Shelterbelt and Windbreak Research in Arid India: A Review of Research Advances and Future Directions

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ABSTRACT

Shelterbelts and windbreaks play a crucial role in enhancing agricultural productivity and environmental sustainability, particularly in arid regions where harsh climatic conditions pose significant challenges to land use. In India, where a substantial portion of the landscape is characterized by dry, aridand semi-arid conditions, the strategic implementation of windbreaks can mitigate soil erosion, reduce evaporationand enhance microclimatic conditions for crops. Globally, research in this area has gained momentum as the impacts of climate change intensify, further exacerbating the vulnerabilities of these fragile ecosystems. In India, the technology was practiced diligently to control movement of sand dunesand to stop desertification extending further from the Thar desert. By integrating native tree species and adopting region-specific management practices, studies have shown that shelterbelts/ windbreaks can significantly improve soil fertility and crop yield, while also providing habitats for biodiversity and other ecosystem services. Furthermore, the socio-economic benefits for local communities, such as improved livelihoods and resilience against climatic extremes, underline the importance of windbreak research in these regions. This review aims to synthesize existing knowledge on windbreak and shelterbelt practices in India's arid landscapes, highlighting successful cases, trends in research and potential pathways for future research. By examining the multifaceted benefits of these ecological structures, we aim to provide a comprehensive understanding of their role in promoting sustainable agricultural practices and enhancing resilience in vulnerable communities and opening vistas for future research.

Key words: Arid zone, Desertification, Research, Shelterbelt, Trends.

Climate plays a crucial role in agricultural productivity, making it unsurprising that intentional microclimate modification has existed as long as agriculture itself. One technology for this, is the introduction of windbreaks and shelterbelts. According to UNCCD, shelterbelts are "Belts of trees, planted in a rectangular grid pattern or in strips withinand on the periphery of, farmland to act as windbreaks." These are essential agroforestry practices grouped under the agri-silviculture system that offer numerous environmental, social and agricultural benefits, particularly in arid, semi-arid and also coastal regions including reduction of wind speed, minimizing damage caused by high-velocity winds, decreasing soil erosion, reduction of temperature, soil water loss and transpiration; and overall creation of favorable microclimates especially in harsh conditions for crop production. Windbreaks that provide shade and shelter have been utilized to create more productive microclimates and have significant potential to enhance livestock and pasture. They also act as alternate habitats for wildlife and birds. Consequently, planting tree windbreaks is regarded as an effective strategy to combat land degradation and improve agricultural output. The windbreaks or shelterbelts are also known by other terms depending on its purpose as hedgerows or vegetated environmental buffers or living snow fences. According to Gupta (1997), a shelter belt is a longer barrier than a wind break and is typically made up of trees and plants; while wind break is any kind of barrier used to protect against winds. Though both terminologies 'shelterbelts' and 'windbreaks' are used in different studies across India, for the purpose of this review, all the terms are used synonymously, as also concluded in the study by Ramanan *et al*. (2022).

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Standardization of shelterbelt technology started after the United Nations launched the Plan of action to Combat Desertification (PACD) programme in 1977, keeping in view the growing problem of desertification globally (Harsh and Tewari, 1997). In literature, the concept of protecting agricultural fields from wind can be traced back to the mid-

15th century when the Scottish Parliament encouraged farmers to plant trees within their farm boundaries to shield their crops (Droze 1977). In the 1930s, the importance of shelterbelts became particularly evident after the severe dust storms of the Dust Bowl, which blanketed the Great Plains of the USA in dust, dirtand sand. The Great Plains Shelterbelt was a project to create windbreaks in this region, that began in 1934, initiated by President Franklin D. Roosevelt and led by the U.S. Forest Service. Similar shelterbelt and windbreak programs have emerged in various countries, including government led programs like Australia's National Windbreak Programme in 1993and China's 'Three Norths Forest Shelterbelt' program stating in 1978 (Ramanan *et al*., 2022). trainings on windbreak/shelterbelt establishment such as the online courses provided by the Minnesota Board of Water and Soil Resources US, publication series such as Shelterbelts for livestock farms in Alberta: planning, planting and maintenance by the Alberta Government and even private players such as the Prairie Shelterbelt Program, Canada. The studies on shelterbelts/ windbreaks have been done since long in several countries. Literature review leads us to conclude that major research works published on shelterbelts/ windbreaks are from China (55%), followed by the USA (9%) as per Web of Science database.

In India, work on shelterbelts for reduction of wind erosion gained momentum with the establishment of the 'Desert Afforestation Research Station' at Jodhpur in 1952 by the Government of India, fearing the spread of the desert to areas like the national capital, Delhi (Yadav, 2018). In India, where approximately 33% of the land area is classified as arid or semi-arid, the implementation of these shelterbelts/ windbreaks is vital for mitigating the adverse effects of wind erosion, improving soil moisture retentionand enhancing crop yields. From this, spread throughout the states of Rajasthan (61.9%), Gujarat (19.6%), Haryana and Punjab (8.6%)andhra Pradesh (6.8%), Karnataka (2.7%) and Maharashtra (0.4%) (Fig 1), the hot and arid region of India spans approximately 31.7 million hectares (Mertia *et al*. 2006; Meghwal *et al*. 2022). Characterized by extreme temperatures (0-50°C), low (100-400 mm) and variable rainfall (CV>50), high wind speeds, low humidityand frequent droughts, combined with the light sandy soil's limited water retention capacity and deficiency of nutrients, agricultural production in the hot arid zone is limited and risky. In arid zones, especially in northwestern regions, from March through September, there is a significant wind pattern that includes strong, dusty winds in May, June and July. According to Prasad *et al*. (2009), the area's highest daily wind velocity often reaches 30-45 km/hr in June and July, with peak winds reaching up to 100 km/hr

