



CLIMATE

BIG BETS

2047

Identifying high-leverage pathways across India's food and circularity systems



An innovation pathways report by the  delta prize







Acknowledgements

This roadmap report has been shaped by the collective expertise, experience, and insights of a wide range of stakeholders across India's circularity and food systems landscape.

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We also extend our appreciation to the broader Climate Futures ecosystem for its continued commitment to address climate vulnerability, strengthen livelihood resilience, and advance sustainable development. This report is a modest contribution to that collective effort and intends to support informed decision-making, enable collaboration, and identify high-leverage technology and market pathways to build climate-resilient livelihoods at scale in India.

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Foreword

A failed monsoon raises food prices. Rising prices force small farmers to sell assets. Asset losses reduce their capacity to invest in the next season. In turn, this reduced investment worsens yields, while worsened yields deepen debt. This is a poverty trap engineered by climate, and it closes faster than any single intervention can open it.

Today, climate change is not a linear decline but rather a series of interconnected tipping points that are beginning to overwhelm the adaptive capacity of traditional systems. What makes this moment particularly dangerous is not any single tipping point, but the way they amplify each other. It is quietly dismantling livelihoods that took generations to build and are reaching a breaking point where “bouncing back” is no longer an option. Instead, we must redesign the system from the ground up.

Solving for the “bottom of the pyramid” requires more than a single silver bullet technology. Some losses, once crossed, cannot be reversed on any human timescale. A soil microbiome depleted by repeated drought and chemical overuse takes decades to restore, if it ever does. A traditional crop variety abandoned by a farming community disappears permanently. A generation of young people who left the land and never returned takes with them agricultural knowledge that no app can fully reconstruct.

Tipping points, in this sense, are not just ecological events. They are permanent closures of possibilities. Acting now is not just about preventing harm but rather about preserving options. This is the uncomfortable truth that conventional aid has been slow to absorb: Fragmented, reactive charity cannot match the speed or scale of systemic failure. What this moment demands is not more of the same but instead, a robust, coordinated toolkit of interventions that unlock market potential from the ground up.

My conviction, sharpened over years at the intersection of innovation and impact, is this: The most complex challenges do not suffer from a shortage of capital but from a shortage of precision. Identifying the right problem is the only way to signal to the market that a solution is not only necessary but investable. Get the problem definition wrong, and even the best-funded effort becomes noise. Better questions do not come from reports or meetings. They emerge from real problems and the people who face them.

This roadmap is built on in-depth conversations with experts and key stakeholders, whose insights shaped the work. Because any roadmap is only as strong as the understanding behind it, this one is grounded in what people closest to the problem said needs urgent attention.

“Climate big bets 2047: An innovation roadmap for climate futures” is an effort to ask those better questions. It moves away from short-term fixes and focuses instead on system-level innovation. The “Big Bets” outlined here, from last-mile soil diagnostics to crop residue valorization, are not just ideas or aspirations. They highlight critical pressure points where focused technological and market interventions can turn existing vulnerabilities into scalable, repeatable opportunities. India is the ultimate “stress test” for climate-resilient livelihoods.

When we solve for a farmer with less than 2 hectares of land or a household that manages a small goat herd, we are not solving for a niche but for the bottom of the pyramid. These are volume markets that have been historically overlooked as “too fragmented” or “too thin-margined.” This roadmap challenges that narrative to reveal a pipeline of opportunities with the potential to

generate massive capital multipliers. It shows that India's structural complexity does not obstruct innovation but serves as a testbed that makes solutions developed here worth exporting everywhere else. India will have the world's largest working-age population through 2050. This is a resource, but only if deployed toward the right problems.

An entire generation of engineers, agronomists, entrepreneurs, and systems thinkers is available to work on climate resilience at a scale no other country can match. The "Big Bets" in this report are also, in that sense, a talent agenda. They define the direction India's innovation energy should take.

While the focus here is India, the implications are global. The structural gaps we see in India's food and circularity systems are mirrored across the Global South. By building, testing, and scaling these "Big Bets" here, we are creating a blueprint for the world. We are proving that resilience goes beyond surviving the climate crisis to build an inclusive prosperity architecture that can withstand it.

I invite innovators, funders, and policymakers to use this report not just as a reference, but as a call to action. The levers are clear, and the pathways are defined. Now is the time to direct our talent and capital toward the problems that matter most.



Mirik Gogri

Principal, Spectrum Impact
Founder, ITRI

Preface

For nearly three decades, MSC (MicroSave Consulting) has worked across sectors in some of Asia and Africa's most vulnerable countries to strengthen systems that enable inclusion, resilience, and opportunity for underserved communities. With more than 4,000 projects implemented and 3.7 billion people reached through MSC-supported interventions, this experience has shown that vulnerability rarely stems from a single failure. Rather, it results from weak livelihood systems, fragmented markets, inaccessible services, fragile institutions, and limited pathways to scale. Climate change has now been intensifying these structural gaps to transform everyday livelihood risks into systemic threats for millions of households.

This report, developed in partnership with The/Nudge Institute, reflects a necessary shift in how we understand and address climate resilience. It positions climate resilience as a challenge in livelihood systems, with a focus on climate-resilient livelihoods across circularity and food systems, including agriculture, livestock, fisheries, forestry, and waste management. These are sectors under compounding stress from climate change and natural resource depletion, and they will not be stabilised by isolated interventions. What they demand is system-level thinking, precisely applied.

The work behind this roadmap was deliberately rigorous before it became focused. Across five sub-sectors within food systems and circularity, we combined evidence reviews with practitioner insights and expert validation to identify critical problem areas, system chokepoints, and genuine opportunity spaces. What emerged was a dual lens: on one side, clearly defined breakthrough problem statements with the potential for prize-led innovation and market activation; on the other, a clearer map of deeper structural constraints — where ecosystems are not yet ready for direct intervention, but where long-term transformation must be built through institutions, policy, and collective infrastructure. Both matter. Neither alone is sufficient.

The roadmap that follows offers a structured approach to intervention — integrating evidence, market potential, stakeholder complexity, and climate impact to guide decisions on where talent, technology, and capital can most effectively unlock climate-resilient livelihoods.

It is designed as a shared resource: for innovators, funders, policymakers, civil society, and ecosystem leaders who are ready to move from diagnosis to action. Its goal is not to document the problem but to channel climate action toward where it matters most — strengthening livelihoods, reducing vulnerability, and building resilience into the everyday systems that sustain communities.

The levers are clear. The pathways are defined. What this moment demands is the collective will to use them — toward a future where resilience is not the exception, but the foundation.



Vikash Kumar Sinha

Associate Partner – Climate Change and Sustainability
MSC (MicroSave Consulting)

From the Director's desk

Six months ago, the^delta prize set out to answer a deceptively big question: Where exactly is climate change breaking India's livelihood systems, and where can focused innovations rebuild them? For a team that has spent five years building the Prize and its platform within The/Nudge Institute, this felt like the natural next frontier. Climate resilience goes beyond an environmental question alone. It is a challenge of livelihood systems, one that demands the same rigor, problem specificity, and solution orientation that Prize-led innovation is built for.

The work behind this report was deliberately voluminous before it became focused. In our work with MSC, we began by mapping every livelihood value chain affected by climate stress: From heat-suppressed worker productivity to natural resource depletion cascading across soils, forests, and fisheries. From that expanse, we narrowed to eight core challenge areas within food systems and circularity, examined 28 distinct value chains, and distilled insights from hundreds of sector experts, practitioners, scientists, and policymakers across India. What emerged is a set of Big Bets: Problem statements sharp enough to attract the brightest solvers and consequential enough to move systems.

A special word of gratitude to Mirik Gogri, whose work at Spectrum Impact and ITRI embodies the belief that the right problem, backed by catalytic philanthropy, is what finally opens the door for disruptive market capital.

Problem definition is not methodology but rather the Prize mechanism itself. The right problem statement excites talent, signals to ecosystems that solutions are within range, and creates the field evidence that unlocks the capital these communities cannot wait for. And when you refine that further to set the right thresholds for what a solution must achieve, at what cost, for whom—you stop inviting incremental answers and start demanding breakthroughs. Climate capital is not absent or timid. It has backed renewable energy and mitigation pathways with conviction. Yet climate-and-livelihoods has been treated as a different story: Too fragmented, too thin-margined, a pipeline not worth backing. This report challenges that story directly. From regenerative agriculture and last-mile soil diagnostics to livestock health monitoring, aquaculture management, and hard-to-recycle waste processing: These are volume markets with 10–30x capital multipliers, waiting for proof that Prize-led innovation is uniquely positioned to deliver.

At the center of this work are communities, which comprise 86% of farmers on less than 2 hectares, 30 million goat-rearing households, 28 million fishers, and 125 million forest-dependent families. They are not peripheral to India's development story. No path to inclusive prosperity bypasses them. The levers are clear, the pathways defined. What remains is collective will from funders, innovators, and ecosystem partners to direct talent, technology, and capital where it matters most.

the^delta prize exists to make that convergence happen. Its goal is to identify the right problems, build the next crop of changemakers, and unlock more than a decade of focused challenges alongside INR 10-plus billion in catalytic and market capital for India's most consequential livelihood problems. This report is your entry point.



Kanishka Chatterjee

Managing Director, the^delta prize

Ecosystem Partner, The/Nudge Institute



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Executive summary

India's food systems and circularity sectors form the backbone of livelihoods for millions. Yet, they remain deeply exposed to the increasing impacts of climate change. Across agriculture, dairy, fisheries, forestry, and waste management, these production systems face increasing pressures from erratic weather patterns, resource degradation, and structural inefficiencies.

These challenges are particularly severe for the bottom 30% of producers, who are thinly capitalized, lack access to resilient infrastructure, and have limited risk mitigation mechanisms. What appears as isolated production losses is a systemic failure, where climate risks cascade across value chains to erode incomes and resilience at scale. Existing interventions have largely been fragmented, reactive, and have failed to address the deeply embedded structural and systemic bottlenecks that increase vulnerability.

The creation of climate-resilient livelihoods in these sectors is a complex, long-term challenge that cannot be resolved through any single policy or program. Resolving this challenge demands a resilience-first, systems-level approach that identifies high-leverage intervention points and does not attempt to optimize every component of complex value chains. Markets are positioned as critical enablers of near-term change, capable of mobilizing capital, innovation, and talent at scale. Yet unlocking this potential requires overcoming persistent barriers: Fragmented supply chains, affordability constraints, and weak ecosystem coordination. **This report focuses on aligning market forces, technology, and catalytic capital to identify actionable pathways for climate-resilient livelihoods.**

The analysis highlights the interconnected thematic challenges:

1. Climate-induced productivity and income loss across agriculture, livestock, and fisheries;
2. Structural value chain inefficiencies;
3. Input and resource fragility that drives cost volatility for smallholders;
4. Systemic gaps in services, diagnostics, and infrastructure;
5. Constrained market access that limits income realization for producers;
6. Unsafe conditions and declining recovery efficiency for informal waste workers.

Together, these reflect deeply embedded bottlenecks that amplify climate risks and suppress livelihood resilience.

This report adopts a rigorous, multi-stage research approach to identify high-impact intervention opportunities. This includes a comprehensive literature review to map climate stress points and structural bottlenecks, followed by a problem decomposition exercise to define measurable thresholds for meaningful change. We conducted stakeholder consultations with sector experts and practitioners to validate ground realities and assess solution maturity. A structured selection and prioritization framework then evaluated opportunities along dimensions of scalability, feasibility, impact potential, and suitability for smallholder contexts.

Finally, listening circles and validation exercises were used to stress-test shortlisted opportunities and refine adoption pathways, which led to the identification of both prize-ready innovations and longer-term systemic gaps that required foundational ecosystem development.

The report highlights a focused set of “Big Climate Bets” on high-conviction, technology-enabled market opportunities across agriculture, livestock, fisheries, and waste circularity. In agriculture, the most investable opportunities lie in:

1. Soil health restoration and productivity enhancement for smallholders;
2. Regenerative farming transition models adaptable across crop types and agro-ecological zones;
3. Decentralized crop residue valorization to eliminate on-farm burning and generate rural income;
4. Last-mile soil diagnostics that enable real-time, field-level decision-making;
5. Next-generation, safety-compliant weed management solutions that are affordable at the smallholder scale.

