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Land-based climate mitigation strategies for achieving net zero emissions in India

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Despite advancements in electrification and the transition to solar-based electricity production, India will continue to depend on land-based carbon offsets to achieve its net-zero target. Land-based climate mitigation strategies in India can be implemented by utilizing underutilized marginal lands or increasing land availability through technological interventions to close agricultural yield gaps. Both below-ground (e.g., soil carbon) and above-ground (e.g., standing tree biomass) options offer viable pathways for such measures. Key strategies include cultivating perennial bioenergy feedstocks, afforestation, establishing fast-growing Miyawaki forests, restoring wetlands and mangroves, and applying biosolids to land. However, caution is essential to prevent unintended consequences, such as clearing natural forests or introducing microplastics into soils. The cost of carbon sequestration and the resilience or permanence of stored carbon will be critical factors in determining the preferred approach. Additionally, land-based strategies often overlap spatially, making GIS-based tools indispensable for identifying optimal solutions tailored to local conditions. Integrating these strategies into the national carbon budget can enhance transparency and contribute significantly to India's net-zero emissions goal.

KEYWORDS

net zero emission, nature based solution, land based solution, afforestation, soil organic carbon, biosolids, bioenergy, climate change

1 Introduction

Limited land availability is often seen as a barrier to implementing land-based solutions like biofuel expansion in India. This concern stems from India supporting over 17% of the global population on just 2.5% of the world's land area. However, India is also a leading generator of land-based carbon credits, with its net-zero strategy relying heavily on measures like afforestation and biofuels. What strategies can help India further leverage land-based approaches to achieve its net-zero target? Here, we address this question by summarizing land-based measures currently being discussed in academic and policy forums in India.

Deep electrification in conjunction with decarbonization of electricity sector can possibly reduce India's carbon emissions to 1,300 Million tons (Mt) of carbon dioxide equivalent (CO_2-eq) year^{-1} by 2050, down from the current 2,600 Mt. CO_2-eq year^{-1} (Prajapati et al., 2024) while sustaining a compounded annual economic growth rate of 5.4% that supports the well-being of more than 1.5 billion people (Vats and Mathur, 2022). Both carbon capture utilization and storage (CCUS) techniques, which target emissions from CO_2-intensive industries (Prajapati et al., 2024), and nature-based solutions (James et al., 2024; Seddon et al., 2021; Soterroni et al., 2023)—including cellulosic bioenergy from perennials (Robertson et al., 2022)—will need to play a crucial role in offsetting remaining residual CO_2-eq emissions. The potential rate of soil carbon sequestration in India is estimated to stand at 143-to-180 Mt. CO_2 year^{-1} (Lal, 2004b), representing slightly more than 10% of the total residual emission that needs to be offset to achieve net-zero emission. Given the significant variability in land use and land cover across India (Supplementary Table S1), a diverse range of practices will need to be implemented (Beaury et al., 2024). This mini-review explores various land-based strategies for climate change mitigation, taking into account the country's unique biogeography, population dynamics, and environmental conditions.