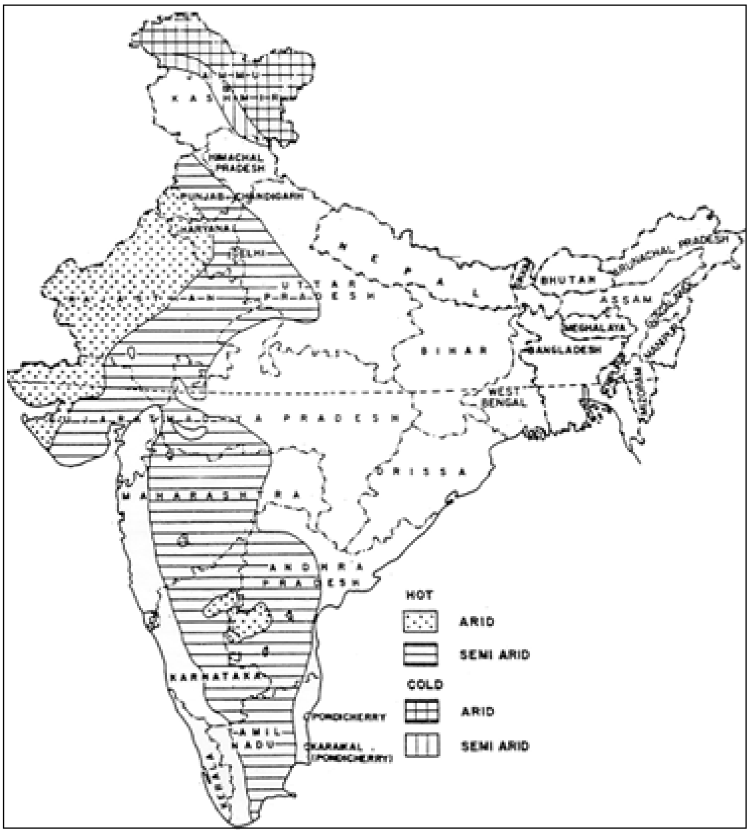

Fig 1: India's arid and semi-arid zones (From Rao *et al*., 1997).

during severe dust storms. Strong winds bury agricultural fields and obstruct highways with the deposition of flying soil particles, while also taking away fertile topsoil and inflict irreversible losses in production.

Shelterbelt research in India began to increase in prominence around the 1960s, initiated by Bhimaya *et al*. (1958), Bhimaya and Chowdhari (1961), Raheja (1963) and Ganguli and Kaul (1969) who recommended different types of shelterbelts for fields and road side plantations mainly in the arid areas of Rajasthan (Gupta, 2000). This period saw increased awareness of the importance of shelterbelts in controlling wind erosion, improving microclimatesand enhancing agricultural productivity, especially in arid and semi-arid regions. With the major contribution of micro windbreak construction, CAZRI has been developing sand dune stabilisation techniques since 1961. The Forest Department of Rajasthan has stabilised over 90,000 hectares of land with this technology (Harsh and Tewari, 1997). Mertia *et al*. (2006) in studies done in hyper arid Jaisalmer region of Rajasthan reports the beneficial role of shelterbelts in lowering air temperatures, increasing humidity and reducing evapotranspiration, besides improving soil organic carbon.

The role of shelterbelts and windbreaks in the arid, semi-arid and coastal zones is unmatched. This review synthesizes research done on windbreaks and shelterbelts established for agricultural purposes in India and particularly the arid regions from 1958 to present, showcases few successful case studiesand outlines future research pathways.

Methodology

A comprehensive search for relevant studies was conducted using Web of Science and Google Scholar. The search terms included windbreaks and/or shelterbelts; with keywords ‘crop’, ‘growth’ ‘soil’ and ‘arid’. Studies conducted in India, as per WoS was only 2%. When we filtered the studies to include only those conducted in India and published in English, using Web of Science, we got only 6 publications. Hence, Google Scholar was further used for obtaining relevant research.

Importance of windbreaks and shelterbelts

Recognizing the irreplaceable role of shelterbelts and windbreaks in the rehabilitation of denuded arid and semi-arid lands in Rajasthan desert, Bhimaya and Kaul (1960) reports the progress in research towards this end including species selection and suitable afforestation techniques going on at Desert Afforestation and Soil Conservation Station, Jodhpur. According to IPCC report (2021), climate models project that the Earth’s average global temperature could rise by an additional 4°C (7.2°F) in the twenty-first century. Climate change, is also expected to cause great variations in temperature and also affect type, frequency and intensity of extreme weather events (Patel *et al*., 2023), such as heat waves, rainfall fluctuations, dust storms, cyclones *etc*. which are more serious in the case of arid, semi-arid and coastal areas. Some studies indicate that by 2050, certain regions may experience a 5-20% rise in temperature and rainfall from December to February, while seeing a decrease in rainfall of the same magnitude between June and August (Hulme *et al*., 2005). These temperature increases are expected to negatively affect most crops, especially in arid regions. Smallholder farmers, lacking financial and irrigation resources, might turn to natural systems to gain ecological benefits as a strategy to mitigate the uncertainties posed by climate change. Agroforestry systems, such as shelterbelts, characterized by their diverse components, can enhance resilience of the farming system (Bhimaya *et al*. 1958; Gupta, 2000). These windbreaks can create more suitable microclimates moderating high velocity winds and extreme temperatures and shielding the understorey from the adverse weather during the day; while at night, the canopy helps retain warmth, safeguarding crops from frost damage in winter. In agricultural systems, windbreaks enhance crop quality and marketability by minimizing crop damage from wind-blown particle abrasion and preventing fruit from rubbing against other plant parts during strong winds. They also facilitate increased honey bee foraging during high winds (Hennessy *et al*., 2020) and shelter livestock during adverse weather (Sheetal *et al*., 2020). Moreover, these systems help mitigate soil erosion, improve water-use efficiency and improve soil fertility (Prajapati *et al*., 2024).

In coastal areas, creation of shelterbelts can disperse the energy of the waves, check ingress and flooding debris to a significant leveland reduce the chances of severe consequences (Dobhal *et al*., 2024). A very long, properly designed and successful shelter belt was planted in 1964 along the sea coast of Orissa in east India, which was found very effective against coastal land degradation by hurricanes, cyclones and super cyclones (Samra, 2020).

