film (LDPE)	83	8	9	87	8	5	85
Thermal polyethylene film (TPE)	83	8	9	85	9	6	84
Bubbled polyethylene plastic film (BPE)	63	14	23	68	14	18	63
Ethylene-vinyl acetate (EVA)	89	8	3	89	7	4	89
Three-layer (3L) coextruded film comprising of EVA and TPE	86	8	6	88	7	5	86
Violet colored polyvinylchloride based film (VPVC)	39	8	52	74	10	16	39

τ-energy transmission; ρ-energy reflectance; α-energy absorption; Q-quantum transmission; PAR- photosynthetically active radiations (400-700 nm); NIR- near-infrared wavelengths (700-1100 nm).

Table 2. Benefit cost ratios of different crops grown under naturally ventilated low-cost greenhouses and the frame and cladding material used for different climate zones

Region/ State (Zone)	Crop grown under greenhouse	B:C ratios for the crops grown in the greenhouses	Construction costs of the greenhouses INR (₹) per m²	Crop yields (kg) per m²	Frame materials used	Cladding materials used	References
Konkan, Maharashtra, India (Hot and humid climate, Tropical)	Capsicum	1.27	674.25	8.31	Bamboo	Polyethylene	Sanap *et al.* (2022)
	Chili			3.44			
	French bean			3.13			
	Tomato	1.67	485.24	50	Bamboo	Polyethylene	Jadhav and Rosentrater (2017a)
		1.92	674.14		metal		
Assam (hot & humid climate), India (Sub-tropical)	Tomato	1.06	62.5	4.76	Bamboo	Polyethylene	Das *et al*. (2016)
Uttarakhan, India (Sub-tropical)	Vegetable peas, squash, and tomato	between 1.64 to 2.2	86	-	Bamboo	Polyethylene	Bhatnagar (2014)
	Bell pepper	2.56	-	8.89	GI pipe	Polyethylene	Debbarma *et al.* (2017)
Meghalaya, India (Sub-tropical)	Capsicum-tomato-lettuce	2.1	156.40	-	Bamboo	Polyethylene	Bhatnagar (2014)
	Tomato-French bean-cabbage,	1.7		-			
Gujrat, India (Tropical)	Cucumber	1.36	-	10.76	-	Polyethylene	Sanjeev *et al.* (2015)
Karnataka, India (Tropical)	Capsicum	1.80	820	10.56	GI pipe	Polyethylene	Murthy *et al.* (2009)
	Cut flower (carnations)	2.50	-	-	-	-	Tarannum and Hemlanaik (2014)
	Capsicum	3.92	-	-	GI pipe	Polyethylene	Sreedhara *et al.* (2013)
Kerala, India (Hot and humid climate, Tropical)	Cucumber	3.42	-	8.9	-	-	Chand (2014)
Bihar, India (Sub-tropical)	Capsicum-Brinjal-Cucumber	3.53	-	10.09	GI pipe	Polyethylene	Udit *et al.* (2020)
Telangana, India (Tropical)	Cucumber	3.0	-	8.3	-	-	Padmaja *et al.* (2022)
Spain (Mediterranean)	Cucumber	-	-	-	Metal	low-density Polyethylene	Lorenzo *et al.* (2005)
North China (Temperate)	Cucumber	-	-	51.24	-	0.1 mm thick Polyethylene	Liu *et al.* (2021)

transmission. Additionally, condensation, manifested as water droplets on the covering material, can also obstruct light. To address these challenges, many manufacturers have developed light-diffusing materials, such as cloudy white plastic films, which scatter incoming light more effectively than clear plastic films. This innovation results in improved light conditions, fostering better growth for crops.

Environmental and economic analysis

1. Environment inside the low cost polyhouse

In low-cost polyhouses, the implementation of closable side vents and a ridge vent—typically kept open—serves as an effective means of environmental management, offering a more affordable and energy-efficient alternative to forced ventilation systems

(Salokhe and Sharma, 2006; Jadhav and Rosentrater, 2017b). Naturally ventilated polyhouses function optimally in climates that are neither excessively hot nor cold. However, in extremely hot regions, the temperatures required for optimal plant growth may not be achievable. To mitigate elevated temperatures within the polyhouse, guidelines recommend that the area of side vents should comprise at least 20% of the total floor area, while the top vent should account for a minimum of 10% of the overall polyhouse area (NHB, 2011). Additionally, the side curtains should overlap the bottom apron (skirting) by at least 0.2 meters to prevent direct airflow during nighttime. Depending on the specific crop and local climatic conditions, the bottom apron should be positioned between 0.6 meters and 1.5 meters above the ground to effectively trap CO_2.