2 Land use changes caused by solar power plants

Utilizing approximately 0.3–1.4% of India's land area could generate enough power to achieve 75% land-based solar integration into the national electricity mix, with a carbon footprint of 0.4-to-10.8 grams of CO_2 equivalents per kilowatt-hour (gCO_2-eq kWh^{-1}; Van De Ven et al., 2021)—a fraction of the current electricity emission intensity of 711 gCO_2-eq kWh^{-1} (Sengupta et al., 2022). The relatively small land-use changes associated with large-scale expansion of solar plants can still influence terrestrial carbon balance, depending on the existing carbon stocks and prior land use (Van De Ven et al., 2021; Gomez-Casanovas et al., 2023). Solar plants can impact soil carbon and nutrient cycling by altering albedo, plant available radiation, temperature, water availability, and wind speed (Armstrong et al., 2014). The installation of solar panels on marginal lands (Supplementary Table S1) with low soil organic carbon (SOC) is unlikely to negatively affect the carbon budget (Van De Ven et al., 2021). However, placing them on productive agricultural land or areas providing essential ecosystem services could result in relatively higher emission intensity (Van De Ven et al., 2021). Recent efforts have focused on integrating solar energy with agriculture using agrovoltaics (Gomez-Casanovas et al., 2023) and ecosystems using ecovoltaics (Sturchio and Knapp, 2023) to balance competition between solar plants and other beneficial land uses. While there is no conclusive evidence yet on the impact of these systems on plant–soil carbon cycling, long-term studies are necessary to fully understand their effects (Gomez-Casanovas et al., 2023). Nevertheless, agrovoltaic and ecovoltaic approaches could lead to solar array designs that could promote climate regulation, local cooling, biodiversity, ecosystem services, and the restoration of degraded land (Ketzer et al., 2020; Kim et al., 2021; Marcuta et al., 2023). Considering that the land required for solar plants in India is relatively small (Van De Ven et al., 2021), the expansion of solar infrastructure is unlikely to significantly impact the agriculture, forestry, and other land use (AFOLU) sectors. This leaves room to efficiently harness biological approaches—such as utilizing plants (Somerville et al., 2010; Duarte et al., 2013; Dwivedi et al., 2015; Jaiswal et al., 2017; He et al., 2024), soil microbes (Silverstein et al., 2023), and land-based recycling of biosolids (Brown and Leonard, 2004; Peng et al., 2023)—to support multiple sustainable development goals (SDGs), including climate action (McElwee et al., 2020).

3 Contribution of AFOLU sector in total emission in India: current status

Recent estimates indicate that gross Agriculture, Forestry, and Other Land Use (AFOLU) emissions in India totaled ~352 Mt. CO_2-eq, with land sector removals offsetting ~181 Mt. CO_2-eq, resulting in net emissions of ~171 Mt. CO_2-eq (GHG Platform India, 2022). Land-based CO_2-eq removal plays a crucial role in India's strategy to meet its Nationally Determined Contributions (NDC) targets (Mathur et al., 2021), mostly relying on increasing forest cover area. Currently, the major contributors to CO_2-eq emissions from AFOLU are biomass burning, livestock, N_2O emissions from managed soils, and rice cultivation, while forests serve as the largest carbon sink (Kumar and Aravindakshan, 2022). Several management options, including the use of nitrification inhibitors (Soares et al., 2023), energy production from crop residues (Athira et al., 2019), and best management practices for reducing methane emissions (Singh et al., 2003), have yet to be adopted at scale with the possibility to significantly lower emissions from the current land uses within the AFOLU sectors in India.

4 Current and past status of SOC in India

The rooting depth (0–30 cm) SOC pool in India's soils is estimated to be 9.55 petagrams (Pg) C, which stands at ~1.3% of the global pool of 684–724 Pg C (Bhattacharyya et al., 2009). The average value of SOC concentrations in India (3.2 g kg^{-1}) is much lower than the recommended threshold value of 11.1 g kg^{-1} in tropical soils (Minasny et al., 2017), and this phenomenon can possibly be attributed to unsustainable field management and cultivation practices (Lal, 2004b), including tillage, removal of crop residues for fodder (Lal, 2004a), deforestation (Padbhushan et al., 2022), and overgrazing. By the late 1960s, cultivated soils in India had already undergone a 30 to 60% decline in SOC concentrations compared to levels in undisturbed or native ecosystems (Lal, 2004b; Swarup et al., 1999). This deterioration has continued, with recent studies estimating that ~98 million hectares of land now show severe degradation with extremely low SOC levels (Space Applications Centre, 2018). Recommended practices for rebuilding SOC stocks in India include afforestation on degraded lands, incorporating crop residues into the soil, and cultivating pulses (Minasny et al., 2017). Additionally, several other land-based climate mitigation strategies, including rebuilding SOC stocks, which hold comparable or potentially greater effectiveness but have received less attention, are discussed in the following sections. It is estimated that 7% of SOC potential sequestration in rice-wheat system can be achieved over a period of 20 years at a cost of 6.8 US$ ton^{-1} of CO_2 (Grace et al., 2012).