Windbreaks are also valued for their broader ecosystem services, which extend beyond the farm. These benefits include enhanced biodiversity, carbon storageand mitigate greenhouse gases (Chavan *et al*., 2023; Manasa *et al*., 2022; Mayrinck *et al*., 2019). In addition, the system yields various outputs, including food, fuelwood, fodder, fertilizerand timber, which collectively enhance farm incomes through improved and sustained productivity (Sheetal *et al*., 2020). The diverse benefits and year-round production of by-products provided by trees planted in windbreaks help mitigate the risk of crop failure, a common issue in monocropping systems, especially in the arid zones. Additionally, incorporating trees into agricultural farms promotes more efficient nutrient recycling, as deep-rooted trees improve nutrient retention on-site while reducing surface runoff and nutrient leaching (Prasad *et al*., 2013).

Review of available literature on research done on shelterbelts or windbreaks is summarized in Table 1. Only those research papers have been considered which had data on crop yields, or water use or wind velocity and other related parameters.

Table 1: Work done on shelterbelts/ windbreaks over the years in India (Note: H is the average height of the shelterbelt).

Shelterbelt/windbreak details	Place of study	Results	Reference
3 row shelterbelts of *Prosopis julijlora-Albizia lebbeck-P. julijlora, Cassia siamea-A. lebbeck-C. siamea* and *Acacia tortilis-Albizia lebbeck-A. tortilis*	Jodhpur, Rajasthan	Studies on the effects of 8-year-old shelterbelt plantations indicate a general reduction in wind velocity, wind erosion and evaporative loss of moisture from fields protected shelterbelts.	Gupta *et al.*, 1983
Tree height and survival among tree species (*C. siamea, A. tortilis, P. juliflora, A. lebbeck*) planted in shelterbelt	Rajasthan	After 7 years (1973-80), *C. siamea* had maximum height (6.5 m) and survival of 79% *A. lebbeck* showed maximum survival (96%)	Muthana *et al.*, 1984
Microshelterbelts of tall annual plants (Bajra)	Jodhpur, Rajasthan	3 rows of pearl millet as shelterbelt increased yield of cowpea and okra crops in order of 21 and 44%, over unsheltered crop in summer. In addition, the sheltered field provided an additional remuneration of Rs. 1,600/ha from bajra fodder.	Gupta *et al.*, 1984
Closely spaced single rows of *Acacia tortilis or A. nilotica var. cupressiformis* to protect orchards	Jodhpur, Rajasthan	Inward row of fruit crops like gonda or lasoora (*Cordia dichotoma*), karonda (*Carissa carandas*), tamarind (*Tamarindus indica*) can be planted for effectiveness.	Dass, 1984
Shelterbelt system of *Cassia siamea* + *Albizzia lebbek vs. Acacia tortilis* + *A. lebbek*	Jodhpur, Rajasthan	*C. siamea* + *A. lebbek* system more efficient in reducing wind velocity than *A. tortilis* + *A. lebbek* Decrease of 5-14% in pan evaporation values at 2H distance Soil moisture content higher in 0-30 cm depth in *C. siamea*+ *A. lebbek* Mean loss of 547 kg ha^{-1} soil from bare field reduced to 351, 300 and 184 kg ha^{-1} by *P. juliflora- A. lebbeck, A. tortilis-A. lebbeck* and *C. siamea-A. lebbeck* shelterbelts, respectively Total nutrient loss was also found to be maximum from bare soil without shelterbelt.	Gupta *et al.*, 1984
Micro wind breaks on sand dunes	Rajasthan, India	Local material like *Leptadenia pyrotechnica, Zizyphus nummularia, Calligonum polygonoides, Lasiurus Panicum turgidum, Eriantus munja.*	Kaul, 1985
Water use efficiency and crop yield with shelterbelt	India	WUE ranged from 1.5-5.6 kg/ha/mm; lowest at 5H and highest at 25H. Bajra yield with and without the sheltered area was 6.8 and 4.8 q/ha, respectively.	Chandrasekharaiah, 1987
Three row shelterbelt of *Cassia siamea -Albizia lebbek-Cassia siamea*	Jodhpur, Rajasthan	36% and 46% reduction in wind speed at 2H distance during summer and winter, respectively.	Gupta and Ramakrishna, 1988
Three row shelterbelt of *Cassia siamea -Albizia lebbek-Cassia siamea*	Jodhpur, Rajasthan	8-12% reduction in evaporation from sheltered area at 2H distance and 20-30% higher pearl millet yield.	Gupta and Ramakrishna, 1988
Shelterbelt along IGNP canal	Jaisalmer, Rajasthan	1 and 2-yr old plantations on windward side of canal reduced sand deposition by 0.513 m^3 and 1.023 m^3 per	Upadhyaya, 1991

Table 1: Continue...

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		running metre length of the canal, respectively; saving desilting cost by Rs. 6,156 and Rs. 12,276 per kilometre per year, respectively. plantations respectively.	
Effect of shade by windbreaks on mandarin fruit quality	Abohar, Punjab	Fruits under partial or complete shade were larger, higher juice content and more acidity.	Monga *et al*., 1992
Windbreak of 18-yr old *Dalbergia sissoo*	Haryana	Windspeed reduction by 15-45% Cotton yield increase by 4 to 10% Leaf number and area, plant height and yield higher in sheltered area as compared to open fields	Puri *et al*., 1992
8-year-old *Eucalyptus tereticornis* shelterbelts	Chandigarh	Economic yield of chickpea, lentil, wheat, cauliflower, berseemand toria in a 12-m-wide strip to the south of shelterbelt reduced by more than half, maximum reduction being in chickpea. Content of soil phytotoxins was maximum in the litter-free top soil surface, compared to that at 30 or 60 cm depths, at all distances from the tree line. Maximum content of phytotoxins was found at 1 m from the tree line for all depths.	Singh and Kohli, 1992
Micro-shelterbelts in arable lands using tall and fast-growing plants like castor on the windward side	Jodhpur, Rajasthan	Shorter plants like vegetables in the leeward side of tall plants helped to increase the yield of lady's finger by 41% and of cowpea by 21%, over the control.	Venkateswarlu, 1993
Single row plantation of Acacia nilotica	Haryana	Yield reduction due to trees up to 15 m distance was 37.8, 49.0, 40.6 and 34.4% in *T. aestivum, T. alexandrinum, C. arietinum* and *G. hirsutum,* respectively. Suggested that small holder farmers should not grow crops in association with *A. nilotica* trees under arid conditions.	Puri *et al.* 1994
Boundary planting of poplar (*Populus deltoides*)	Hoshiarpur, Punjab	Yield reduction in wheat crop was 29, 19, 18 and 17 per cent in northern, southern, eastern and western aspects, respectively at 2 m from the base of the poplarine. Average reduction up to 20 m was 8.7% in northern direction whereas in others, the reduction varied from 11-14%.	Thind and Dhillon, 1995
Microshelterbelt of raya	Hisar, Haryana	Maximum wind speed reduction (69.2%) observed with intercropping of raya and gram at 4H distance compared to 1:1 pure gram field. Relative humidity was 8-15% lesser and temperature was higher by 1-2°C in sheltered gram compared to pure gram.	Singh *et al*., 1996

Table 1: Continue...