In general, low-rise naturally ventilated polyhouses exhibit temperature ranges that are 5-7 °C higher than those in open field conditions. Isaac (2015) reported that the average temperature within a polyhouse measuring 16m × 6m × 4m varied from 27 °C to 34 °C, with soil temperatures ranging from 30 °C to 32 °C and relative humidity levels between 75% and 88% during evaluations of leafy vegetable performance in such environments. Additionally, Gill (2018) measured maximum and minimum light intensities of 56.67 klux and 43.85 klux, respectively, in March and December under naturally ventilated polyhouses. Singh and Sirohi (2006) observed significantly higher productivity for tomatoes (93.20 t/ha) and capsicum (76.40 t/ha) grown inside these polyhouses. This increased productivity can be attributed to the elevated temperatures (4-9 °C higher than outside) recorded between December and February, as well as the enhanced utilization of carbon dioxide within the greenhouse environment. Similarly, Ranjan *et al.* (2013) noted that the maximum temperature in a 100 m² naturally ventilated bamboo polyhouse (20 m × 5 m) during November to March reached 16 °C, which was 4 °C higher than the maximum temperature of 12 °C observed in open field conditions in the Kumaon hills of Uttarakhand, India. The polyhouse featured a central height of 3.5 m and side heights of 2.0 m.

Sanap *et al.* (2022) investigated the variations in microclimatic conditions within two naturally ventilated bamboo polyhouses, each covering an area of 128 m² and featuring a ridge height of 4.52 m. One polyhouse (Polyhouse 1) was equipped with a top vent covered by an insect-proof net, while the other (Polyhouse 2) had a fully open top vent. The maximum temperature recorded inside Polyhouse 1 was 40.1 °C, compared to 39.8 °C in Polyhouse 2, with the ambient temperature at 38.6 °C. Notably, the maximum temperature difference reached 2.8 °C in Polyhouse 1 at 11:51 AM, while a difference of 1.6 °C was observed in Polyhouse 2 at 1:54 PM. Both polyhouses are situated in the same climatic region—the west coast plains and hills of the Konkan region—highlighting the influence of structural design on internal temperature management.

Further research conducted at the Dapoli Center under the AICRP-PEASE scheme in the Konkan region (DBSKKV, Dapoli, Maharashtra) revealed that the low-rise bamboo polyhouse (LRBP), with a gutter height of 2 m and a ridge height of 3.5 m, recorded a maximum temperature of 42.18 °C in February. In contrast, the low-rise bamboo polyhouse without cladding material (LRBP-WCM), which had the polyethylene cover removed but retained an internal movable shade net, reached a maximum temperature of 36.46 °C in May. This study found a temperature difference of 6 °C, with the LRBP exhibiting higher temperatures compared to the LRBP-WCM (Mhade, 2022).

In the Mediterranean climatic zone, effective heating is crucial for creating a favourable microclimate for greenhouse crops. In Turkey, Canakci *et al.* (2013) estimated the total annual heat requirements for gothic-roofed plastic greenhouses, which ranged from 3,592,848 to 10,459,688 MJ/ha when using coal as a fuel source; however, the authors did not specify whether the greenhouses utilized natural or mechanical ventilation systems, such as fan-pad types. In Southeast Spain, the energy needed to heat a low-cost parral-type naturally ventilated polyhouse was measured at 62 W/m² during a low heating level in February 1997. This was necessary to maintain greenhouse temperatures between 17 °C and 18 °C while the outside temperature fluctuated between 8.5 °C and 12 °C. In contrast, a higher heating level of 134 W/m² was required in March 1998 to sustain temperatures between 24 °C and 28 °C when external temperatures ranged from 10 °C to 17 °C (Baille *et al*., 2006). This heating was achieved using a mobile air-convection system with an integrated propane burner that discharged exhaust gases directly into the greenhouse. Additionally, Lopez *et al.* (2002) compared various air heating strategies for greenhouse-grown snap beans in a low-cost plastic “parral” greenhouse during the winter months of November 1998 to March 1999. The strategies included T_{12}, which maintained a constant night temperature of 12 °C; $T_{14}T_{12}$, which heated to 14 °C during the vegetative stage and 12 °C thereafter; $T_{14\text{-}12}$, which used a split night temperature of 14 °C in the first half and 12 °C in the latter half of the night; and T_{14}, which maintained a constant night temperature of 14 °C. The study, conducted in specially created compartments within the parral-type greenhouse, found that heating energy consumption was highest for the T_{14} strategy (250 MJ/m²) and lowest for T_{12} (120 MJ/m²), with the other two strategies showing similar consumption (~180 MJ/m²). The authors concluded that the $T_{14}T_{12}$ heating strategy is the most advantageous for greenhouse farmers, as it consumed 30% less energy while providing similar yields and early growth compared to T_{14}, alongside a higher heating energy efficiency of 63 MJ/kg.