5 Land sparing for conservation by improving agricultural efficiency

India's total land under grain production covers approximately 130 Mha (Department of Agriculture and Farmers Welfare, 2023), and recent trends indicate that current yields are significantly lower than their potential. Several yield gap analyses highlight the potential to substantially increase yields of large land area occupying crops such as grains (Jain et al., 2017), oilseeds (Jha et al., 2011), pulses (Rimal and Kumar, 2018), and sugarcane (Singh et al., 2021). The inefficiencies in the current agricultural system present opportunities for improvement through technological interventions, such as precision and smart agriculture (Roy and George, 2020; Balasundram et al., 2023), and through breeding and biotechnological approaches (De Souza et al., 2022; Senapati et al., 2022; Xiong, 2024). Intensifying agricultural practices could free up land for implementing mitigation strategies, potentially making them more effective than land-sharing (Phalan et al., 2011).

6 Repurposing marginal land

Marginal lands (Supplementary Table S1), often unsuitable for intensive agriculture, can be effectively repurposed for cultivating perennial grasses, which are ideal for both bioenergy production and carbon sequestration. In India, with estimates of marginal land availability ranging from 45 to over 140 Mha (Department of Land Resources and NRSC, 2011; Edrisi et al., 2022; Edrisi and Abhilash, 2015; MoRD and NRSC, 2019; NBSS and LUP, 2005), there is significant untapped potential to increase their role in the climate mitigation strategies. Advanced biofuels using perennial grasses as feedstock are said to be a robust way to reduce greenhouse gas (GHG) emissions (Dwivedi et al., 2015; Jaiswal et al., 2017; Field et al., 2020; He et al., 2022) and in fact ameliorate some of the undesirable effects of climate change on temperature and rainfall patterns via atmospheric cooling (He et al., 2022). Introducing improved species of grasses (Lal et al., 1997) and legumes (Kumar et al., 2018) that are more efficient at capturing and storing carbon can also enhance the carbon content of soils in marginal grasslands. Identifying suitable grasses for degraded and marginal lands that can sustainably supply feedstock for biomass energy remains an underexplored area (MoPNG, 2018). Given the sustained high demand for liquid fuels in the foreseeable future (IEA, 2024), land-based, lower-carbon biofuels and feedstocks (Long et al., 2015) are anticipated to play a significant role in meeting the energy needs of India more sustainably (Nouni et al., 2021).

India encompasses a total of 55.76 Mha of land characterized as gullied areas, scrublands, waterlogged regions, degraded forests and pastures, degraded land under plantation crops, shifting cultivation lands, mining and industrial wastelands, sandy terrains, barren rocky stretches, and snow-covered zones, often classified as wasteland (Ayog, 2024). Of this, approximately 20.32 Mha are estimated to be highly suitable and 16.14 Mha are moderately suitable for agroforestry (Ayog, 2024), offering potential for carbon sequestration both above and below ground while also enhancing biodiversity (Nair et al., 2009). Planting oilseed-bearing trees like Karanj offers the dual benefits of agroforestry (Chaubey and Bohre, 2014) and the sustainable production of feedstock for biodiesel production (Mishra et al., 2021). Caution is needed when repurposing marginal lands in India for CO_2 offset projects, considering the risk of natural forest clearing specially after the forest (Amendment) Act 2023 (Thakur, 2023).