In livestock, priority opportunities include affordable animal health and estrus monitoring at the farm level, and aggregation-led market-linkage models that enable smallholder poultry farmers to transition toward higher-value, free-range production systems. In fisheries, the critical gap lies in assessing preventable pond-level risks, which include water quality stress, disease vulnerability, feed inefficiencies, and seasonal environmental variability to maintain optimal pond conditions and prevent avoidable income loss for small-scale fish farmers. The waste and circularity sector presents a huge opportunity to develop cost-efficient processing technologies for hard-to-process, low-value waste streams.

While these opportunities are not exhaustive, they offer critical entry points to catalyze systemic change in India’s food and circularity sectors. By directing technology, markets, and catalytic capital toward the highest-leverage problem areas, this report charts a course toward a future in which resilience is embedded within everyday production systems to ensure livelihoods are sustained and strengthened in the face of growing climate uncertainty.

1. Introduction

Vulnerability to climate change in India is clear. Agriculture in the country has been grappling with soil health collapse, crop risks have claimed 15–25% of production, while post-harvest leakage has increased year on year. Nearly 86% of Indian farmers operate on less than two hectares. Dairy smallholders who own between two and eight animals face heat stress, which costs India ~INR 400 billion annually. Feed fragility and unsafe housing hobble the 23.79 million backyard households that make up India’s poultry sector. Water quality crashes and disease outbreaks roil the fisheries sector, draining USD 2.48 billion yearly. Forestry-fringe communities stare down 30–40% drops in non-timber forest produce in extreme years. Meanwhile, the waste and circularity sector bears the human cost for 1.5–4 million pickers who chase low-value recyclables. What often appears as a production problem is a system failure where climate risk travels unchecked from farmgate to market.

If we want to improve a sector’s economy and bring more wealth to those in it, we may assume the solution would be to fix every moving particle, to perfect every spoke of the wheel. Yet data, insights, and past transformative stories, from the White Revolution’s cooperative milk grids to the aquaculture boom in Andhra’s ponds, tell us a different story. If we can make a deeply meaningful difference in one part of the puzzle, it will affect that activity and influence other parts to play out coherently. We call these high-leverage intervention points “Big Bets.”

We propose here that sectoral transformation need not entail tweaking every activity in the value chain. It may mean fixing specific factors adeptly by enabling systems that may impact the overall health in a positive way, such as catalytic capital, tech-enabled diagnostics, and aggregation models. This would allow a shift from reactive interventions to a “resilience-first” approach that strengthens enabling infrastructure and aligns finance with climate volatility.

We argue that compared to policy, markets can play a critical role to mitigate the impacts of climate change and empower vulnerable populations to climate-proof their livelihoods. Markets mobilize capital, talent, and innovation on faster timelines to make them an essential near-term lever. However, adoption constraints, affordability gaps, and fragmented systems often prevent promising innovations from scaling and require direction through clear problem definition, aligned incentives, and ecosystem coordination to ensure solutions are usable, investable, and resilient. Through this Roadmap report, we bring to light those factors that can potentially lift up the economy through market interventions. With advancements in technology, from NIR soil scanners to IoT pond monitors, now is the best time to capitalize on sunrise sectors that require the capital inducement to scale to great heights.

This Roadmap does not attempt to fix every pressure point in the system. Instead, it identifies a set of Big Bets — carefully chosen, high-leverage opportunities where targeted market interventions can catalyze system-wide resilience and unlock real income gains in the face of climate volatility.

The objective is twofold: to identify where catalytic breakthrough solutions can be incentivized through mechanisms like the Δ prize, and to signal clearly where the ecosystem is not yet ready for such interventions — so that foundational work can begin in parallel. Both signals matter. One without the other is an incomplete map.

This Roadmap does not attempt to fix every spoke of the wheel. Instead, it identifies a set of “Big Bets”—carefully chosen, high-leverage opportunities where targeted market interventions can catalyze system-wide resilience and income gains in the face of climate volatility.

This report’s objective is twofold. First, it seeks to identify areas where catalytic breakthrough solutions can be incentivized through mechanisms, such as the ^delta prize. Second, the report intends to activate markets to solve identified problems and highlight areas where the ecosystem is not yet ready for such interventions.

About the ^delta prize

the ^delta prize is committed to helping India by enabling changemakers and shaping pathways to build resilient livelihoods. It does so through its Grand Challenge model—the first of its kind in India—by guiding changemakers to solve for the underserved and using competition to direct talent and capital into areas that private investment typically neglects.

the ^delta prize provides catalytic inducements aligned with seed-to-series funding needs, ensuring solutions are not only socially impactful but investable and scalable. It mobilizes ecosystems across corporates, government, academia, and funders to create systemic momentum and long-term adoption of proven solutions, while generating credible evidence through rigorous monitoring and evaluation processes. The prize prioritizes technology-led breakthroughs that deliver time-bound, quantifiable impact, unlock 10–30× downstream capital multipliers, and lead to sustained market or policy adoption.

the^delta prize challenges across food and circularity systems

- 01 **restore mitti challenge**
Soil health
identifying smallholder transition pathways to regenerative farming
- 02 **decode mitti challenge**
Soil health
why diagnosis must precede the cure
- 03 **fasal protect challenge**
Crop health
next-generation herbicides for sustainable & resilient agriculture
- 04 **cattle.ai challenge**
Dairy
enhancing productivity and animal welfare through early, affordable disease and estrus detection
- 05 **backyard2bazaar challenge**
Poultry
enhancing farmer income through access to specialty markets for organic and free-range eggs, which provides higher returns
- 06 **the aqualife challenge**
Fisheries
enhancing smallholder aquaculture productivity through optimal pond environmental management
- 07 **trash transformation challenge**
Waste and circularity
develop processing technologies for hard-to-process waste streams
- 08 **the parali challenge**
Rural waste management
unlocking additional farm income through crop residue management
- 09 **the re-freshwater challenge**
Wastewater treatment and reutilization
decentralized water treatment for residential and commercial buildings



2. Research approach and methodology

This roadmap was developed to identify high-impact opportunities to build climate-resilient livelihoods across food systems and the circular economy. Our research spanned agriculture, livestock, such as dairy, poultry, goatery, and fisheries, forestry-linked livelihoods, and waste circularity, with a deliberate focus on the bottom 30% of producers who face the highest climate and income vulnerability. Our twofold objective was to identify areas where a **prize-led intervention could catalyze breakthrough solutions** and activate markets to solve for the same, and to clearly surface critical problem areas where the ecosystem is **not yet ready** for such an intervention.

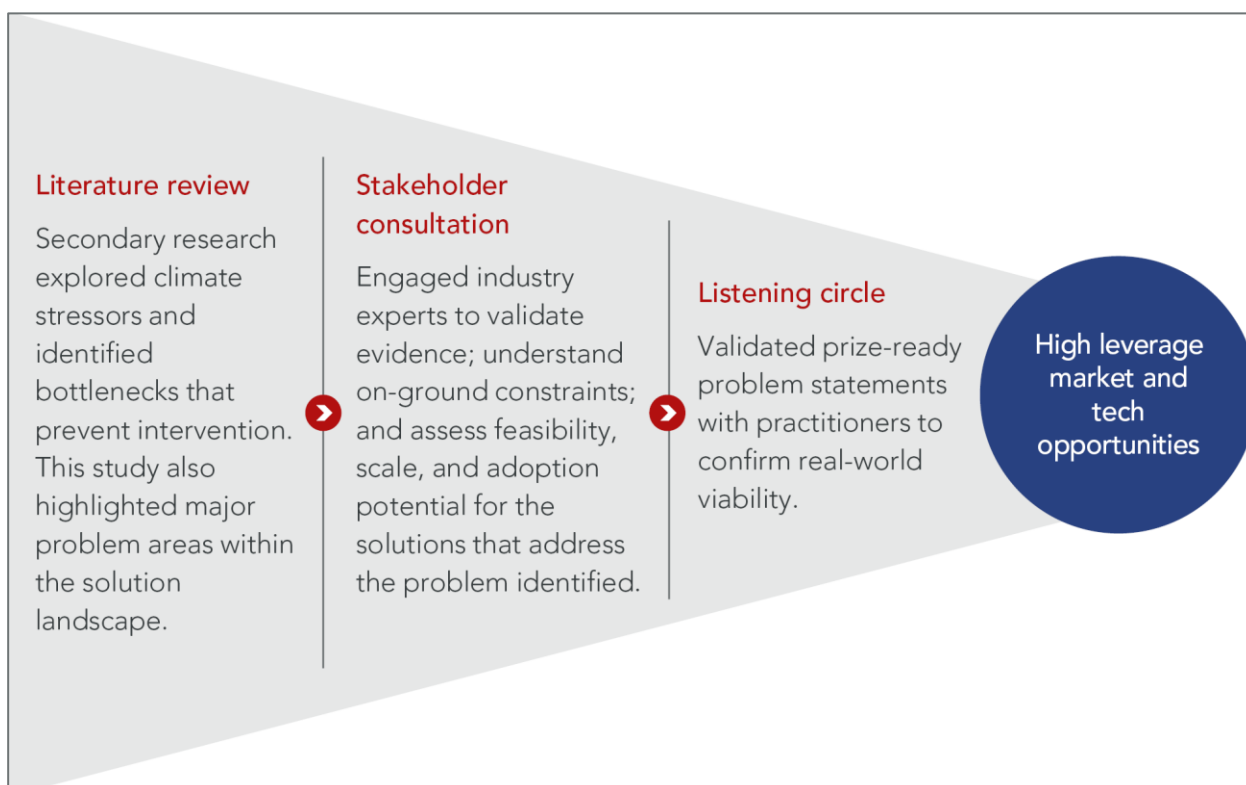


Figure 1: Our three-step research process

2.1 Literature review

The process began with a comprehensive review of secondary literature, based on internal research, academic studies, government data, evaluations, reports from multilateral institutions and market actors, including studies based on randomized controlled trials (RCTs). This review was done to:

- Identify climate-driven stress points across value chains;
- Diagnose structural bottlenecks and chokepoints limiting productivity, resilience, and income;
- Map existing public, private, and philanthropic interventions globally and in India.

We analyzed the evidence across quantitative outcomes, such as productivity, mortality, income, and qualitative insights, such as adoption barriers, behavioral constraints, and implementation learnings. The analysis was intentionally biased toward **technology-enabled or tech-supported solutions** with potential for step-change impact or scale, particularly those relevant to smallholder contexts.

2.1.1 Identification of problem areas

For each value chain, key problem areas were mapped across:

- The core areas under climate stress;
- The binding chokepoint that prevented resolution;
- Quantifiable thresholds beyond which meaningful livelihood or resilience gains could be unlocked.

These thresholds were designed to be measurable, realistic, and aspirational. These served as anchors for potential problem statements. Thresholds focused on access, affordability, reliability, or delivery, where solutions appeared to exist but failed to reach smallholders, rather than new inventions.

