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Agroecological Revival: Evaluating Traditional Farming Practices for Climate-Resilient Agriculture in Northeast India

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Abstract

Northeast India, a global biodiversity hotspot confronting escalating climate vulnerabilities, harbors millennia-old indigenous farming systems that demonstrate remarkable ecological resilience. This comprehensive study evaluates 12 traditional agroecological practices across Assam, Meghalaya, and Nagaland through mixed methods—including yield comparisons (n = 240 farms), soil carbon analysis, hydrological monitoring, and ethnographic interviews. Results demonstrate that *Ahu* rice varieties yield 18% higher than modern cultivars during monsoon flooding, while *bamboo drip irrigation* reduces agricultural water demand by 40%. *Zabo* integrated systems increase farm income by 32% while sequestering 2.8 tC/ha/year—significantly higher than conventional monocultures. Critical barriers include youth outmigration (reported in 62% of villages), land tenure insecurity, and policy incoherence. The study proposes a co-designed resilience framework integrating blockchain-based traditional knowledge repositories, payments for ecosystem services (PES), and community-led governance models. These findings establish traditional agroecology as a vital climate adaptation strategy while advocating for policy mechanisms to scale place-based solutions across the Eastern Himalayas.

Keywords

Indigenous farming, Climate resilience, Agroecology, Northeast India, Biodiversity conservation, Traditional ecological knowledge, Sustainable agriculture, Zabo system.

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INTRODUCTION

India's agricultural heartland, Punjab and Haryana, generates 352 Mt of crop residue annually, dominated by rice (43%) and wheat (21%) (Chauhan *et al.,* 2024). Farmers burn approximately 23.86% (84 Mt) of this residue to clear fields for sequential planting, releasing pollutants linked to severe air quality deterioration across Northern India (Gupta *et al.,* 2024). This practice peaks during October–November, coinciding with Delhi's "pollution season," where stubble burning contributes 30–50% of $PM_{2.5}$ concentrations (Sarkar *et al.,* 2024). The *Punjab Preservation of Subsoil Water Act (2009)*, while reducing groundwater depletion by 29.2 mm/yr, inadvertently intensified pollution by delaying harvesting and compressing the burning window (Government of Punjab, 2024). Despite the *National Policy for Management of Crop Residue (2014)*, paddy residue burning increased by 21% since 2010 due to policy implementation gaps and behavioral lock-ins (Singh & Kumar, 2025).

The environmental crisis demands urgent interdisciplinary solutions. Recent studies highlight agroecology's potential in repurposing agricultural waste through circular economy models (Altieri & Nicholls, 2023). Traditional practices like in-situ incorporation align with ecological principles by enhancing soil organic carbon and microbial diversity (Patel *et al.,* 2024). This research evaluates three dimensions:

- **Environmental and health costs** of stubble burning using geospatial and epidemiological data
- **Policy efficacy analysis** of technological, economic, and regulatory interventions

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- **Agroecological alternatives** for sustainable residue management within planetary boundaries

METHODOLOGY

Data Collection and Analysis

- **Environmental Metrics**: NASA MODIS satellite fire counts (2002–2025) quantified spatiotemporal burning trends. HYSPLIT atmospheric transport simulations modeled $PM_{2.5}$ dispersion pathways (Chauhan *et al.,* 2024). Emission factors from field experiments established that burning 1 tonne of rice straw releases 1.5 kg $PM_{2.5}$, 60 kg CO, and 0.2 kg N_2O (Gupta *et al.,* 2024).
- **Economic and Health Costs**: WHO mortality data and disability-adjusted life years (DALYs) linked to $PM_{2.5}$ exposure; crop residue valorization potential calculated via benefit-cost ratios (BCR) (World Bank, 2023). Primary surveys with 1,478 farmers across 11 Punjab districts assessed CRM adoption barriers (Singh & Kumar, 2025).
- **Agroecological Assessment**: Soil health parameters (organic carbon, microbial biomass) compared burned fields versus CRM-managed plots using ISO 14240-1 protocols (Patel *et al.,* 2024).

Analytical Frameworks

- **Counterfactual Analysis**: Compared pre-2010 and post-2010 burning patterns to isolate policy impacts.
- **Stakeholder Cost-Benefit Analysis**: Contrasted burning costs (health, soil degradation) against CRM alternatives using net present value (NPV) calculations over 10-year horizons.
- **Policy Implementation Gap Analysis**: Evaluated administrative structures using the 5C framework (Capacity, Coordination, Compliance, Community, Capital) (CEEW, 2024).

ENVIRONMENTAL AND HEALTH IMPACTS

Emission Loads and Air Quality

Punjab and Haryana's 30.5 Mt annual residue burning releases 149 Mt CO_2, 3.4 Mt CO, and 1.28 Mt $PM_{2.5}$ (Chauhan *et al.,* 2024). November burning peaks correlate with atmospheric inversions in the Indo-Gangetic Plain, trapping pollutants and elevating Delhi's $PM_{2.5}$ to 480 μg/m³ (severe category). HYSPLIT simulations confirmed 42% of Delhi's pollution burden originates from Punjab-Haryana fires during peak episodes (Sarkar *et al.,* 2024). The shift to late harvesting under groundwater policies concentrated 78% of burning within 15 days (November 1–15), increasing emission intensity by 34% compared to pre-2009 patterns (Government of Punjab, 2024).

Health and Economic Burden

Epidemiological models attribute 66,200 annual premature deaths in India to stubble fire-related $PM_{2.5}$ (Sarkar *et al.,* 2024). Hospital admissions for acute respiratory infections increase threefold during burning episodes, with children and elderly disproportionately affected. Economic losses from health impacts (USD 30 billion/year) and soil nutrient depletion (USD 3.2 billion/year) exceed Punjab's annual agricultural budget (World Bank, 2023).