7 Miyawaki forest

The Miyawaki technique (Miyawaki, 1975) to establish thick forest cover regardless of varying soil and climatic conditions (Hanpattanakit et al., 2022) in ecologically and environmentally degraded regions (Poddar, 2021) allows trees to grow more rapidly, resulting in rapid canopy closure while sequestering carbon at a much greater rate (Schirone et al., 2011; Kueh et al., 2016). Currently, the Miyawaki method is popular only in land-constrained regions such as urban areas (Kuittinen et al., 2023; Daou et al., 2024) but has a high cost (~50,000 USD acre^{-1}) of establishment. Claims in the gray literature indicate that the carbon sequestration rate of Miyawaki forests is approximately 10–15 times greater than that of natural regeneration over a period of 20–30 years (ICLEI South Asia, 2022; Sandip et al., 2022). The estimated cost of CO_2 sequestration through the Miyawaki method was found to be approximately \$26 ton^{-1} of CO_2 (Supplementary Table S2), significantly higher than the cost (\$3 ton^{-1} of CO_2) of natural regeneration (Ravindranath and Somashekhar, 1995) but requiring lesser land area. Their significant potential for positive impacts on biodiversity conservation underscores the need for further investigation into their suitability and long-term sustainability on a larger scale. Currently, most Miyawaki forests in India are funded through corporate social responsibility (CSR) projects, but increased support from government initiatives could further enhance their implementation and impact.

8 Recycling of carbon and nutrients by land application of biosolids

The role of biosolids in land-based greenhouse gas mitigation often goes unrecognized (P. Smith et al., 2013), despite its significant contributions to carbon sequestration. India's biosolid generation could reach between 34 and 85 Mt. year^{-1} by 2070, based on a rate of 20–50 kg biosolids year^{-1} capita^{-1} (Tezel et al., 2011) and a projected population of 1.7 billion (UN-DESA, 2024), compared to the current sludge production of 2.4 Mt. year^{-1} (Figure 1A). Improvements in wastewater collection and treatment infrastructure, coupled with a growing population, are expected to lead to an increased availability of biosolids in the future. Land application of biosolids in King County, located in Washington in the northwestern USA, is estimated to generate up to 4.5 t CO_2 credits per dry ton, accounting for fertilizer replacement, no-till land management, biofuel production, composting, and digester gas-powered fuel cells (Brown and Leonard, 2004). With improved wastewater collection and management, biosolids in India could potentially contribute to carbon credits ranging from 153 to 382 Mt. CO_2 year^{-1}, assuming similar credit values as those observed in the northwestern USA. However, these carbon credits are highly dependent on local conditions, and we anticipate that region-specific methodologies will emerge, facilitating participation in the voluntary carbon market in India in the future. While the potential for soil carbon credit from biosolids application may be limited by biogeochemical constraints (Torri et al., 2014; Wiesmeier et al., 2019), credits from other processes (composting, fuel cells, fertilizer value, and biofuel production) can be expected to be comparable in order of magnitude. While land application offers environmental benefits such as enhanced soil quality, improved plant growth, and increased carbon sequestration, it can also lead to adverse effects like nutrient losses and elevated soil respiration (Gravuer et al., 2019; Rodrigues et al., 2021). Therefore, implementing appropriate regulations is essential to ensure the safe and sustainable reuse of biosolids in agriculture. The inherent local