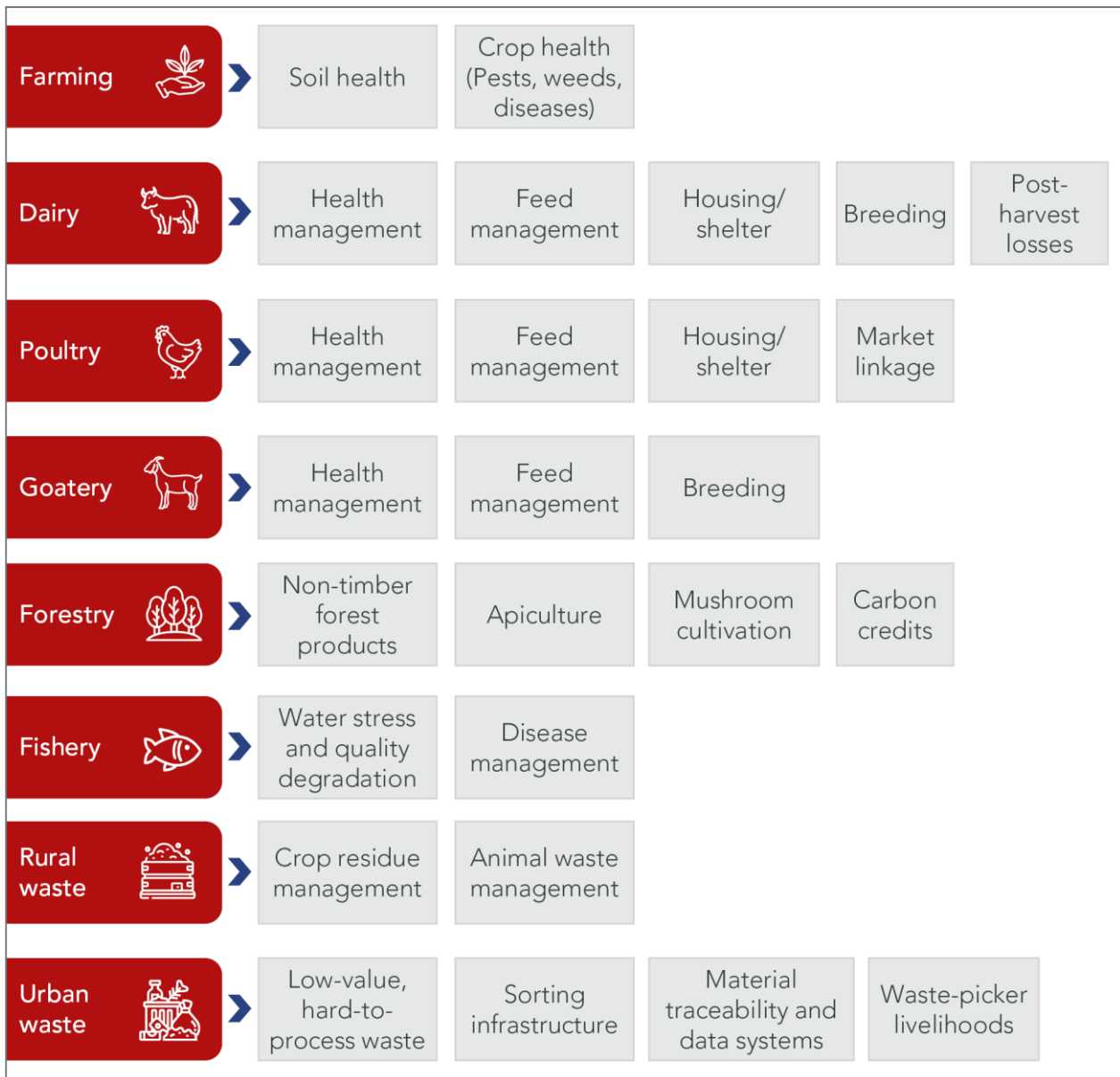


Figure 2: We covered 28 climate change-affected problem areas across eight sub sectors

2.2 Stakeholder consultation and validation

We validated the initial problem areas, chokepoints, and thresholds through structured consultations with industry experts, practitioners, researchers, and ecosystem actors across each value chain. These consultations were used to:

- Test whether identified constraints were truly binding on the ground;
- Assess solution maturity and market readiness;
- Understand the feasibility of inducing action through a prize mechanism.

Based on this stage, we iteratively defined and assessed the problem statements using a selection rubric that considered feasibility, scalability, replicability, and adaptability for smallholder contexts. Where stakeholders found a prize-led intervention not yet viable, the research ended with the documentation of problem areas, chokepoints, and potential solution directions.

2.3 Listening circles and final validation

For problem areas identified as prize-ready, the research progressed to a final validation layer through listening circles — structured sessions with domain experts actively working in the field. These were used to stress-test feasibility, validate thresholds and milestones, and assess adoption pathways and delivery risks. Where foundational constraints remained unresolved, listening circles were not conducted; stakeholder consultation alone was sufficient to determine that the ecosystem was not yet ready for prize-led intervention.

This process produced two core outputs.: a roadmap of high-priority problem areas for building climate-resilient livelihoods across food systems and circularity, and a set of clearly defined, quantifiable breakthrough problem statements where prize-led innovation can plausibly accelerate solutions or unlock scale.



3. India's food and circularity systems: Livelihood risks, climate impacts, and resilience pathways

India's food systems quietly absorb its deepest economic and climate shocks. From small farms and dairy sheds to fishing ponds, forests, and waste yards, livelihoods sustaining nearly half the country's workforce (Press Information Bureau 2025) and the majority of its rural households are increasingly exposed to forces they can neither control nor easily recover from. Climate change, resource depletion, and inefficiencies embedded across value chains converge, turning everyday production systems into sites of compounding risk.

These problems are already reshaping incomes, productivity, and survival strategies across rural and peri-urban India.

At the heart of India's food economy lies a structural imbalance. Nearly 86% of Indian farmers operate on less than two hectares of land (Press Information Bureau 2022). The average agricultural household incomes remain below INR 8,337 (approx. USD 90) per month (The Hindu 2021). High input costs, fragmented markets, and limited access to formal risk mitigation mean that even small shocks translate into outsized losses. Agriculture and allied sectors employ a disproportionate share of the workforce, while they generate relatively modest economic value. The system is dominated by small and marginal crop farmers, livestock keepers with a handful of animals, fishers who operate in climate-sensitive inland waters, and forest-dependent communities reliant on fragile ecosystems. These livelihoods are highly productive in aggregate, yet individually precarious.

Climate change magnifies this precarity at every level. Erratic rainfall disrupts sowing cycles. Heat stress suppresses crop yields, milk output, and animal fertility. Floods, cyclones, and droughts wipe out assets in a single season. For many producers, losses are no longer episodic — they are cumulative. Repeated shocks erode savings, deepen indebtedness, and force households to exit primary livelihoods altogether.

The damage continues further along the farm gate. Rising temperatures accelerate spoilage of milk, fish, fruits, and vegetables even where basic preservation is attempted. Weak cold chains and fragmented logistics bleed value after it has already been created. What presents as a production problem is in fact a systems failure — climate risk traveling unchecked from farmgate to market.

Livestock, fisheries, and forest-based livelihoods face parallel and compounding stresses. Heat stress alone drives substantial annual milk losses, directly eroding income for millions of dairy households. Inland fisheries suffer from declining water quality, oxygen depletion, and flood-induced losses that can wipe out entire batches of stock in a single event. Forest-dependent livelihoods — from honey collection to non-timber forest produce — face mounting threats from degradation, fires, and ecological instability. Across these sectors, climate change does not merely reduce output. It destabilizes the conditions required for livelihoods to exist at all.

These vulnerabilities are not unique to food production. They reflect a broader pattern in how essential production systems in India are highly decentralized, thinly capitalized, and exposed to climate and market volatility.

India's waste and resource-recovery systems exhibit the same structural vulnerabilities at a different scale. In rural areas, agricultural residues and animal waste are generated across

dispersed geographies and managed through informal, under-resourced practices — constrained by weak aggregation, limited finance, and negligible local processing capacity. Seasonal surges and climate variability push these systems further toward open dumping, burning, and material underutilization.

Urban systems face a different order of pressure but structurally similar constraints. Rapid urbanization has increased waste volumes faster than municipal capacity to collect, segregate, and process them. Inadequate source segregation, overstretched infrastructure, and dependence on informal labor limit both efficiency and resilience. Heat, flooding, and extreme rainfall further disrupt collection and treatment — compounding public health and environmental risks that fall hardest on the most exposed communities.

Across both rural and urban contexts, the structural logic is the same: materials that could hold value are lost, workers who hold the system remain unprotected, and the environmental cost is externalized onto the communities least equipped to bear it. The problem is not volume — it is how risk is organized, and who absorbs it.

India's food and waste systems reveal a shared reality. Livelihoods that underpin economic and nutritional security are operating with diminishing buffers against climate and market volatility. Small producers, informal workers, and decentralized enterprises continue to absorb shocks through income loss, asset depletion, and precarious work, while system-level inefficiencies remain structurally embedded.

The challenge, therefore, is not confined to any single sector. It lies in how essential production systems are designed, how value is retained or lost along the chain, how risk is distributed, and whose livelihoods ultimately bear the cost of instability.

The challenge, therefore, is not confined to any single sector. It lies in how essential production systems are designed, how value is retained or lost, how risk is distributed, and whose livelihoods bear the cost of instability. We need to shift from reactive, sector-specific interventions towards a resilience-first approach that strengthens enabling infrastructure, aligns finance with volatility, and supports technologies suited to real operating conditions.

We must reframe food and circular systems as resilience infrastructure to create a space to protect livelihoods at scale and unlock durable economic value. The choice is not between growth and resilience, but between continuing to absorb losses quietly across millions of households or deliberately rebuilding systems that can withstand the pressures they already face.

3.1 How and where catalytic capital can unlock opportunities

Investment opportunities are concentrated in areas where private capital can capture value through scalable service delivery, infrastructure development, and digital platforms that reduce transaction costs and improve transparency. Soil health and crop health services, aquaculture value chain upgrades, and circular waste solutions that convert organic waste into value-added products stand out as the most investable segments, given the strong demand and measurable economic benefits.

However, the main barriers to investment are fragmented smallholder supply chains, limited access to affordable finance, uneven data and digital infrastructure, and regulatory complexity. These barriers can be addressed through aggregation models, blended finance structures, insurance and risk-sharing instruments, and performance-based incentives linked to outcomes.

Farming

Indian agriculture and food system stand at a critical juncture. The sector is overwhelmingly driven by smallholder crop farmers who cultivate exceedingly small plots. 86% of the country's 126 million farm households own less than 2 hectares, with average landholdings of just 1.08 hectares, according to the [Agriculture Census, 2015-16](#). These farmers form the backbone of India's food system, yet they operate under severe economic constraints. The average farm household earns only INR 8,337 (approx. USD 837) per month from all sources, while spending approximately INR 3,740 (approx. USD 40) per month on cultivation inputs alone, according to [NABARD's All India Rural Financial Inclusion Survey, 2018-19](#). This precarious income-to-cost ratio leaves little room for investment in resilience, technology, or risk mitigation.

Climate vulnerability compounds these economic pressures. Rising temperatures, unpredictable rainfall, and more frequent extreme weather events are already reshaping agricultural outcomes. Studies by [FAIFA in 2025](#) warn that without adaptive measures, climate change could reduce India's agricultural productivity by up to 25% by 2050. Smallholders in arid and semi-arid zones, with limited land, minimal technology adoption, and no financial buffers, bear the heaviest burden of these climate shocks.

Against this backdrop, three interconnected challenges systematically erode the viability of smallholder agriculture and weaken the broader food system:

Where interventions can reshape farming systems

Target segment: Smallholder farmers with landholding size less than 2 hectares			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
Soil health	INR 2.1 trillion (2.54% of the GDP) (USD 22.5 billion)	<ul style="list-style-type: none"> 97.8 million hectares or 29.7% of India's land now stands degraded. Arid and semi-arid regions, such as Rajasthan, Gujarat, Haryana, Andhra Pradesh, and Karnataka, are among the hardest hit. (MoEFCC, 2021) About one millimeter of topsoil is lost each year, which amounts to more than 5.3 billion tonnes lost annually due to erosion Soil organic carbon (SOC), the engine of soil fertility, collapsed from 	<ul style="list-style-type: none"> Regenerative agriculture transition models: Food and agribusiness firms partner with farmers to provide SOPs, extension support, and regenerative input packages (e.g., biologicals, no-till, crop diversification, mulching), monetizing outcomes through carbon credits and regenerative certification premiums. India's regen-ag market is projected to grow from INR 4.95 billion (USD 53 million) in 2024 to INR 19.97 billion (USD 214