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Shelterbelts of two-row belts of *Populus deltoides* and *Dalbergia sissoo*	Chandigarh	Wheat yield deleteriously affected in initial 0-3 m block in the fields sheltered by poplar compared to those sheltered by shisham. In poplar sheltered fields reductions in crop density, biomass and yield up to 9-12 m from tree line.	Singh *et al.* 1999
Boundary planting of poplar (*Populus deltoides* M.)	Baraut, Uttar Pradesh	Plantation at the boundary of wheat field caused 7.5% higher water use than control up to 3 m distance from tree line which further intensified up to 12.7% and extended up to 6 m distance with 4-yr old plantation. WUE of wheat reduced by 4.6% between 0 and 3 m distance from tree line with 3-yr old plantation, intensifying to 18.6% with 4-yr old plantation. However, WUE increased to 9% between 3 and 9 m distance from tree line.	Sharma *et al.* 2001
Eucalyptus windbreak	Hisar, Haryana	Yield attributes and grain yield of wheat increased significantly with successive decrease in shade level from 0-6 m distance to 18-24 m from tree line.	Singh *et al.* 2005
Single-row and double-row *Dalbergia sissoo* shelterbelt	Mohangarh, Jaisalmer, Rajasthan	Double row provided double the sheltered area (8H) compared to single row (4H) Improvement is soil OC and reduction in air temperature from 2H to 5H.	Prasad *et al.* 2009
Shelterbelts of *Acacia tortilis, Eucalyptus camaldulensis, Dalbergia sissoo, Tecomella undulata*	Jaisalmer, Rajasthan	Significant wind speed reduction from 21.5% to 36.0% at a distance of 2H (mostly from 2H to 10H), gradually diminishing up to 20H. Double-row shelterbelts reduced wind speed more B effectively on the upwind side, while single-row belts offered a larger sheltered area on the leeward side. Improved soil organic carbon levels, lower daily air temperatures in sheltered areas, mainly up to 5H. Generally, fairly tall (approximately 10 m) and dense (double-row) shelterbelts with an L/H ratio of 10-13 found most effective in providing protection against wind-related hazards.	Prasad *et al.* 2013
Boundary planation of casuarina windbreaks	Tiruchirappalli, Tamil Nadu	Higher average intercrop (Moringa PKM 1) yield	Buvaneswaran *et al.*, 2016
Boundary planation of casuarina windbreaks beside teak (*Tectone grandis* L. f.) rows	Tiruchirappalli, Tamil Nadu	Better height growth of teak, particularly in bund planting system and in windy localities. Self- pruning of branches in teak tree in the mid of casuarina windbreaks helps to produce clean boles of teak without knots will attract good marketing.	Buvaneswaran *et al.*, 2016

Table 1: Continue...

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Eucalyptus Bund Plantation	Hisar, Haryana r	Total biomass yield of dhaincha and barley was significantly educed up to 3 m distance from tree line in both east-west and north-south planted rows of eucalyptus. Organic carbon and available N, P and K content were significantly highest in the western aspect in 0-3 m distance and these decreased with increase in the distance.	Bhardwaj *et al.* 2017
Neem bund plantation	Yadagir, Karnataka	In pigeonpea, at 5 m distance away from the neem tree line significantly lower grain (1192 kg ha^{-1}) and biomass (5563 kg ha^{-1}) yields recorded, compared to the distances of 10 m.	Doddabasawa *et al.*, 2018
Boundary planting of poplar (*Populus deltoides*)	Hisar, Haryana	Reduction in dry matter accumulation in wheat found near tree line at a distance of 0-2 and 2-4 m. Cultivation of wheat variety HD-2967 with poplar boundary planation found more beneficial compared to other wheat varieties, towards end of poplar rotation.	Sirohi *et al.* 2021
Boundary planting of poplar (*Populus deltoides* M.)	Hisar, Haryana	Significant reduction of fodder biomass of sorghum (10-60%) and wheat yield (7.2-29.5%) observed up to 9 m from tree line, from second eight years. However, from 9 to 15 m distance from the tree line crop yields increased compared to control. Economic analysis revealed benefit of E-W popular boundary plantation giving maximum net returns of Rs.5,49,367 ha^{1}.	Chavan *et al.* 2022
Casuarina equisetifolia L. Windbreak	Navsari, Gujarat	Paddy growth and yield increased with distance from windbreak. Highest yield observed at 17 m distance. Wind velocity reduced from 4.6 to 3.3 km/hr from tree line to 17 m distance. Considerable increase soil OC (0.68%), available nitrogen (234.46 kg/ha), phosphorus (75.75 kg/ha) and potassium (398.07 kg/ha) compared to control.	Prajapati *et al.* 2024

Research landscape in shelterbelt and windbreak research

Research on windbreaks and shelterbelts in India has expanded over the last few decades, focusing on species selection, design configurationsand management practices tailored to local conditions. Initiating from the need to stabilize deserts and reduce erosion, the research focus has moved over to integration of these systems in to farming system as boundary plantations in order to harvest all benefits of the tree based ecological system, especially in the fragile north western arid and hyper-arid regions. The success of such systems depends on the species chosen, the planting geometry and pattern and management practices; which have been detailed below:

Species selection

Studies emphasize the use of native species, such as *Prosopis cineraria*, *Acacia nilotica* and *Ziziphus jujuba*, which are well-adapted to arid conditions. Research shows that mixed-species plantations outperform monocultures in terms of biodiversity and resilience. The trees, shrubsand grasses suitable for establishing a silvipastoral system include *Acacia tortilis, Acacia senegal, Prosopis cineraria, Ziziphus nummularia, Calligonum polygonoides, Acacia jacquemontii, Cenchrus ciliaris, Lasiurus sindicus*and *Cenchrus seligerus*. Additionally, the architecture and phenology of these trees are crucial factors (Singh, 1996). For instance, *Dalbergia sissoo* has a broad canopy with numerous branches and a slow rate of leaf fall, resulting in significant shading that can impact yield. This effect is most pronounced near the tree belt, where decomposing leaves may release phytotoxic chemicals through leaching or microbial processes, potentially inhibiting or delaying germination and initial growth (Kohli *et al*., 1997). Research has shown that leaf litter from *Populus deltoides* can release allelochemicals that adversely affect crops (Singh 1996; Kohli *et al*., 1997). Similarly, Soni *et al*. (2021) suspects the presence of allelopathic compounds in leaf litter of *Acacia senegal* and *Acacia tortilis* leading to reduction in mustard yields.

According to Kaul (1996), when selecting plants for afforestation, desirable species should have the following characteristics: (a) a mix of plants with deep vertical roots to access moisture from lower zones and shallow roots to utilize surface moisture after light rains, while also exhibiting a high root binding index; (b) resilience against the abrasive forces of blown sand and high wind velocities; (c) tolerance to extreme temperatures, both frost and heat; and (d) the ability to regenerate naturally.

According to Sheetal *et al*. (2020), the preference for shelterbelt species has shifted from previously preferred fast-growing species to economically beneficial timber or horticultural trees like *Dalbergia sissoo, Zyziphus mauritiana*, *etc*.

Design and configuration

The effectiveness of shelterbelts in reducing the wind velocity depends on velocity, direction of wind, site conditions and also on canopy growth, design and geometry of shelterbelts. Optimal spacing and height of windbreaks have been explored to maximize their effectiveness. For instance, staggered rows have been shown to improve wind reduction and enhance the protective benefits for adjacent crops.

Shelterbelts should ideally have a triangular cross-section or a pyramidal structure, with the tallest trees positioned in the center row, flanked by medium-height treesand bushy plants in the outer rows. To prevent tunneling effects, these trees should be planted in a staggered or zig-zag arrangement. To ensure year-round wind protection, it is essential to include both evergreen and deciduous trees in the shelterbelt. There should be adequate spacing between fast- and slow-growing trees to avoid competition. Shelterbelts established in pyramidal shape such as of *Prosopis juliflora, Azadirachta indica* and *Albizzia lebbek* as three row shelterbelt along the highways were found suitable in desert areas (Kaul, 1985). For spacing, (i) the distance between rows should be a minimum of 2.4 meters and a maximum of 7.6 to 9.1 metersand (ii) within each row, shrubs should be spaced a minimum of 0.9 meters apart, while tall trees can be spaced up to 6.1 meters apart. Shelterbelts are typically planted at right angles to the prevailing wind direction. Successful examples include shelterbelts of *Acacia nilotica* var. indica and *Dalbergia sissoo* established in the early 1960s over a length of 1-2 kilometers at the Central Mechanized Farm in Suratgarh, Bikaner district, by the Central Arid Zone Research Institute in Jodhpur. In the 1970s, three rows consisting of *Acacia tortilis*, *Cassia siamea*and *Prosopis juliflora* as flank rows, with *Albizia lebbek* as the central row, were established at CAZRI, Jodhpur.

The plantations are to be taken up after proper consideration of the tree-crop-water dynamics at the site. Lack of proper planning, a poor understanding of tree-crop interactions and the urge for rapid gains, have led to farmers facing severe economic losses. Singh and Kohli (1992) highlight the case of large-scale plantations of Eucalyptus undertaken by farmers leading to huge losses to crop.

Trends in shelterbelt research

Over the decades, research in India has evolved from basic establishment and soil conservation strategies to a broader understanding of windbreaks as multifunctional systems that emphasize sustainable cropping, biodiversityand climate resilience. These trends reflect a growing recognition of the multiple roles that shelterbelts and windbreaks play in sustainable land management. According to Table 1, the research has been mainly concentrated in the arid zone of Rajasthan, with some research also done in semi-arid parts of Haryana and Punjab. Here's an overview of trends in shelterbelt and windbreak research in India from the 1960s to the present, along with suitable references for each period:

- **Initial Studies and Implementation**

Early research emphasized the establishment of shelterbelts to combat soil erosion and wind damage, particularly in arid and semi-arid regions. The planting details of *Acacia nilotica* and *Dalbergia sissoo* shelterbelts along the roadways and railway tracks, as well as at Central Mechanised Farm in Suratgarh, were covered by Bhimaya and Chowdhari (1961). Gupta (2000) discusses the plantation of three types of shelterbelts at Jodhpur comprising of three rows: *Acacia tortilis - Albizzia lebbek - Acacia tortilis, Cassia siamea - Albizzia lebbek- Cassia siamea, Prosopis juliflora - Albizzia lebbek -Prosopis juliflora*. The central row comprised of tall growing Albizia lebbek forming pyramidal structures. Pyramid-shaped, three- or five-row shelterbelts were designed, depending on the level of wind erosion hazard utilizing above-mentioned tree species and also native shrubs (Yadav, 2018). By the 1980s, focus shifted to wind speed reduction studies due to the shelterbelts and related benefits including evaporation reduction and reduction in soil erosion (Gupta *et al*., 1983; Gupta and Ramakrishna 1988).

- **Integration into agroforestry systems**

The integration of shelterbelts into agroforestry systems gained momentum, recognizing their role in enhancing agricultural productivity and sustainability. Harsh and Tewari (1997a) discusses the plant species suitable for micro windbreaks in dune systems according to rainfall. Vashishtha and Prasad (1997) discusses the different tree, shrub, fruit trees and grass species suitable for shelterbelt plantation according to rainfall zone in horti-silvi-pasture systems.