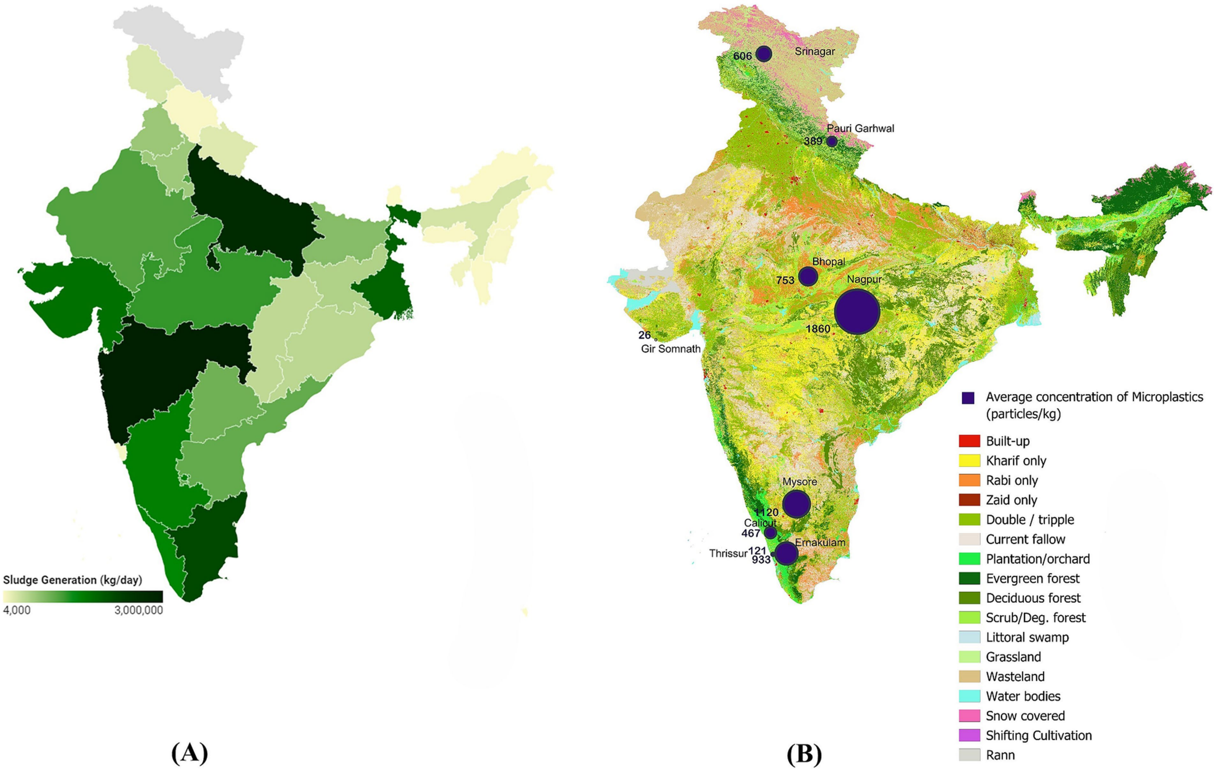

FIGURE 1
(A) Sludge generation in India (wet basis) based on Central Pollution Control Board [CPCB, 2021]; **(B)** Average microplastics concentration in soil, sewage, and sediment across sampled Indian sites. See Supplementary Table S3 for data sources.

control seems to be playing a greater role than the rate of application in deciding actual climate benefits as a consequence of land application of biosolids (Villa and Ryals, 2021). This is because the maximum potential for carbon sequestration is often specific to soil characteristics, while climate plays a critical role in regulating the rate of mineralization and immobilization – key processes that ensure nutrient availability to plants from organic sources.

Nevertheless, the land application of biosolids presents challenges, one of the most pressing being the introduction of microplastics into the soil environment (De Souza Machado et al., 2019; Zhang et al., 2020; Baho et al., 2021; Rillig et al., 2021; Kannankai et al., 2022; Singh S. et al., 2023). Their widespread presence across various locations in India (Figure 1B) necessitates further research into their impact on land-based climate mitigation strategies (Chia et al., 2023), because soil hydraulic properties (Guo et al., 2022), contaminant transport (Ren et al., 2021), soil microbiome (Sun et al., 2022), and soil respiration (Rillig et al., 2021) are greatly impacted by microplastics.

9 Mangroves and freshwater wetland

Intricately linked to land systems, mangroves and freshwater wetlands occupy only about 0.5% (Alongi, 2014) and 1% (Hu et al., 2017) of the global land surface, respectively, yet they store a disproportionately large share of the world's carbon stock relative to their area (Duarte et al., 2013; Macreadie et al., 2021; Malerba et al., 2022). The waterlogged conditions in these systems inhibit the decomposition of organic material by creating an anaerobic condition, resulting in the buildup of carbon within the soil (Richardson and Vepraskas, 2000), with life spans ranging from a few decades to several million years (Were et al., 2019). However, while wetlands are substantial carbon sinks, they are also sources of CH_4 and N_2O which can result in net greenhouse gas emissions. This underscores the need for continuous monitoring and management when evaluating these systems as climate solutions (Malerba et al., 2022).