Target segment: Smallholder farmers with landholding size less than 2 hectares

Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
		<p>approximately 1% in the 1950s to just 0.3% today</p> <ul style="list-style-type: none"> ▪ Nutrient stress is systemic. 97% N deficient, 83% P deficient, 71% K deficient + widespread micronutrient deficiencies ▪ Vicious cycle where farmers must apply ever-increasing quantities of fertilizer to achieve stagnating yields. Nitrogen use efficiency has fallen from 48% in 1961 to just 35% today. 	<p>million by 2033) (16.7% CAGR) (IMARC, 2025).</p> <ul style="list-style-type: none"> ▪ Improved soil diagnostics: Current government soil testing covers only chemical parameters, which do not cover the physical and biological attributes that drive long-term fertility. Next-generation portable devices that use near-infrared (NIR) spectroscopy can deliver comprehensive soil profiling on a smartphone, paired with actionable advisory in local languages, so farmers can take corrective action. India's soil testing equipment market was valued at INR 10.64 billion (USD 114 Mn) in 2024 (TechSci Research, 2024).
Crop health	INR 0.9 –1.5 trillion (USD 10.8 – 18.1 billion)	<ul style="list-style-type: none"> ▪ 15–25% of production lost to pests, diseases, and weeds ▪ Current pest management remains largely reactive rather than preventive, with less than 5% of farmers accessing precision detection or integrated pest management solutions 	<ul style="list-style-type: none"> ▪ AI + satellite early pest and disease detection: Platforms, such as CropIn and DeHaat, use multispectral imagery and AI to detect crop stress weeks before visible symptoms via low-cost mobile apps. India's precision agriculture market is projected to grow from INR 28.4 billion (USD 305 million) in 2024 to INR 65.4 billion (USD

Target segment: Smallholder farmers with landholding size less than 2 hectares			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
			701 million) by 2033 (IMARC, 2025)
Post-harvest losses	INR 926.51 billion (USD 11.16 billion)	<ul style="list-style-type: none"> 74 million tonnes of crops are lost annually post-harvest For perishables like fruits and vegetables, losses can reach 30–40% of production. <6% cold chain coverage; minimal rural processing infrastructure 	<ul style="list-style-type: none"> Decentralized cold chain and cooling-as-a-service: Pay-per-use solar cold rooms remove the capital barrier for smallholders. India has only ~500 rural packhouses against a need of 125,000+. The cold chain market is projected to grow from INR 871.5 billion (USD 10.5 billion) in 2024 to INR 6.18 trillion (USD 74.5 billion) by 2033 at 24.7% CAGR (Grand View Research, 2025). Near-farm micro-processing: Small processors, FPO enterprises, or social ventures set up dehydration, or pulping, or minimal processing to convert surplus into storable SKUs These are monetized through processor offtake contracts and branded or B2B ingredient sales

Table 1: Market and non-market interventions (farming)

Dairy

India is the world’s largest producer and consumer of milk, home to more than 300 million cattle and buffaloes (DAHD, 2023). The dairy sector contributes approximately 5% to national GDP and supports the livelihoods of more than 80 million farmers (GoI, 2022). Yet this vast industry rests largely on the shoulders of smallholders. 92% of dairy households own just 1–4 animals, and

together they produce around 70% of India's milk (DAHD, 2024). Operating with thin margins and limited resources, these farmers are highly vulnerable to shocks, whether from disease, market fluctuations, or a changing climate.

Climate change is increasingly threatening smallholder dairy in multiple ways. Rising temperatures and more frequent heatwaves cause heat stress in cows and buffaloes. This reduces feed intake, lowers milk yields, and suppresses fertility as it weakens heat signals and conception rates (Veterinary World, 2016). Buffaloes are particularly vulnerable as the ponds they rely on for cooling are drying up (Dialogue Earth, 2024). Shifting rainfall patterns and prolonged droughts have made fodder and water scarcer and more expensive, which squeezes already tight farm budgets (Scroll, 2024). Extreme weather events, such as floods damage shelters, accelerate the spread of diseases, and in severe cases, lead to animal deaths. With limited capacity to invest in cooling systems, improved shelter, or insurance, many small farmers find it increasingly difficult to sustain their herds. Against this backdrop, four interconnected challenges systematically erode the productivity, profitability, and resilience of Indian smallholder dairy farming.

Where interventions can reshape dairy systems

Target segment: Bovine dairy farmers (cow and buffalo) with a herd size of 2 to 8 animals			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
Health and breeding management	~ INR 996 billion (USD 12 billion) (Dairy Herd Management, 2024)	<ul style="list-style-type: none"> ▪ Mastitis alone accounts for nearly 70% of milk production losses in India, costing more than INR 71.65 billion (USD 0.86 billion) annually, while almost half of affected farmers remain unaware that their cattle are infected (Financial Express, 2020). ▪ Farmers face a significant shortage in veterinary services, with a ratio of approximately one veterinarian for every 4,616 cattle units (ICAR) ▪ Difficulty in accurately tracking heat means India's artificial insemination conception rate is ~35%, compared to 	<ul style="list-style-type: none"> ▪ Low-cost wearables for disease and estrus detection: IoT-enabled pedometers and smart collars, such as Stellapps mooON, and Prompt BovSmart, track activity, rumination, and body temperature and other early parameters to detect and flag potential diseases, disorders, and heat cycles in real time through mobile alerts. This enables timely intervention through veterinary care, reduces AI rates, and inter-calving periods. India's livestock monitoring market is projected to reach INR

Target segment: Bovine dairy farmers (cow and buffalo) with a herd size of 2 to 8 animals			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
		60%+ in dairy-developed countries (NDDDB)	64.57 billion (USD 778 million) by 2030 at 19.8% CAGR (Grand View Research, 2025).
Feed management	Significant productivity loss and cost (feed makes up 60–70% of production cost)	<ul style="list-style-type: none"> ▪ India faces a chronic fodder deficit at 11–35% shortfall in green fodder, 23% in dry fodder, and 29–44% in concentrates nationally (USDA GAIN Report, 2023). ▪ Inadequate feeding accounts for nearly half of lost potential productivity in dairy animals (Down to Earth, 2025). ▪ Fodder prices nearly tripled in some regions during 2024 and distress sales of cattle was reported due to the inability to feed animals (Devex, 2024). 	<ul style="list-style-type: none"> ▪ Alternative feed enterprises: Hydroponic fodder units, azolla cultivation systems, TMR block manufacturing, and silage technology startups address the chronic fodder gap. These offer 3–5x higher biomass yield per liter of water than conventional fodder and year-round feed security independent of rainfall. ▪ National Livestock Mission fodder development: The NLM supports fodder seed distribution, fodder banks, and mineral mixture programs through cooperatives, with up to 50% capital subsidy (INR 5 million) for fodder entrepreneurship. But, as India faces a 35% deficit in green fodder and 10% in dry fodder, these interventions need to be expanded significantly to bridge

Target segment: Bovine dairy farmers (cow and buffalo) with a herd size of 2 to 8 animals			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
			the supply gap at the smallholder level (DAHD).
Shelter	A 5% drop in milk yield due to heat stress translates to more than INR 400 billion (USD 4.82 billion) in annual losses	<ul style="list-style-type: none"> Heat stress reduces milk production by 10–30%, suppresses fertility, and makes cattle more susceptible to diseases (<u>Frontiers in Veterinary Science, 2023</u>). Economic losses projected at INR 11–12 billion (USD 132–145 million) annually in the North Indian Plains alone due to heat stress (<u>Journal of Dairy Research, 2022</u>) Climate-smart shelters with cooling systems remain unaffordable for most smallholders with limited incomes 	<ul style="list-style-type: none"> Low-cost modular shelter and cooling solutions: Prefabricated shade structures with reflective roofing, low-pressure sprinkler–fan combinations, and solar-powered ventilation systems designed for 2–8 animal herds can reduce ambient temperature by 5–8°C at a fraction of commercial dairy-farm costs
Post-harvest losses	<1% physical spoilage; quality or adulteration issues are, however, significant	<ul style="list-style-type: none"> Physical milk losses are minimal due to rapid sales in the unorganized sector and cold chain in the organized sector Primary issues are quality-related: poor milking hygiene and mastitis lead to milk rejection; adulteration remains wide spread in informal channels 	<ul style="list-style-type: none"> Expanding organized procurement and village-level quality infrastructure: Only ~40% of India’s marketable milk surplus flows through organized channels (cooperatives, FPOs, private dairies) that offer electronic quality testing and rapid chilling at village collection centers; the remaining ~60% is handled by

Target segment: Bovine dairy farmers (cow and buffalo) with a herd size of 2 to 8 animals			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
			unorganized vendors with no cold chain or quality assurance. Expanding village-level collection infrastructure and bringing more smallholders into organized networks is critical to reduce quality losses and improve price realization (NDDB; USDA GAIN).

Table 2: Market and non-market interventions (dairy systems)

Poultry

Poultry has become a central pillar of India’s food and livelihood systems. It is the country’s fastest-growing livestock system and one of its most important protein sources. It produces more than 10 million tonnes of meat and 140 billion eggs annually, and contributes nearly half of total meat production (DAHD, 2024). The sector supports 23.79 million backyard households, alongside a rapidly expanding commercial industry of more than 850 million birds, and contributes 1% of national GDP and 14% of livestock GDP (DAHD, 2023). Its appeal lies in speed and efficiency. Broilers reach market weight in 35–40 days (ICAR, 2020), and layers begin laying within 18–20 weeks, which creates fast income cycles for smallholders and land-constrained households (ICAR, 2020).

Yet this structure also creates fragility. Poultry operates on thin margins and high-input dependence. Climate change intensifies these risks. Rising temperatures, humidity, and extreme weather events increase heat stress, disease pressure, and feed system instability. For small producers without buffers, insurance, or institutional support, even a single heatwave or disease outbreak can wipe out an entire production cycle and household working capital.

As climate variability accelerates, poultry is shifting from a high-return livelihood to a high-risk enterprise.

Where interventions can reshape poultry systems

Target segment: Smallholder poultry farmers with less than 100 birds			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
Feed system fragility	Income volatility, rising input costs, shrinking margins, and higher debt risk	<ul style="list-style-type: none"> ▪ Feed equals 60–70% of production costs ▪ When <u>maize prices</u> (Yes Bank - FICCI, 2023) rise faster than egg prices → structural margin squeeze ▪ Egg production growing faster than maize supply → supply pressure ▪ <u>>80% feed</u> (Yes Bank - FICCI, 2023) dependence on maize & soybean ▪ Climate-driven mycotoxins reduce <u>FCR, growth, egg quality</u> 	<ul style="list-style-type: none"> ▪ Enable backward linkages that support collective input aggregation through poultry FPOs and cooperatives ▪ Support waste-to-feed innovations (BSF, agro-by-products) alongside quality control
Climate-amplified disease burden	Flock wipeouts, income collapse, asset loss, cycle failure	<ul style="list-style-type: none"> ▪ Routine mortality: 8–15%; outbreaks: 20–100% losses (Oyegunle Emmanuel Oke 1 2, 2024) ▪ ND and Avian Influenza can cause total flock loss ▪ Heat stress reduces vaccine response by 25–35% (D. Renaudeau, 2012) ▪ Disease shifting from episodic chronic risk ▪ Weak last-mile vaccination, 	Build village-level preventive care delivery models combining Pashu Sakhi-based services, public vaccination outreach, and ICT-enabled farmer awareness on biosecurity, vaccination schedules, and disease prevention

Target segment: Smallholder poultry farmers with less than 100 birds			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
		surveillance, cold-chain delivery	
Climate-unsafe housing infrastructure	Heat stress mortality, productivity loss, and high vulnerability to extreme events	<ul style="list-style-type: none"> ▪ Egg production drops 10–20%; broiler weight drops 15–25% (Goel, 2021) ▪ As per field evidence, only 42% have ventilated or insulated sheds, and only 33% use cooling systems (Rashmi Vishwakarma, 2025) ▪ Climate-resilient housing costs exceed smallholder affordability 	Promote community-scale adoption of low-cost, climate-smart poultry housing through standardized designs, local fabrication, and capital subsidies, linked to SHGs or FPOs and rural housing or disaster-resilience schemes
Limited market access and value capture	Low price realization, dependence on local traders, and inability to monetize quality or access high-value markets.	<ul style="list-style-type: none"> ▪ 23.79 (DAHD, 2024) million backyard households largely sell into informal, low-margin local markets ▪ Commodity pricing absorbs productivity gains, which keeps farmer incomes flat ▪ Limited access to organized, premium, or differentiated markets 	Enable aggregation and market linkage for crossbred and free-range systems through an aggregator and certifying agencies to allow farmers to capture higher margins and access specialty markets

Table 3: Market and non-market interventions (poultry systems)

Goatery

India's goatery sector occupies a pivotal position in the country's rural economy. With a population of 148.9 million goats (DAHD, 2024), India hosts nearly 17% of the world's goat population. Goat-based livelihoods support more than 30 million households, with around 83% of goats owned by landless and smallholder farmers. This makes the sector one of the most widely distributed livelihood systems in rural India. Low capital requirements, rapid reproduction, and adaptability to

harsh environments have made goats a primary livelihood asset for communities who operate at the economic margins, making goats a poor man’s cow.