- **Research on shelterbelt-based cropping systems**

Increased attention on using diverse and native species for shelterbelts to improve ecological balance and resilience against climate variability. The effect of use of different tree species on system, crop growth and yield, water use parameters and economics of the system were prioritized. Research towards understanding the role of shelterbelts in climate change mitigation, with an emphasis on their ability to reduce wind speed and protect crops is also emphasized. The potential of revenue through carbon capture to increase farmers' profits from agroforestry plantations is also being evaluated by current research (Singh *et al*., 2024).

Notable case studies of shelterbelt implementation

The Thar Desert, Rajasthan

In this region, the introduction of shelterbelts has been instrumental in combating desertification. With the advent of Indira Gandhi Nahar Pariyojna (IGNP) massive afforestation work on shelterbelts has been done in Western Rajasthan. According to an estimate about 278 Rkm (Running Kilometer) shelterbelts covering an area of about 9271 ha has been successfully planted in IGNP command area of Jaisalmer district (Mertia *et al*., 2006).

In a paper by Gajja *et al*. (2007), primary data was collected from 80 farmers each from shelterbelt and non-shelterbelt, selected randomly from tubewell and canal command area of IGNP Phase-II in Mohangarh tehsil of Jaisalmer district. The study found that net returns increased by 430.8% as a result of shelterbelt plantation. Of this increase, 399.4% can be attributed to the use of shelterbelt technology, while 31.4% resulted from greater use of complementary inputs. Within the 399.4% attributable to shelterbelts, 305.6% was directly linked to the transition from non-shelterbelt to shelterbelt systems, while the remaining 93.8% reflects improvements in input usage among non-shelterbelt areas, likely due to enhancements in soil properties. The results indicated that total additional employment generated by shelterbelt technology was 106.4%, of this 76.5% employment was generated by shelterbelt alone and remaining 29.9% by complementary inputs. Gajja *et al*. (2014) in another study indicated that total additional employment generated by adoption of shelterbelt technology was 106.4%, of which 76.5% employment was generated by shelterbelt alone and remaining 29.9% by complementary inputs.

Future directions and research opportunities

Despite the progress, several avenues for future research remain

Long-term Impact Studies

There is a need for long-term studies assessing the ecological and economic impacts of windbreaks and shelterbelts, particularly their effects on soil health and crop resilience over time. Studies on greenhouse gases mitigation, carbon sequestration, resource utilization and above- and below- ground interactions between the different components can be focused on. Lond term effects of the shelterbelt on biodiversity in the region are also to be monitored, especially the effect on pollinators. Research should also focus on the economic valuation of ecosystem services provided by these structures.

Integration with modern technologies

Utilizing remote sensing and GIS tools can enhance the design and monitoring of windbreaks, allowing for more precise management and assessment of their effectiveness.

Community involvement and knowledge transfer

Engaging local communities in research and implementation can facilitate knowledge transfer and ensure that practices are culturally appropriate and economically viable. Developing supportive policy frameworks that incentivize the adoption of windbreaks and shelterbelts is crucial for promoting these practices at a larger scale.

CONCLUSION

In conclusion, windbreaks and shelterbelts offer a multifaceted solution to the challenges facing arid agricultural regions in India. Their capacity to provide simultaneous economic, ecological and public benefits positions them as a strategic approach for sustainable intensification and diversification of agro ecosystems. As global discussions intensify around effective carbon sequestration, reducing greenhouse gas emissionsand adapting to climate change, agroforestry systems-including windbreaks-emerge as crucial tools for enhancing climate resilience and mitigation while also boosting agricultural production and diversification. This multifunctionality is vital for producers seeking more resilient and productive systems, particularly in areas already suffering from wind erosion and crop losses, which are projected to worsen.

Despite significant advancements in shelterbelt research, continued exploration is essential to refine practices, optimize benefits and enhance resilience against climate variability. By embracing an integrated approach that considers ecological, economicand social dimensions, future research can pave the way for sustainable land management practices that not only support farmers but also contribute positively to the environment. Ultimately, the integration of windbreaks into agricultural landscapes represents a promising pathway toward achieving sustainability and resilience in the face of mounting climate challenges.

Conflict of interest

All authors declare that they have no conflict of interest.

REFERENCES

Bhardwaj, K.K., Dhillon, R.S., Kumari, S., Johar, V., Dalal, V. and Chavan, S.B. (2017). Effect of eucalyptus bund blantation on yield of agricultural crops and soil properties in semi-arid region of India. International Journal of Current Microbiology and Applied sciences. 6(10): 2059-2065.

Bhimaya, C.P. and Chowdhari, M.D. (1961). Plantation of wind break in the central mechanized farm Suratgarh - An appraisal or technique and results. Indian Forester. 86: 453-468.

Bhimaya, C.P. and R.N. Kaul. (1960). Some afforestation problems and research needs in relation to erosion control in arid and semi-arid parts of Rajasthan. Indian Forester. 86(8): 453-468.

Bhimaya, CP., Misra, D.K and Das, R.B. (1958). Importance of shelterbelts in arid zone farming. Farm forestry symposium. Indian Council of Agricultural Research. New Delhi. pp. 65-72.

Buvaneswaran, C., P. Masilamani and S. Senthilkumar. (2016). Windbreaks of casuarina for tailoring growth and branching pattern of teak trees in bund planting system. International Journal of Applied Agricultural Research. 15(1): 33- 42.

Chandrasekharaiah, T.G. (1987). Sheltetbelts on farm land. My Forest. 23(1): 43-51.

Chavan, S.B., Dhillon, R.S., Sirohi, C., Uthappa, A.R., Jinger, D., Jatav, H.S., Chichaghare, A.R., *et al* (2023). Carbon sequestration potential of commercial agroforestry systems in indo-gangetic plains of India: Poplar and Eucalyptus-Based Agroforestry Systems. Forests. 14(3): 559; https://doi.org/10.3390/f14030559.

Chavan, S.B., R.S. Dhillon, Chhavi Sirohi, A. Keerthika, Sushil Kumari, K.K. Bharadwaj, Dinesh Jinger, Vijaysinha Kakade, A.R. Chichaghare, Tarek K. Zin El-Abedinand *et al.* (2022). Enhancing farm income through boundary plantation of poplar *(Populus deltoides)*: An Economic Analysis. Sustainability. 14: 8663. https://doi.org/10.3390/su14148663.