India's commitment to wetland conservation is demonstrated by its 80 Ramsar sites (MoEFCC, 2024), which collectively cover an area of 1.35 Mha (MoEFCC, 2024) out of the total 15.98 Mha of wetlands in the country (Space Applications Centre, 2013), making it the largest network of Ramsar sites in Asia. India's mangrove cover spans around 499,200 ha (FSI, 2021), with total carbon stocks estimated at 33.9 Mt. (Singh A. et al., 2023). The Indian government has launched an initiative to add 54,000 ha of Mangroves over a five-year period from 2023 to 2028 (MOEFCC, 2023b).

10 Technical challenges

Identifying suitable plant species (Long et al., 2015; Kumar and Balasubramanian, 2024) for various land-use-based strategies is crucial, considering not only their potential to mitigate CO_2 emissions but also their resilience to anticipated climate change. This is essential because the effectiveness of such measures should be assessed over several decades. Establishing standard protocol for Monitoring, Reporting, and Verification (MRV) of carbon budgets along with quantification of uncertainty is also critical. Usage of ecosystem models capable of simulating carbon cycle (Table 1) in the MRV protocols for the assessment and issuance of carbon credits (Brummitt et al., 2024) is challenging (Garsia et al., 2023), due to poor records of high-resolution land-use history (Tian et al., 2014), leakage of stored soil carbon and lack of trained manpower. Some of these shortcomings can be overcome by machine learning-based approaches (Berardi et al., 2020; Dangal et al., 2022; Mathers et al., 2023) along with coupling with other processes (Lang, 2019; Surendran and Jaiswal, 2023). It is to noted that many of the land-based mitigation strategies presented here may overlap spatially (Beaury et al., 2024) and GIS modeling could help identify the best strategies given local conditions. Incorporating spatially explicit information on the contribution of land to the total carbon budget within the NDC accounting framework (Prusty et al., 2024) can enhance transparency, address negative externalities associated with climate-friendly new technologies (Blanco et al., 2023), and play a pivotal role in achieving the shared global goal of a net-zero world. Emerging pollutants like microplastics pose a significant challenge, as standardized protocols for analyzing soil and plant samples are yet to be established. Furthermore, the quantitative and qualitative impacts of microplastics on the terrestrial carbon cycle remain poorly understood.

11 Discussion

A combination of policy measures, financial incentives, and community engagement is essential for increased adaptation of these land-based approaches. The implementation would need to be carried out through a mix of top down and bottom-up approaches relying upon both government and private corporation for the necessary policy and regulation, financing and investment, innovation and technology, implementation, monitoring and execution, scaling up, and public awareness and advocacy. Afforestation, often less commercially viable than using land for commodity crops, is typically led by governments for public benefit. However, linking such efforts with income-generating activities like ecotourism can attract non-governmental participation, even in initiatives with limited initial commercial appeal (Wunder, 1999). Some of the measures may need enactment of new laws, regulations, and policy support from government and their success at implementation stage is heavily dependent on the coordination among different sections within the government. For example, judicious and sustainable land repurposing for biofuel production while accounting for the impact of direct and indirect land use changes (Jaiswal et al., 2017) can blur the divide between agriculture-based and industry-based economies while integrating land-based climate mitigation strategies into the decarbonization of India's heavily fossil-dependent energy sector (Li and Wang, 2019). Simultaneously, it can potentially support the mission of

TABLE 1 Land use types and models applied in various studies across the world for different Land Use and Land Cover (LULC) types.