The majority of smallholders maintain herds of 3–10 animals, and under low-input extensive systems, a household with around five goats typically earns INR 10,000–15,000 (approx. USD 107-161) per year from goat rearing (M. K. Singh, 2018). With more than 85% of goats raised under extensive systems with no input, incomes remain highly dependent on animal survival, feed access, and basic animal health services.

Climate change is increasing these vulnerabilities. Declining fodder availability, rising heat stress, water scarcity, and shifting disease ecologies are destabilizing production systems that were historically adaptive to variability but not to persistent climate pressure. As a result, four structural pressures converge to undermine the sustainability of smallholder goat systems. These are the collapse of commons-based feed access, climate-amplified disease risk, exposure to thermal extremes due to inadequate housing, and unstructured breeding systems under environmental stress.

Where interventions can reshape goatery systems

Target segment: Farmers in an extensive system with less than 10 goats			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
Collapse of commons-based feed systems	Rising feed costs, income volatility, shrinking margins, and higher dependence on purchased inputs	<ul style="list-style-type: none"> ▪ <u>~35.6% national</u> fodder deficit across green, dry fodder, and concentrates ▪ Rapid shrinkage of common property resources (CPRs) due to land-use change and climate stress ▪ FAO/IPCC projections: Up to <u>60%</u> (Intergovernmental panel on Climate Change (IPCC), 2014)<u>biomass decline</u> in tropical grazing systems under warming ▪ <u>Transition from no-input systems → purchased feed models</u> (Sonu, 2025) 	Establish community-managed fodder banks and local fodder aggregation systems, supported by CPR regeneration, Panchayat oversight, and land-use planning to stabilize feed access under climate stress.

Target segment: Farmers in an extensive system with less than 10 goats			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
Climate-intensified disease burden	Asset loss, herd mortality, income collapse, livelihood instability	<ul style="list-style-type: none"> Vaccination coverage <u>only 30–35% vs ~70%</u> herd immunity threshold (Dr. S Vasantha Kumar, 2021) Deworming coverage <50%, mostly self-administered PPR outbreaks with mortality frequently >50% in affected herds Disease burden shifting from episodic outbreaks → chronic production constraint 	Strengthen continuous village-level animal health systems through routine vaccination and deworming delivered by trained community workers, combined with farmer sensitization and integration into public disease-control programs
Climate-vulnerable housing systems	Heat/cold stress, kid mortality, productivity loss, survival risk	<ul style="list-style-type: none"> Heat and cold stress <u>drive 10–35%</u> productivity losses (Das S. , 2025) Majority housed in kutcha or thatched structures High exposure to heatwaves, floods, cold spells <u>Field evidence</u> of rising kid mortality during extreme events Climate-resilient housing adoption limited to pilots and NGO-led models 	Scale low-cost, climate-resilient goat housing using aggregated demand models and targeted capital support through SHGs/FPOs
Unstructured breeding systems	Falling fertility, genetic dilution,	<ul style="list-style-type: none"> <u>~65% non-descript goats nationally</u> (K. Tamarasan, 2024) 	Enable community breeding services through buck rotation

Target segment: Farmers in an extensive system with less than 10 goats			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
	low productivity, poor survival	<ul style="list-style-type: none"> ▪ <u>Field evidence</u> suggest dominance of natural breeding systems ▪ Repeated use of same buck → inbreeding risk ▪ AI coverage extremely limited outside pilots. ▪ Climate stress disrupting <u>estrus cycles and reproductive efficiency</u> (DK Bagri, 2024). 	systems and expansion of AI-based reproduction beyond pilots, supported by trained technicians, semen logistics, and extension services

Table 4: Market and non-market interventions (goatery systems)

Inland fisheries

India's fisheries sector is a critical pillar of rural livelihoods, nutrition, and exports, supporting around 28 million fishers and fish farmers (Department of Fisheries 2023), at the primary level, with nearly twice that number engaged in post-harvest and allied activities. As the world's second-largest fish producer, India contributes about 8% of global fish production (PIB 2025). In 2023–24, the country produced 18.4 million tonnes of fish, where inland fisheries and aquaculture accounted for more than 70% of this total (PIB 2025).

Inland fisheries now dominate both production and employment and surpass marine fisheries in scale and reach. They engage more than 13.5 million men and 4.95 million women (Department of Fisheries 2023) in full-time roles, yet more than 60% of fishers earn low, vulnerable incomes. Ponds, tanks, and wetlands provide predictable harvests and steady employment, but these high-turnover, low-margin livelihoods remain highly sensitive to environmental shocks, disease outbreaks, and market fluctuations.

These systems are increasingly affected by climate change. Rising temperatures reduce dissolved oxygen and increase metabolic stress on fish, while droughts, floods, and erratic rainfall disrupt pond ecosystems. Saline intrusion and water pollution further threaten growth and survival. Such climate-driven shocks compound existing challenges, including disease outbreaks, feed limitations, and market volatility, intensifying income insecurity for smallholders.

Pond- and tank-based aquaculture offers a practical way to address these risks. By allowing farmers to manage stocking density, feed inputs, and harvest timing, these systems reduce exposure to

climate and disease shocks, improve predictability of yields, and strengthen the resilience of smallholder livelihoods.

Where interventions can reshape fisheries systems

Target segment: Extensive and semi-intensive fish farmers with ponds of less than 2 hectares			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
Water quality stress	Significant productivity losses from water pollution and poor water management, particularly for smallholder aquaculture	<ul style="list-style-type: none"> Water-related shocks are among the most reported causes of fish mortality, income losses, and farm abandonment for smallholders, especially in states, such as Andhra Pradesh, West Bengal, and Odisha (Kumar, Choudhary, and Choudhary 2019) Poor water quality leads to oxygen depletion, algal blooms, and mass mortality events in inland aquaculture systems. Stable water parameters boost fish health and yields, which often increases harvests by <u>20–35%</u> (Farmonaut 2025) when managed with technology 	<ul style="list-style-type: none"> Precision water quality monitoring systems: Develop and scale low-cost sensors and analytics for dissolved oxygen, pH, temperature, ammonia, and turbidity to optimize rearing conditions and prevent stress-triggered mortality Adoption of real-time monitoring is part of a broader precision aquaculture market expected to <u>grow ~15% CAGR through 2035</u> (Future Markets 2025), with India among the fastest-growing regional segments
Disease outbreaks and biosecurity failure	Estimated economic burden of aquatic diseases is approximately INR 23.17 crore (USD <u>2.48 billion per year</u>)	<ul style="list-style-type: none"> Disease outbreaks (viral and bacterial) routinely cause 15–30% mortality per cycle, with occasional total 	<ul style="list-style-type: none"> Rapid diagnostic and health monitoring kits: Develop field-deployable pathogen detection tools that enable early intervention and targeted

Target segment: Extensive and semi-intensive fish farmers with ponds of less than 2 hectares			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
	~15% of aquaculture production value (Patil et al. 2025)	<p>crop loss in shrimp and freshwater aquaculture</p> <ul style="list-style-type: none"> Limited access to diagnostics and veterinary services delays response and accelerates disease spread Weak biosecurity enforcement and limited farmer awareness exacerbate systemic risk 	<p>treatment. Vaccines, probiotics, and biosecurity inputs: Region-specific health solutions to reduce mortality and antibiotic dependence</p> <ul style="list-style-type: none"> Digital disease surveillance platforms: Develop apps that provide early alerts based on local outbreaks, water conditions, and weather patterns
Low-quality feed and nutrition	Indirect but persistent economic losses through poor growth, high feed conversion ratios, and elevated mortality	<ul style="list-style-type: none"> Several feed ingredients commonly available in India <u>have highly variable nutrient composition</u>, which makes it difficult to produce consistent, high-quality aquafeeds, especially for shrimp and other target species. This reduces feed efficiency and increases stress on cultured fish Variable quality of commonly available feed ingredients reduces growth 	<ul style="list-style-type: none"> High-quality formulated feeds: Expansion of nutritionally balanced, species-specific feeds with traceability and quality certification. India aquaculture feed market was valued at approximately INR 30,400 crore (USD 3.25 billion) in 2025 and estimated to grow from approximately INR 32,400 crore (<u>USD 3.47 billion</u>) in 2026 to reach <u>USD 4.84 billion by 2031</u>, at a CAGR of 6.83% during the forecast period 2026-2031 (Mordor Intelligence 2026).

Target segment: Extensive and semi-intensive fish farmers with ponds of less than 2 hectares			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market opportunities
		rates and weakens fish immunity	
Monitoring and advisory gaps	System-wide productivity and income losses due to delayed decision-making	<ul style="list-style-type: none"> ▪ Most small-scale farmers rely on visual stress indicators, which results in late detection of water quality or health issues ▪ Farmers faced critical challenges, such as inadequate technical support and high input costs, which limit the <u>effective adoption of improved fish farming methods</u> ▪ Limited extension and real-time advisory services hinder uptake of best practices in water quality, biosecurity, and nutrition 	<ul style="list-style-type: none"> ▪ Mobile advisory platforms: Develop local language digital tools that will deliver best practices on water quality, disease prevention, nutrition, and market updates ▪ Farmer alert systems: Build digital disease surveillance apps that will inform nearby outbreak trends and triggers to prompt proactive measures

Table 5: Market and non-market interventions (fisheries systems)

Forestry

India's forestry and forest-based livelihoods sector is a silent economic backbone for rural and tribal India. Around 300 million people depend (PIB , 2023) partially or fully on forests for their income and subsistence. Approximately 125 million people (Haque, 2020) forest dwellers, primarily Scheduled Tribes and other forest-dependent communities, rely on non-timber forest produce (NTFP), such as tendu leaves, mahua, lac, bamboo, honey, and medicinal plants, for seasonal income. For many tribal and forest-fringes households, NTFPs contribute 20-40% of annual household earnings (Boyapati and Muthukumarappan, 2025). This rises to more than 60% during lean agricultural seasons, which makes this sector a critical seasonal risk buffer.

Forest-based livelihoods operate within fragile ecological and market systems. Climate change now disrupts regeneration cycles, shortens collection windows, and increases yield volatility, which directly affects their income stability.

Unlike agriculture or dairy, forestry systems depend heavily on common property resources and natural ecological cycles, which limits smallholders' control over productivity drivers. With minimal access to working capital, aggregation mechanisms, or climate-risk buffering instruments, forest livelihoods are shifting from a traditional safety net to an increasingly volatile and high-risk income source.

Forest-dependent livelihoods face multiple, connected pressures rather than a single challenge. When forest productivity declines, households collect less produce and earn less income. Rising labor stress means people must work longer hours or travel farther to earn the same amount. Loss of biodiversity reduces the availability of high-value forest products and limits income options. At the same time, increasing climate variability makes harvest seasons less predictable, which leads to greater income uncertainty. Together, these factors reduce profitability, shrink earning periods, and weaken the long-term resilience of forest-dependent households. Without interventions that both restore forest ecosystems and provide alternative income sources, these pressures may push households toward distress-driven extraction and deeper livelihood insecurity.

Interventions that can help the forest dwellers

Target segment: Forest dwellers who live inside the forest and forest fringes			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
Decline in forest productivity	<ul style="list-style-type: none"> Reduced NTFP yields and shorter harvest windows Lower seasonal cash income Higher income volatility during drought or excess rainfall years 	<ul style="list-style-type: none"> NTFP yields <u>decline 30–40%</u> (Thakur, 2016) in extreme climate years With an average income of INR 15,000 to 30,000 (approx. USD 161 to 322) per year per household from NTFP (Thakur, 2016), the income loss is around INR 4,500 to 9,000 (approx. USD 48 to 97) annually 	<ul style="list-style-type: none"> Community-aggregated carbon credit platforms linked to assisted natural regeneration and agroforestry and structured as revenue-generating nature-based assets with INR 2,000 to 3,000 (approx. USD 21 to 32) per hectare annual carbon income potential Honeybee farming can help strengthen pollination cycles, support natural regeneration, and create an INR 45,000 to 60,000 (approx.