Dass, H.C. (1984). Cultivation of fruits in arid zone. Indian Farming. 34: 45-48.

Dobhal, S., Raj Kumar, Bhardwaj, A.K., Chavan, S.B., R. Uthappa, M. Kumar, A. Singh, D. Jinger, P. Rawat, A. K. Handa and N. Ramawat. (2024). Global assessment of production benefits and risk reduction in agroforestry during extreme weather events under climate change scenarios. Front. For. Glob. Change. Sec. People and Forests. 7-2024. https://doi.org/10.3389/ffgc.2024.1379741.

Doddabasawa, B.M.Chittapur and Murthy Mahadeva M. (2018). On-farm evaluation of pigeonpea (*Cajanus cajan* L. Millsp.) - Neem (*Azadirachta indica* A. Juss.) agroforestry systems in the Deccan Plateau. Legume Research. 43(1): 87-92. doi: 10.18805/LR-3941.

Droze, W.H. (1977). Trees, prairiesand people: A History of Tree Planting in the Plains States. Denton: Texas Woman's University Press.

Gajja B.L., Prasad Rajendra, Mertia R.S. and Samra J.S. (2007). Impact of shelterbelts on net returns from agricultural production in arid western Rajasthan. Agricultural Economics Research Review. 20: 622

Gajja, B.L., R. Prasad, R.S. Mertia and J.S. Samra. (2014). Contribution of shelterbelts in employment generation in arid zone of western Rajasthan. Annals of Arid Zone. 53(1): 49-53.

Ganguli, J.K and Kaul, R.N. (1969). Wind Erosion Control: ICAR Tech. Bull. (Agric.) 20, New Delhi. pp. 50.

Gupta, J.P. (1997). Wind erosion and its control in arid regions. In: Silvipastoral systems in arid and semi-arid ecosystems [Eds.) M.S. Yadav, M. Singh, S.K. Sharma, J.C. Tiwari and U. Burman]. Central Arid Zone Research Institute, Jodhpur, India. pp. 105-112.

Gupta, J.P. (2000). Technology Approach for Greening Degraded Arid Lands. Division of Integrated Landuse Management and Farming System Central Arid Zone Research Institute, Jodhpur, India. pp. 51.

Gupta, J.P. and Ramakrishna, Y.S. (1988). Role of Shelterbelts in Checking Wind Erosion and Increasing Crop Production in sandy waste lands of western Rajasthan. In: Wastelands Development and their utilization. Scientific Publishers, Jodhpur, pp. 271-280.

Gupta, JP., Rao, G.G.S.N., Ramakrishna, Y.S. and Ramana Rao, B.V.(1984). Role of shelter belts in arid zone. Indian Farming. 34(7): 29-30.

Gupta. J.P., Ran. G.G.S.N. Gupta, G.N. and Ramana Rao, B.Y. (1983). Soil drying and wind erosion as affected by different types of shelterbelts planted in the desert region of western Rajasthan. Environment. 6: 53-58.

Harsh, L.N. and Tewari, J.C. (1997). Sand dune stabilization and shelterbelt plantation technique for arid regions. In: Silvipastoral systems in arid and semi-arid ecosystems (Eds. M.S. Yadav, M. Singh, S.K. Sharma, J.C. Tiwari and U. Burman). Central Arid Zone Research Institute, Jodhpur - 342 003, India. pp. 113- 122.

Harsh, L.N. and Tewari, J.C. (1997)a. Stabilization of sand dunes and their management in Indian Arid zone. In book: Desertification control in the arid ecosystems of India for sustainable development (Eds. Surender Singh and Amalkar). Agro Botanical Publisher, Bikaner.

Hennessy, G., Harris, C., C. Eaton, P. Wright, E. Jackson, D. Goulson and F.F.L.W. Ratnieks. (2020). Gone with the wind: effects of wind on honey bee visit rate and foraging behaviour. Animal Behaviour. 161: 23-31.

Hulme, M., Doherty, R., Ngara, T.and New, M. (2005). Global warming and African climate change. In: Climate change and Africa. (Ed. P. S. Low). Cambridge: Cambridge University Press. Pp. 29-40.

IPCC. (2021). Climate change (2021): The physical science basis. contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. Available at: https://www.ipcc.ch/report/ar6/wg1/.

Kaul, R.N. (1985). Sand dune fixation and afforestation traditional procedures for dune fixation: The hedge system. In Sand Dune Stabilization, Shelterbelts and Afforestation in arid zones. FAO Conservation Guide, pp. 65-74.

Kaul, R.N. (1996). Sand dune stabilization in the thar desert of India: A Synthesis. Annals of Arid Zone 35(3): 225-240.

Kohli, R.K., Singh, H.P. and Batish, D.R. (1997). Phytotoxic potential of *Populus deltoides* bartr. ex Marsh. I. Comparative contribution of different parts. Indian Journal of Forestry 20: 300-304.

Manasa, C.P.A., Salimath, S.K., Hegde, R. and Gooli, M. (2022). Bund and boundary plantation: A Prominent Feature of Indian Agroforestry. Indian Journal of Agroforestry. 24(1): 52-59.

Mayrinck, C.R., Laroque, P.C., Amichev, Y.B. and Rees, V.K. (2019). Above- and below-ground carbon sequestration in shelterbelt trees in Canada: A review. Forests. 10: 922. https://doi.org/10.3390/ f10100922.

Meghwal, P.R., Akath Singh and Dalpat Singh. (2022). Underutilized fruits and vegetables in hot arid regions of India: Status and prospects: A review. Agricultural Reviews. 43 (1): 38-45. doi: 10.18805/ag.R-2087.

Mertia, R.S., Prasad, R., Gajja, B.L., Samra, J.S. and Narain, P. (2006). Impact of shelterbelts in arid region of western Rajasthan, Central Arid Zone Research Institute, Jodhpur, India. 76p.

Monga, P.K., Harmail Singh, S. K. Thatai and Harish Kumar. (1992). Effect of shade by windbreak and direction of fruits on tree on fruit quality in kinnow mandarin. Indian Journal of Horticulture. 49(4): 321-325.