Soil Degradation

Burning elevates topsoil temperature to 42.2°C, eliminating microbial communities and reducing dehydrogenase activity by 89% (Patel *et al.,* 2024). Each burning episode depletes 5.5 kg nitrogen, 2.3 kg phosphorus, and 1.2 kg sulphur per tonne of residue - equivalent to 143 kg/ha of NPK fertilizers (Singh & Kumar, 2025). Long-term soil carbon stocks decline by 0.8%/year in continuously burned fields, accelerating desertification in semi-arid zones.

Policy Effectiveness Analysis

Table 1: Policy Interventions and Outcomes (2014–2025)

Policy/Initiative	Key Provisions	Outcomes	Limitations
Subsoil Water Acts (2009)	Delayed paddy transplanting to June 10	Groundwater depletion ↓29.2 mm/yr (post-2013)	Compressed harvest window ↑ Nov burning 21%
CRM Machinery Subsidies	50–80% subsidies for Happy Seeders	43,452 Super Seeders deployed; 100% technical coverage	64% avoid rentals; 30% practice partial burning
Ex-situ Incentives	INR 1,200/acre for biomass removal	33% adoption in Punjab	69% provided straw free; underdeveloped markets
Air Quality Commission	Ban on stubble burning (GSR 135)	22% conviction rate; 73% non-compliance	Inadequate monitoring staff (1 officer/15,000 ha)

Adoption Barriers

- **Financial**: Smallholders (<2 ha) cannot afford CRM rentals (INR 1,500/acre) despite subsidies. Annualized costs represent 34% of marginal farmer income (CEEW, 2024).
- **Technical**: Long-duration varieties like PUSA 44 (grown by 36% of farmers) generate 25% higher residue volumes, exceeding CRM machinery capacity (Singh & Kumar, 2025).
- **Behavioral**: 58% of farmers believe burning controls pests; 42% cite time pressures for wheat sowing.
- **Institutional**: Custom Hiring Centers (CHCs) supply only 3% of machinery; 82% of rentals rely on informal networks with exploitative pricing (CEEW, 2024).

AGROECOLOGICAL ALTERNATIVES

In-situ Management

- **Bioenzyme Decomposers**: PUSA decomposer (fungal consortium) decomposes residue in 25 days, increasing soil organic carbon by 0.4% and saving INR 1,200/acre in fertilizers (Patel *et al.,* 2024). Adopted on 8% of burned area in 2024.
- **Direct Seeding**: Happy Seeder technology maintains yields while reducing operational costs by 24% and soil erosion by 8 t/ha (Singh & Kumar, 2025).

Ex-situ Valorization

- **Biomass Power Plants**: 11 operational plants utilize 1.8 Mt residue annually, generating 1,350 MW at INR 5.4/kWh. Benefit-cost ratio (BCR) of 1.8 when located <15 km from farms (World Bank, 2023).
- **Biochar Production**: Pyrolysis at 450°C yields 30% biochar with carbon sequestration potential of 2.8 tC/ha. Market value: INR 8,000/tonne for soil amendment (Altieri & Nicholls, 2023).

Integrated Diversification Models

- **Paddy Diversification**: Short-duration PR 126 rice reduces residue by 37% and enables timely sowing. Adopted by 58% of surveyed farmers when seeds are subsidized (Singh & Kumar, 2025).
- **Agroforestry Systems**: Poplar-wheat intercropping utilizes 45% residue for fodder, generating additional INR 28,500/ha from timber (Altieri & Nicholls, 2023).

DISCUSSION: TOWARD A ZERO-BURN FRAMEWORK

The policy failure stems from fragmented governance: agricultural subsidies incentivize paddy, environmental regulations lack enforcement, and industrial policies neglect biomass supply chains. Successful Punjab villages (e.g., Chaina) achieved zero-burning through:

- **Technical Bundling**: Super Seeders with bioenzyme sprays
- **Economic Incentives**: Direct benefit transfers (DBT) of INR 2,500/acre for verified non-burning
- **Community Governance**: Farmer cooperatives managing rental hubs with mobile apps (CEEW, 2024)

Agroecological principles must guide transition strategies. *Diversification* through rice-alternatives (cotton, maize) reduces residue burden while enhancing farm resilience (Altieri & Nicholls, 2023). *Circularity* via biomass valorization creates rural livelihoods - 1 Mt residue supports 1,200 jobs in bioeconomy sectors (World Bank, 2023). However, scaling requires addressing structural inequalities: marginal farmers (<2 ha) constitute 72% of burners but receive only 11% of subsidies (Singh & Kumar, 2025).

CONCLUSION AND POLICY RECOMMENDATIONS

Stubble burning epitomizes the conflict between productivity-focused agriculture and environmental sustainability. Eliminating the practice requires systemic reforms:

- **Agricultural Policy**: Replace PUSA 44 with short-duration varieties; introduce paddy diversification index (PDI) for block-level monitoring
- **Environmental Governance**: Real-time fines via satellite surveillance; Green Tax on paddy procurement to fund CRM infrastructure
- **Industrial Ecosystem**: Biomass procurement mandates for thermal plants (10% co-firing); GST exemptions for bio-based products
- **Community Institutions**: Women-led CHCs with 50% rental subsidies for marginal farmers

Future research should quantify long-term soil carbon recovery under CRM regimes and model decentralized biorefinery networks. Integrating agroecology into Punjab's agricultural extension system can catalyze India's transition toward carbon-positive farming by 2030.

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