Target segment: Forest dwellers who live inside the forest and forest fringes			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
			<p>USD 483 to 645) per year alternative income</p> <ul style="list-style-type: none"> ▪ Mushroom farming can generate a short-cycle (30–45 days) income stream of INR 40,000 to 80,000 (approx. USD 430 to 860) annually
Increase in labor stress	<ul style="list-style-type: none"> ▪ Longer collection distances ▪ Reduced productive workdays ▪ Lower income per labor hour ▪ Increased distress migration 	<ul style="list-style-type: none"> ▪ 10–25% decline (Mishra, Mishra, Basu, and H, 2023) in effective labor productivity per season ▪ Around 9–14 earning days lost annually (out of 60–90 collection days) ▪ Daily earnings are around INR 250 to 300 (approx. USD 2.7 to 3.2), which leads to an annual loss of INR 2,500 to 4,000 (approx. USD 27 to 43) (Mishra, Mishra, Basu, and H, 2023) per household 	<ul style="list-style-type: none"> ▪ Decentralized primary processing and value-addition unit can increase income per unit collected, improving returns ▪ Skill training and production clusters will help enhance productivity without increasing extraction intensity
Loss of habitat and biodiversity	<ul style="list-style-type: none"> ▪ Decline in high-value NTFP species availability ▪ Reduced quality and price realization ▪ Localized seasonal income wipeouts 	<ul style="list-style-type: none"> ▪ Nearly <u>25–30% of forest areas</u> (FSI, 2023) have degraded ▪ India’s NTFP economy is at about <u>INR 200 billion (approx. USD 2 billion) annually</u> 	<ul style="list-style-type: none"> ▪ Biodiversity-linked carbon or nature credit platforms, which monetizes the conservation outcomes, and rewarding

Target segment: Forest dwellers who live inside the forest and forest fringes			
Problem area	Economic or system loss and impact	Scale of the challenge	Market and non-market interventions
	due to fires and degradation	(Bhattacharya & Anjali, 2025), and around INR 50 to 60 billion (approx. USD 540 to 640 million) of NTFP is at risk.	community-led habitat protection

Table 6: Market and non-market interventions (forestry)

Waste and circularity

India generates more than 62 million tonnes (CPCB 2022) of municipal solid waste annually, with volumes projected to reach 125 million tonnes (NITI 2021) by 2031. At the same time, waste composition is shifting toward multilayer packaging, composite plastics, blended textiles, treated paper, and electronic waste. These materials are poorly suited to low-capital recovery processes. As complexity increases and per-unit material value declines, informal recovery becomes less viable, which leads to selective extraction, higher leakage, and declining incomes. Recovery is increasingly constrained by upstream design and material choice, while informal workers and municipalities continue to bear the operational and financial burden.

Informal recovery was effective when materials were simple, visually identifiable, and economically recoverable through manual sorting. Current waste streams do not meet these conditions. Mixed waste increases contamination, complex materials require specialized processing, and resale values are insufficient to offset labor and transport costs. Informal workers, therefore, prioritize a narrow set of high-value materials, which leaves much of the waste stream outside recovery pathways.

This pattern is a structural outcome rather than a failure of implementation. Its effects are system wide. Increased pressure on landfills, rising environmental and public health risks, greater income insecurity for waste workers, and growing losses of recoverable material. What once functioned as a low-cost recovery backbone is increasingly a point of systemic vulnerability.

Where interventions can reshape waste systems

Problem area	Economic or system loss and impact on waste pickers	Scale of the challenge	Market and non-market opportunities
Low material recovery	<p>Unlocking the value of such waste streams can recover material value, reduce landfill costs, and create employment. For context, India could lose INR 12.4 lakh crore (USD 133 billion) in plastic material value by 2030, of which approximately INR 9.3 lakh crore (USD 100 billion)—about 75%—could be recovered through improved technology (FICCI and Accenture 2020). In the e-waste sector, secondary metal extraction has a potential of 6 billion, with only INR 10,200 crore (USD 1.1 billion) recovered today; advanced technologies could unlock the full extractable value. (Redseer Strategy Consultants 2025).</p>	<ul style="list-style-type: none"> ▪ India generates roughly <u>62 million tonnes</u> per year and is projected to reach <u>125 million MT</u> a year by 2031 Only about 50% of India’s municipal solid waste is treated (CPCB 2021), with the rest landfilled or unaccounted for Waste pickers focus on the <u>25–30%</u> of waste that is dry and has resale value, which leaves the low-value waste largely uncollected. ▪ Hard to process waste largely comprises low-value streams, such as multi-layered plastics (MLP), mixed textiles, e-waste, and construction debris. These are difficult to process due to their heterogeneous composition, mixed materials, and low purity, unlike high-value, single-material streams such as PET or mono-fiber fabrics. India’s overall plastic recycling rate of around <u>~25%</u>, underscores the 	<ul style="list-style-type: none"> ▪ Cost-efficient processing technologies: Develop modular, scalable solutions to convert low-value or hard-to-process waste, such as multilayer plastics composites, into usable feedstocks or secondary raw materials ▪ This improves efficiency beyond conventional recycling or waste-to-energy approaches

Problem area	Economic or system loss and impact on waste pickers	Scale of the challenge	Market and non-market opportunities
		broader challenge of managing such low-value waste.	
Human cost of informal recovery	There are <u>1.5-4 million informal waste pickers</u> across India, which forms a critical part of the recycling and resource recovery economy. Most earn irregular incomes below INR 100–400 (approx. USD 1-4) per day due to informal, inconsistent collection systems	<ul style="list-style-type: none"> ▪ Current systems rely on informal or irregular cash-for-waste payments, leaving waste pickers with inconsistent incomes and low motivation. There is a gap for structured, transparent, and technology-enabled incentive systems that are easy to adopt by both waste pickers and waste management actors, unlocking consistent participation at scale. ▪ Daily exposure to hazardous waste (biomedical, electronic, chemically treated plastics) without adequate PPE ▪ Limited access to social protection, healthcare, or formal recognition as essential service providers. ▪ Incentive systems that fairly compensate waste pickers can increase their incomes by <u>20–25%</u> or more, 	<ul style="list-style-type: none"> ▪ Tech-enabled incentive systems for waste pickers: Implement digital platforms to reward collection efforts, improve accountability, and increase incomes from INR 6,000–7,000 (approx. USD 64–75) to INR 20,000 (USD 215) within 12 months, supporting living-income standards. ▪ Integration with formal systems: Combine incentives with training, PPE, and social protection to enhance safety, efficiency, and professional recognition.

Problem area	Economic or system loss and impact on waste pickers	Scale of the challenge	Market and non-market opportunities
		depending on the design and scale of deployment	
Technological and infrastructure gaps	<p>Underutilized assets and inefficiencies are observed across the value chain</p> <p>Tech-enabled automation can <u>increase sorting accuracy, processing efficiency, and material recovery rates</u>, while doubling throughout without major infrastructure expansion. Research on IoT in waste management reports up to <u>30% reduction in collection costs</u> when smart sensors and analytics are used.</p>	<ul style="list-style-type: none"> ▪ Source segregation remains weak, and collection rates can fall below 50% in smaller cities ▪ Sorting remains predominantly manual, which limits the recovery of complex materials ▪ <u>Most waste management facilities operate</u> with minimal automation and inefficient sorting systems, which results in <u>low material recovery (<20-30%)</u> and wasted recyclable streams ▪ <u>Small</u> and medium municipalities often lack access to <u>cost- and land-efficient technologies</u>, which creates a gap between available technology and practical deployment ▪ Facilities operate below capacity due to contamination and inconsistent feedstock 	<ul style="list-style-type: none"> ▪ Modular upgrades for existing facilities: Retrofit material recovery facilities (MRFs), recycling hubs, and collection depots with scalable automation and sorting technologies to double throughput, reduce contamination, and optimize operational efficiency.

Problem area	Economic or system loss and impact on waste pickers	Scale of the challenge	Market and non-market opportunities
		<ul style="list-style-type: none"> ▪ Tech-enabled automation can <u>increase sorting accuracy, processing efficiency, and material recovery rates</u>, while doubling throughput without major infrastructure expansion ▪ Research on IoT in waste management reports up to <u>30% reduction in collection costs</u> when smart sensors and analytics are used 	

Table 7: Market and non-market interventions (waste systems)



4. Unpacking food and waste systems: A closer look

4.1 Farming deep dive

Sowing on shifting ground: The vulnerability of India's small farms

Indian agriculture is overwhelmingly driven by smallholder crop farmers who cultivate on exceedingly small plots. These farmers typically own less than 2 hectares (ha) of land and form the backbone of India's food system. Yet, they are economically constrained and highly vulnerable. Landholdings are tiny and fragmented, with an average of about 1 hectare per holding. Small and marginal farms now account for 86% of all farmers in the country, but they control only approximately 47% of total crop area. Such land inequality means millions of smallholders struggle to produce enough surplus to sustain their families, which leads to chronic rural distress.

Snapshot: Indian smallholder farmers

Share of farmers: 86% hold <2 ha of land

Average landholding: ~1.08 ha

Average monthly income: INR 10,218 (USD 109.4)

Average cultivation cost: INR 3,740/month
(approx. USD 40/month)

Rainfed dependence: 51% of cultivated land

Climate risk: Up to 25% yield loss by 2050 (without adaptation)



Low incomes and high costs further undermine the resilience of smallholders. The average farm household earns only about INR 10,218 (USD 123.3) per month from all sources, as of 2018-19 ([NSO, 2021](#)). At the same time, an average farmer spends roughly INR 3,739 (USD 45.0) per month on crop cultivation, including inputs, labor, and imputed costs ([NSO, 2021](#)), a significant expense relative to income. Many smallholders resort to credit or cut back on inputs, which can trap them in low productivity. Reliance on rain-fed farming is another risk factor, as only about 56% of marginal farms have access to irrigation, which leaves nearly half of smallholders entirely dependent on monsoon rains ([TRIF-Sambodhi, 2023](#)). An erratic or weak monsoon can mean disaster for these farmers, as about 49% of India's net sown area remains unirrigated ([MoJS, 2022](#)).

Climate change intensifies these challenges. Erratic rainfall patterns and more frequent extreme weather events already impact Indian agriculture. Smallholders with limited resources and no irrigation are the most exposed, as a delayed monsoon or a sudden drought can wipe out their season's earnings. Those in resource-constrained regions, such as arid and semi-arid zones, are especially susceptible to climate shocks due to limited land, minimal technology adoption, and a lack of financial buffers. Rising temperatures and shifting climate zones are also leading to new pest and disease pressures on crops. Post-harvest losses, already estimated at 74 million tonnes annually, worsen as heat waves damage stored grain and unpredictable weather disrupts harvest timing and market access. Smallholders who lack cold storage and processing facilities are particularly vulnerable, as they lose a significant share of their produce before it ever reaches

market. According to The Federation of All India Farmer Associations (**FAIFA**), climate change could reduce India’s agricultural productivity by up to 25% by 2050 without adaptive measures. In summary, Indian smallholder farmers face a precarious situation as small landholdings, low incomes, high cultivation costs, and mounting climate risks accumulate. This underscores the urgent need for resilient practices and supportive policies.