2. Economic analysis

Sharma *et al.* (2014) conducted a study involving 60 polyhouse growers, including 27 small farmers and 33 large farmers, randomly selected from two blocks in Mandi district, Himachal Pradesh, India, to highlight the progress and benefits of protected cultivation. The majority of the participants were small and marginal farmers. The authors reported that the average areas dedicated to protected cultivation were 228 m² for small polyhouse owners and 673 m² for large polyhouse owners, with corresponding capital investments of INR 2,80,000 and INR 7,60,000, respectively. Notably, the findings indicated that profitability was higher among small farmers, possibly due to superior management practices adopted in these smaller units. Furthermore, the study revealed that protected cultivation has begun to make a significant contribution to gross farm income in the region.

According to a case study on tomatoes and capsicums conducted by Murthy *et al.* (2009), polyhouse technology serves as an effective method for off-season vegetable cultivation, helping to mitigate biotic and abiotic stresses. This approach has become a specialized production technique designed to address challenges posed by pests and environmental conditions while also breaking through seasonal production barriers. Polyhouse cultivation ensures year-round production of high-value vegetables, such as capsicum, particularly during off-peak seasons. Moreover, numerous researchers have noted the profitability of off-season nursery and vegetable production under low-cost polyhouses, primarily due to their relatively low initial construction costs (Sanap *et al.*, 2022; Gopi *et al.*, 2019; Jadhav and Rosentrater, 2017a; Das *et al.*, 2016). Similarly, the cultivation of high-value off-season vegetables in low-cost protected structures has been identified as a viable technology for successful winter vegetable production with temporary protection (Yadav *et al.*, 2014). The benefit-cost ratios of various crops grown under naturally ventilated polyhouses are summarized in Table 2. Overall, polyhouse cultivation not only increases productivity but also enhances the quality of vegetables, making it a widely adopted practice in over fifty countries worldwide.

CONCLUSION

The construction of naturally ventilated polyhouses using bamboo as a framing material and plastic for covering significantly reduces costs compared to traditional galvanized iron (GI) or metal polyhouses. Additionally, the use of mud, bricks, and polyethylene film supported by wooden or bamboo poles, commonly referred to as Ladakhi polyhouses, offers a feasible solution for farmers in hilly and cold arid climates to cultivate vegetables. Similarly, trench-type greenhouses provide a cost-effective and efficient option for high-altitude regions. Moreover, the establishment of low-cost polyhouses lowers the initial investment required, making protective cultivation accessible to rural smallholder and marginal farmers. The off-season cultivation of nursery plants, leafy greens, and high-value vegetables under these low-cost polyhouses is increasingly recognized as a sustainable practice, particularly in developing countries like India. This approach not only facilitates successful vegetable production but also enhances crop productivity and improves vegetable quality by enabling better environmental control within the polyhouse.

Low-cost polyhouses represent a transformative approach to vegetable cultivation, particularly in regions facing climatic and economic challenges. Their ability to create controlled microclimates not only enhances the productivity and quality of high-value crops, but also offers a viable solution for off-season production. The evidence from various studies highlights the significant benefits that polyhouse technology provides, especially for small and marginal farmers who can leverage these systems to improve their income and food security.

As the global agricultural landscape continues to evolve, the adoption of low-cost polyhouses can play a crucial role in addressing pressing issues such as climate change, resource scarcity, and the need for sustainable farming practices. Future research should focus on optimizing design, improving energy efficiency, and exploring innovative management practices to further enhance the effectiveness of these structures. By promoting the widespread implementation of low-cost polyhouses, we can pave the way for a more resilient and productive agricultural sector that meets the demands of a growing population while ensuring environmental sustainability.

Authors' contribution

Conceptualization of review paper work (RRM and HTJ); Preparation of manuscript (RRM, ANM, JHT).

Conflicts of interest

The authors declare that they have no conflicts of interest.

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