Land use type	Model	References
Mangroves	MCAT-DNDC	Dai et al. (2018)
	NUMAN	Chen and Twilley (1999)
Wetlands	Wetland DNDC	Zhang et al. (2002)
Tropical Rainforest	RothC	Jenkinson et al. (1992); Coleman et al. (1997); Cerri et al. (2003)
	Forest DNDC	Kiese et al. (2005); Werner et al. (2007)
	Forest BGC	Running and Gower (1991); Ichii et al. (2007)
	Century	Parton et al. (1983); Sanford et al. (1991)
	TEM	McGuire et al. (1995)
Tropical Deciduous	Forest DNDC	Kiese et al. (2005)
	Forest BGC	Running and Gower (1991); Vargas et al. (2008)
	TEM	McGuire et al. (1995)
Temperate forest	Forest DNDC	Butterbach-Bahl et al. (2001)
	Forest BGC	Running and Gower (1991); White et al. (2000)
Grassland	RothC	Jenkinson et al. (1992); Coleman et al. (1997); Xu et al. (2011)
	Century	Parton et al. (1983, 1993)
	DNDC	Li et al. (1997)
	DayCent	Parton et al. (1994); Pepper et al. (2005)
Agricultural Land	Century	Parton et al. (1983); Smith et al. (2000)
	DayCent	Parton et al. (1994); Del Grosso et al. (2002); Pepper et al. (2005)
	DNDC	Li et al. (1997)
	RothC	Jenkinson et al. (1992); Coleman et al. (1997); Diels et al. (2004)
	EPIC	Williams (1990); Izaurralde et al. (2006)
Savanna	Century	Parton et al. (1983); Ardö and Olsson (2003)

increasing farmers' incomes (Silalertruksa et al., 2012) by incentivizing agricultural diversification and establishing markets for diversified crops – essential element, alongside yield improvement, to enhance farmers' incomes and living standards. Achieving this requires robust coordination among the Ministry of New and Renewable Energy (MNRE), Ministry of Earth Sciences (MoES), Ministry of Petroleum and Natural Gas (MoPNG), Ministry of Agriculture and Farmers' Welfare (MoA&FW), and potentially several other stakeholders, which, specially at the implementation stage, remains a significant challenge. The emerging carbon emission market, especially in the context of India, can be reconciled with the net-zero emissions goal by creating a market-driven approach and utilizing revenue to support projects like afforestation, soil carbon sequestration, land rejuvenation, renewable energies, and promotion of sustainable land use practices. As the use of carbon credits often involves MRV, carbon credits may also promote accountability. Compliance mechanism under the carbon credit trading scheme (CCTS) by the Indian government has recently been introduced to facilitate the achievement of India's enhanced NDC (Bureau of Energy Efficiency, 2024). As many of the land-based strategies overlap, therefore, developing countries like India need to have flexibility in designing accounting framework for GHG such that appropriate policies can be chosen based on their consistency with the NDC (Prusty et al., 2024).

Overall, land-based measures include the reduction of GHG emissions and/or enhanced CO_2 removal from the atmosphere compared to the baseline scenario. Typically, land-based measures are considered cheaper and easier to implement than purely technological intervention and cost of mitigation for India is estimated to be 50–100 $ ton^{-1} of CO_2 (Roe et al., 2021). India's NDC is supported by various government initiatives, such as National Afforestation Program (MoEFCC, 2019), National Mission on Sustainable Agriculture (Department of Agriculture and Farmers Welfare, 2010), Amrit Dharohar scheme (MOEFCC, 2023a), Mangrove Initiative for Shoreline Habitats and Tangible Incomes (MISHTI; MOEFCC, 2023a), etc. India is also one of the largest contributors to the global voluntary carbon markets (VCMs; Nozaki, 2023). The efforts by both central & state governments, along with contributions from private corporations, have made India the only major country whose emissions pathways are consistent with carbon budget required to limit the global warming within 2°C (Vishwanathan et al., 2023). However, post-COVID-19 pandemic, the trend in GHG emissions has become more concerning. We conclude this paper by emphasizing that a wide range of land-based carbon offset measures can play a pivotal role in helping India achieve its pledge to become a net-zero country by 2070.

Author contributions

DJ: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. KS: Conceptualization, Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. TJ: Data curation, Visualization, Writing – review & editing. AS: Data curation, Visualization, Writing – review & editing. AK: Data curation, Visualization, Writing – review & editing. SS: Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The authors declare that Gen AI was used in the creation of this manuscript. We have used ChatGPT to improve the writing and phrasing sentences.

Publisher's note

Supplementary material

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