	Soil health and land preparation	Nutrient management	Crop health management	Harvest, post-harvest handling and market access
Core functions	<ul style="list-style-type: none"> ▪ Maintain soil organic carbon and soil structure ▪ Support root growth, moisture retention, and microbial activity ▪ Reduce erosion and long-term land degradation 	<ul style="list-style-type: none"> ▪ Apply balanced macro and micronutrients ▪ Improve fertilizer use efficiency ▪ Sustain crop growth without degrading the soil further 	<ul style="list-style-type: none"> ▪ Manage weeds, insect pests, diseases and nematodes ▪ Enable early detection and timely response ▪ Protect yield and crop quality 	<ul style="list-style-type: none"> ▪ Harvest crops at the right maturity ▪ Reduce losses during drying, grading, storage and transport ▪ Preserve saleable quality ▪ Improve price realization through aggregation and market access
Key risks	<ul style="list-style-type: none"> ▪ Soil organic carbon has fallen sharply in many regions ▪ Continuous monocropping and residue burning degrade soil fertility ▪ Excessive tillage weakens soil structure ▪ Salinity, alkalinity, acidity, and chemical contamination reduce productivity 	<ul style="list-style-type: none"> ▪ Nutrient deficiencies are widespread across Indian soils ▪ Fertilizer application is heavily imbalanced and nitrogen-skewed ▪ Poor soil organic matter reduces nutrient retention ▪ Farmers often apply more fertilizer with falling returns 	<ul style="list-style-type: none"> ▪ Weeds are the largest source of biotic crop loss ▪ Pest and disease outbreaks are often detected late ▪ Resistance to herbicides and insecticides is rising ▪ Counterfeit or substandard pesticides reduce control of pests ▪ Extension and early warning systems remain weak 	<ul style="list-style-type: none"> ▪ Harvest delays increase exposure to weather and spoilage ▪ Storage, handling and transport are often inadequate ▪ Perishable crops face severe fungal and quality losses after harvest ▪ Smallholders often sell quickly due to weak storage and bargaining power
Climate impact	<ul style="list-style-type: none"> ▪ Erratic rainfall and extreme weather accelerate soil erosion ▪ Drought and heat reduce biological 	<ul style="list-style-type: none"> ▪ Higher temperatures and degraded soils reduce nutrient use efficiency 	<ul style="list-style-type: none"> ▪ Rising temperatures speed up pest reproduction and spread 	<ul style="list-style-type: none"> ▪ Untimely rain and heat damage crop quality before harvest ▪ Humidity increases fungal

	Soil health and land preparation	Nutrient management	Crop health management	Harvest, post-harvest handling and market access
	<ul style="list-style-type: none"> activity and soil moisture Climate stress worsens long-term land degradation 	<ul style="list-style-type: none"> Heavy rainfall increases nutrient runoff and leaching Climate stress makes the imbalance in fertilizer use more damaging 	<ul style="list-style-type: none"> Heat and humidity increase pathogen pressure Climate change strengthens weed growth and insect-borne disease transmission Stressed crops become more vulnerable to pest and disease attack 	<ul style="list-style-type: none"> spoilage in storage and transit Climate shocks reduce marketable surplus and worsen distress sales

Table 8: Climate-linked risks and impacts across the crop farming value chain

4.1.1 Soil health

Beneath our feet: Reviving India’s living soil for a resilient future

For India’s 263 million farmers and agricultural workers (RIO), soil is not an abstract environmental concern, as it is the foundation of daily survival and generational livelihoods. Across the country’s diverse agricultural landscapes, from the rice paddies of Punjab to the cotton fields of Maharashtra, soil quality directly determines whether families can feed themselves, send children to school, or weather economic hardships. Healthy soil is a living ecosystem teeming with microorganisms, earthworms, and organic matter that work together to cycle nutrients, retain moisture, and support strong crop growth season after season. In a nation where agriculture contributes approximately 16% to the GDP and employs nearly half the workforce (India Budget), the condition of India’s soils carries immense weight for national food security and rural prosperity. However, Indian farmers increasingly confront a troubling reality as the soils that sustained their ancestors fail them. What once required minimal chemical inputs now demands heavy fertilizer applications to achieve the same yields, while crops become more vulnerable to droughts and pests. Soil health has degraded, which is the soil’s ability to function as a vital living system. This threatens not only agricultural productivity but the very fabric of rural India, where generations have depended on the land’s natural fertility to sustain their communities and culture.

Climate change and unsustainable agricultural practices accelerate soil degradation

Climate change has significantly accelerated soil degradation across India through multiple interconnected pathways. Rising temperatures and increasingly erratic monsoon patterns have intensified soil erosion. Extreme rainfall events wash away fertile topsoil while prolonged droughts leave land parched and vulnerable to wind erosion. The changing climate has also disrupted the delicate balance of soil microorganisms, which are essential for maintaining soil health and nutrient cycling. According to the National Bureau of Soil Survey and Land Use Planning, soil degradation now affects approximately 146.8 million hectares, or around 30% of India’s total land area (MDPI). Climate-related factors play an increasingly prominent role.

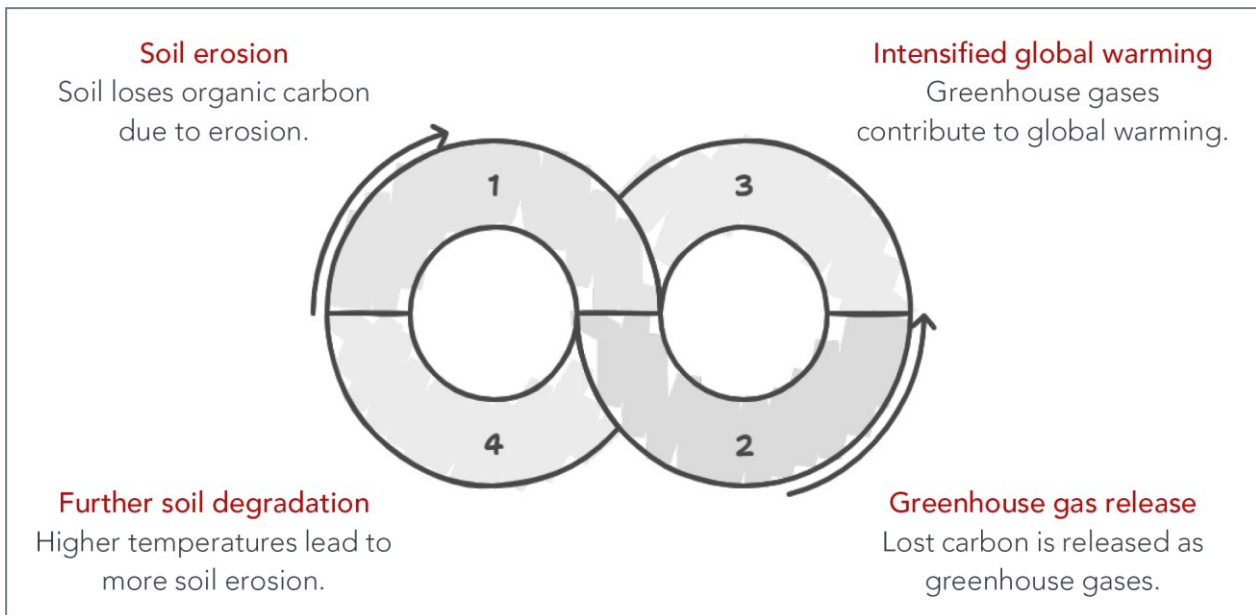


Figure 3: Soil degradation and climate change cycle. Source: [DrishtiIAS](#)

Agricultural practices have compounded these climate-driven challenges, which creates a concerning cycle of soil depletion. The Green Revolution's legacy of intensive monoculture farming, excessive use of chemical fertilizers and pesticides, and over-irrigation has severely damaged soil structure and fertility across vast swathes of agricultural land. Continuous cultivation without adequate fallow periods or crop rotation has stripped soils of essential nutrients. The shift away from traditional organic inputs to synthetic chemicals has decimated beneficial soil fauna and reduced organic carbon content. The practice of burning crop residue, particularly in Punjab and Haryana, where an estimated 23 million tonnes are burned annually ([BBC, 2020](#)), further degrades soil organic matter and beneficial microbes. Research indicates that the average soil erosion rate in India is approximately 16.4 tonnes per hectare annually. This results in an annual total soil loss of 5.3 billion tonnes throughout the country, which threatens the long-term sustainability of India's food security and the livelihoods of millions of farmers ([MDPI](#)).

The multi-dimensional crisis of soil degradation

Indian agriculture faces a convergence of soil degradation challenges that threaten the foundation of the nation's food security. The National Academy of Agriculture Sciences identifies four primary pathways through which this degradation occurs: nutrient and organic matter depletion, soil toxification by chemicals, salinization or alkalinization, and acidification. Together, these processes are systematically undermining the productive capacity of India's agricultural soils.

The collapse of soil organic carbon

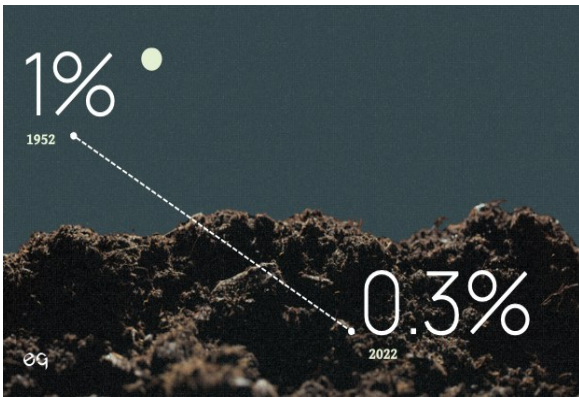


Figure 4: Fall in soil organic carbon level in India from 1952 to 2022. Source: [Equilibrium](#)

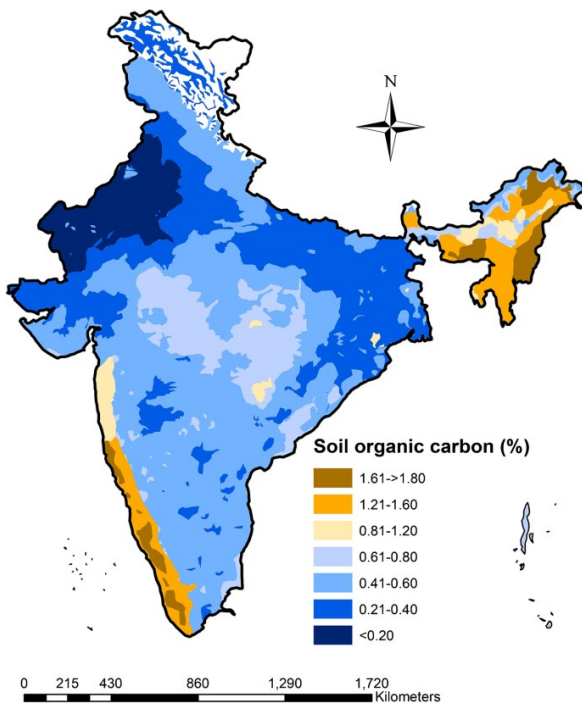


Figure 5: Map of soil organic carbon levels across India. Source: [Punia & Bharti](#)

The most alarming indicator of soil health decline is the dramatic fall in soil organic carbon (SOC) levels. According to the National Rainfed Area Authority (NRAA), SOC content has declined from approximately 1% in the 1950s to just 0.3% across most agricultural regions by 2022. This level is below the 1-1.5% threshold considered essential for healthy soils ([Business Standard, 2022](#); [Equilibrium White Paper, 2025](#)). In some dryland areas, SOC levels have fallen to as low as 0.1%.

This decline of SOC level has profound ramifications. SOC functions as the soil's life force, as it enhances water retention, maintains soil structure, supports beneficial microorganisms, and stores nutrients for plant uptake. When SOC falls below critical thresholds, the soil loses its capacity to retain applied nutrients, microbiological activity diminishes, and the natural fertility cycles of the soil break down. Research indicates that SOC below 1% reduces effective nitrogen supply to plants. This creates a vicious cycle where farmers must apply ever-increasing amounts of fertilizer to achieve lower returns ([Loveland and Webb, 2003](#)).

Nutrient deficiencies and the fertilizer efficiency crisis

Indian soils exhibit widespread deficiencies across macronutrients and micronutrients. Soil health assessments from 2015 to 2019 reveal that approximately 97% of Indian soils are deficient in nitrogen, 83% lack adequate phosphorus, and 71% are deficient in potassium ([DownToEarth, 2022](#)). Micronutrient deficiencies are equally concerning, with noticeable deficiencies in boron, iron, sulfur, and zinc.