Muthana, K.D., Mahendra Singh, Mertia, R.S. and Arora, G.D. (1984). Shelterbelt plantation in arid regions. Indian Farming. 33(11): 19-20.

Patel, A., Sheetal, K.R., Renjith, P.S. and Kanwat, M. (2023). Unprecedented extremes: A closer look at recent weather events in the arid region of Kutch, Gujarat, India. Desert Environment Newsletter. 25(1-2): 7-10.

Prajapati, V.M., D.J. Jilariya, R.J. Mevada, M.B. Tandel, B.N. Bhanderi, D.P. Patel, L.K. Arvadiya and M. Husain. (2024). Effect of windbreaks (*Casuarina equisetifolia* L.) on productivity of paddy in south Gujarat. International Journal of Plant and Soil Science. 36 (5): 800-807.

Prasad, R., Mertia R.S., Gajja B.L., Singh D. and P. Chandra. (2013). Morphological characteristics of tree shelterbelts and their impact on wind regimes, air temperature and soil quality. Indian Journal of Agroforestry. 15(1): 74-81.

Prasad, R., R.S. Mertia, R.N. Kumawat and J.S. Samra. (2009). Shelter efficiency of dalbergia sissoo roxb. Shelterbelt in IGNP command area in arid Western Rajasthan, India. Indian Journal of Agroforestry. 11(1): 41-43.

Puri, S., S. Singh and A. Kumar. (1994). Growth and productivity of crops in association with an *Acacia nilotica* tree belt. Journal of Arid Environments. 27(1): 37-48

Puri, S., Singh, S. and Khara, A. (1992). Effect of windbreak on the yield of cotton crop in semiarid regions of Haryana. Agroforest Systems. 18: 183-195.

Raheja, P.C. (1963). Shelterbelts in arid climate and special techniques for the planting. Annals of arid zone. 2.

Ramanan S.S., Manoj Kumar S., A. Arunachalam, A.K. Handa and V. Priyanka. (2022). Conceptual analysis of ‘windbreaks’ and ‘shelterbelts’ in agroforestry. Indian Journal of Agroforestry. 24(2): 39-45.

Rao, A.S., Gupta, J.P. and Faroda, A.S. (1997). Changing climatic scenarios and strategies for drought management in the Indian Arid Region. Drought Network News (1994-2001). 73.

Samra, J.S. (2020). Land degradation neutrality in India: A dynamic process. Indian Journal of Soil Conservation. 48(2): 109-119.

Sharma, N.K., J.S. Samra and H.P. Singh. (2001). Influence of boundary plantation of poplar (*Populus deltoides* M.) on soil-water use and water use efficiency of wheat. Agricultural Water Management. 51(3): 173-185.

Sheetal, K.R., Birbal, Subbulakshmi V., Renjith P. S., Moharana P. C., Bagdi G.L., Yadava N.D. (2020). Farmers’ perception towards shelterbelts in hot arid regions of Rajasthan: An analysis by Garrett’s ranking technique. Indian Journal of Extension Education. 56(3): 126-132.

Singh H.P. (1996). Phytotoxic effects of populus in natural and agro-ecosystems. Unpublished Ph.D. Thesis, Panjab University, Chandigarh, India.

Singh, A., Raj Singh and R.K. Pannu. (2005). Performance of wheat (*Triticum aestivum*) varieties in Eucalyptus plantation. Indian Journal of Agronomy. 50(1): 61-63.

Singh, D. and Kohli, R.K. (1992). Impact of *Eucalyptus tereticornis* Sm. shelterbelts on crops. Agroforestry Systems. 20: 253-266.

Singh, H.P., Kohli, R.K. and Batish, D.R. (1999). Impact of populus deltoides and dalbergia sissoo shelterbelts on wheat - a comparative study. International Tree Crops Journal. 10: 51-60.

Singh, N., Biswas Deepa, Gokhale Yogesh, Kumar Kapil. (2024). Incentivising agroforestry through carbon revenue: Augmenting Farmers' Income in India. Agricultural Science Digest. 44(4): 679-683.

Singh, R., O.P. Bishnoi, V.U.M. Rao and D. Singh. (1996). Effect of shelterbelt on the microclimate of the gram (*Cicer arietinum*) crop. Mausam. 47(2): 173-178.

Sirohi, C., R.S. Dhillon, A.K. Hnada, S.B. Chavan and A. Arunachalam. (2021). Dry matter accumulation of winter wheat (*Triticum aestivum* L.) at different distances from tree line under poplar (*Populus deltoides*) boundary plantation Indian Journal of Agroforestry. 23(2): 30-38.

Soni, M.L., Subbulakshmi, V., Verma, A, Yadava, N.D. and Nathawat, N.S. (2021). Yield and nutrition of moth bean-mustard rotation in soils amended with tree leaf litters in the arid region of Rajasthan. Indian Journal of Agricultural Research. 55(5): 577-583.

Thind, H.S. and Dhillon, G.P.S. (1995). Quantification of Yield Reduction in Wheat Grown Adjoining Poplar Boundary Plantation. In: IUFRO-DNAES International meet on Resource Inventory Techniques to Support Agroforestry and environment activities [Eds.) R.K. Kohli and K.S. Arya]. pp. 173-175.

Upadhyay, A.K. (1991). Shelter belt plantations effectively check sand deposition in Indira Gandhi Canal. Indian Forester. 117(7): 511-514.

Vashishtha, B.B. and Prasad, R.N. (1997). Horti-Silvi-Pasture Systems for Arid Zone. In: Silvipastoral Systems in Arid and Semi-arid Ecosystems [Eds.) M.S. Yadav, M. Singh, S.K. Sharma, J.C. Tiwari and U. Burman]. Central Arid Zone Research Institute, Jodhpur, India. pp. 277-284.

Venkateswarlu, J. (1993). Problems and Prospects in Desertification Control - Role of Central Arid Zone Research Institute. In Desertification and Its Control in the Thar, Sahara and Sahel Regions [Eds.), A.K. Sen and Amal Kar]. Scientific Publishers, Jodhpur, pp. 249-267.

Yadav, O.P. (2018). Six-decades journey of CAZRI: Addressing arid zone crop production system in inclusive way. Indian Farming. 68(9): 6-15.