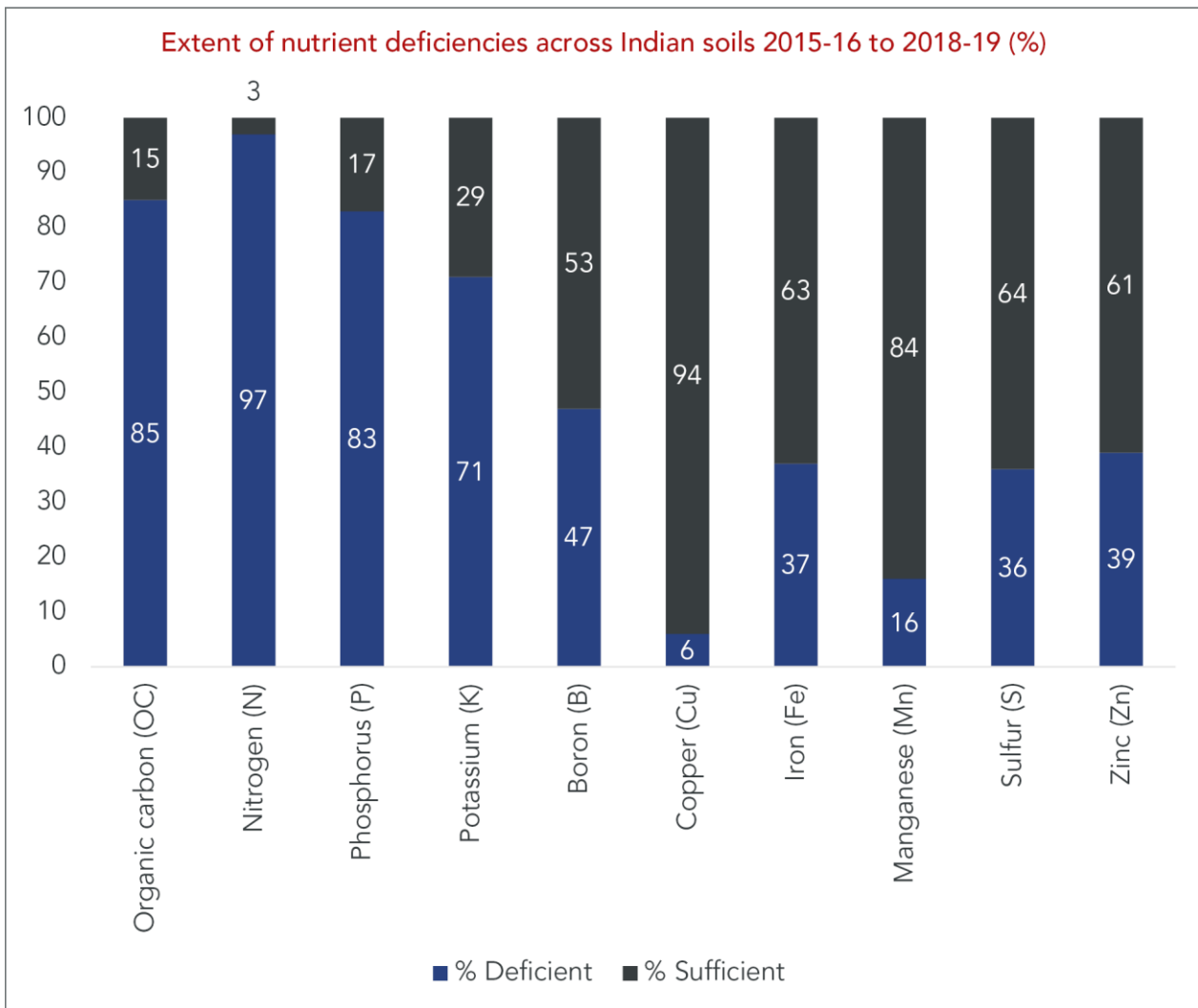


Figure 6: Extent of nutrient deficiencies across Indian soils 2015-16 to 2018-19 (%)

Source: Soil Health Card (SHC) scheme, Union Ministry of Agriculture and Farmers' Welfare, India. Figures are for the period 2015-16 to 2018-19.

This problem worsens with the decline in fertilizer use efficiency in India. Despite increasing applications of nitrogen, phosphorus, and potassium (NPK), crops absorb progressively less of what farmers apply. Nitrogen use efficiency (NUE) has fallen from 48% in 1961 to just 35% in 2018, which means nearly two-thirds of applied nitrogen is lost to the environment rather than being used by crops ([Singh, 2022, Agricultural Research](#)). The root causes are twofold. First, severely depleted SOC means soils cannot effectively retain or cycle nutrients, and without adequate organic matter, applied fertilizers either leach away, volatilize, or become chemically bound in unavailable forms. Second, India's fertilizer use is dramatically imbalanced. The ideal NPK ratio is 4:2:1, but actual application ratios have deteriorated nationwide to 7.7:3.1:1, reaching extremes of 31:8:1 in Punjab ([EPW, 2023](#)). Heavy subsidies on urea make nitrogen artificially cheap, and this imbalance starves soils of phosphorus and potassium while oversaturating them with nitrogen that crops cannot efficiently use. The result is a paradox, in which farmers apply more fertilizer, but see yields stagnate or decline.

Toxification, salinization, and acidification

Beyond nutrient depletion, Indian soils face multiple forms of chemical degradation. Soil toxification from heavy metals that include cadmium, lead, chromium, and zinc increases due to industrial discharges, contaminated irrigation water, and long-term accumulation from chemical fertilizers and pesticides. Studies have found heavy metal concentrations exceeding safe limits in agricultural areas near industrial zones, with these toxins that enter the food chain and pose human health risks (Chemosphere, 2019; PMC, 2021).

Salinization and alkalinization affect approximately 6.7 to 7 million hectares of land, with an additional 10% of the area that becomes salinized annually. Experts project that by 2050, half of India's arable land could be salt-affected if current trends continue (PreventionWeb, 2024). This salt accumulation restricts plant water uptake, damages soil structure, and causes annual crop losses of approximately 16.8 million tons (C4S).

Meanwhile, soil acidification affects about 48 million hectares out of 142 million hectares of arable land, with acidic soils widespread in the humid southwestern, northeastern, and Himalayan regions (Down to Earth, 2024). Acidic conditions reduce the availability of essential nutrients, such as phosphorus and calcium. They also increase the solubility of toxic elements, such as aluminum, which damages root systems. Acidification affects crop growth and productivity through a reduction in the availability of plant nutrients and predisposition of plants to other biotic and abiotic stress factors. Together, these chemical imbalances compromise soil structure, suppress beneficial microbial communities, and diminish the land's capacity to support healthy crop production.

The way forward: Regenerative farming as a smallholder-first pathway to restore India's soils

Regenerative farming offers a fundamentally different approach to agriculture, one that works with natural systems rather than against them. Conventional farming in India has relied on intensive tillage, monocultures, and heavy chemical inputs that have systematically depleted soil health. However, regenerative agriculture seeks to rebuild the soil as a living ecosystem. Through practices such as minimal tillage, mulching, diverse crop rotations, organic manure, and biological inputs, regenerative farming restores the natural cycles of nutrient availability, water retention, and microbial activity that healthy soils depend upon.

For Indian smallholders, regenerative farming must tackle soil degradation head-on to improve resilience to climate shocks and sustain long-term productivity. Such models should seek to:

1. Restore soil organic carbon to functional levels;
2. Improve fertilizer use efficiency by rebuilding the soil's capacity to retain and cycle nutrients;
3. Correct both macronutrient and micronutrient imbalances;
4. Reduce chemical toxification and pesticide residue risks;
5. Build resilience to salinity, alkalinity, and acidity.

The importance of regenerative agriculture has gained recognition, and a growing ecosystem of organizations has recently worked to scale these practices among Indian smallholders. Solidaridad Asia has worked with more than 17,000 cotton farmers in Maharashtra, demonstrating up to 30%

input cost reductions through efficient farm management and substitution of chemical inputs with on-farm bio-inputs ([Solidaridad Network, 2022](#); [Solidaridad Network, 2024](#)). The Nature Conservancy's PRANA initiative promotes no-burn, regenerative practices across Punjab ([TNC](#)). Varaha has implemented regenerative protocols across the Indo-Gangetic Plain ([Varaha](#)). Further, the Regenerative Production Landscape Collaborative (RPLC), founded by Laudes Foundation, IDH, and WWF India in 2020, is working to scale regenerative and restorative farming across Madhya Pradesh through two multi-stakeholder Compacts targeting a combined 140,000 smallholder farmers ([IDH, 2023](#); [Laudes Foundation, 2022](#)). Organizations, such as Swayam Shikshan Prayog and PRADAN, pioneer women-led regenerative models in drought-prone regions, which demonstrate 10-15% productivity gains and reduce cultivation costs.

The opportunity ahead is significant. For regenerative models to achieve transformative scale across India's 126 million smallholder households, they must be designed to work across diverse crop types and agro-ecological regions. These models must be easily adoptable by resource-constrained farmers, and critically, deliver improved crop quality and yields without the increase of cultivation costs.

“

India has more than 62 different soil types and 127 agro-climatic zones, which makes one solution impossible to implement across different regions.

- **Manoj Kumar Rupa, Co-founder and Managing Director in Capsber Agrisciences**

Organizations that demonstrate regenerative models to improve both soil health and farmers' livelihoods will drive widespread adoption. The pioneering work already underway proves this is achievable. The task now is to refine, validate, and scale these models into a nationwide transformation of Indian agriculture.

restore mitti challenge

identifying smallholder transition pathways to
regenerative farming

the big bet

<p>The opportunity</p>	<p>The world over, an estimated 3.6 million hectares of cropland are abandoned each year due to poor soil fertility, and India is no exception. Around 115 to 120 million hectares of land in the country are now considered degraded, and roughly one quarter of this area faces desertification, which costs the economy an estimated 2.54% of the GDP each year. A critical indicator of soil health degradation is the depletion of soil organic carbon (SOC), which averages just 0.3% in India compared to 1-2% in healthy soils or soils in many developed countries.</p> <p>The root cause is not just low soil organic carbon, but a broader breakdown of soil health, which includes loss of soil structure, nutrient imbalances, declining biological activity, and rising chemical toxification. Degraded soil health reduces water retention and fertilizer efficiency and increases vulnerability to droughts, pests, and climate shocks. A major opportunity is to transition smallholders to regenerative agriculture. Through it, soil can be rebuilt as a living system that restores nutrient cycling, improves income, enhances climate resilience, and sustains yields while reducing the dependence on chemical inputs.</p>
<p>Choke points</p>	<ul style="list-style-type: none"> ▪ Awareness of regenerative agriculture and its adoption remains limited among smallholders. Soil management is often reduced to fertilizer application, with little understanding of holistic soil health, including biological activity, structure, and nutrient balance. ▪ Restoration of soil health is a gradual, multi-season process that requires consistent adoption of multiple regenerative practices. No single intervention can rapidly deliver improvements across soil, yield, and income outcomes.
<p>Solution space</p>	<p>If smallholder farmers can be transitioned to regenerative agriculture models, it would lead to sustained, multidimensional improvements in soil health. Solutions should increase farmer incomes through improved crop quality and yields without increasing cultivation costs.</p>
<p>Target output(s)</p>	<p>Technical outputs:</p> <ul style="list-style-type: none"> ▪ 0.3% increase in SOC ▪ Soil NPK ratio of ~4:2:1, along with sufficient micronutrient profile (zinc, iron, boron, manganese, copper) ▪ Inputs should be non-toxic (LD50>5,000 mg/kg) to humans, animals, and soil organisms. ▪ The harvested crop should meet FSSAI residue limits (<0.01 mg/kg). ▪ Soil pH of 6.0-7.5 ▪ Soil electrical conductivity of E_{Ce} <2 dS/m (salinity)

- Bulk density
 - Sandy soils: < 1.60 g/cm³
 - Silty soils: < 1.40 g/cm³
 - Clayey soils: < 1.10 g/cm³

Farmer-centric outputs:

- 25% increase in income through improved crop quality and yield
- Cost of cultivation per acre should be comparable to existing chemical farming practices in the region.
- Should be applicable across crop types: Cereals, oilseeds, pulses, fruits & vegetables, cash crops.
- Smallholder farmers should be able to easily adopt the recommended regenerative practices and inputs.

The big bet

Scalable, smallholder-friendly regenerative agriculture transition models should be designed. These should deliver multidimensional improvements in soil health within 18 months, deliver a 25% increase in income per harvest cycle, and maintain cultivation costs. The solutions should be adaptable across crop types and agro-ecological zones and demonstrate clear economic and agronomic benefits for smallholder farmers.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Partha Ghosh	Program Lead, Social Alpha
2	Dr. Ramanjaneyulu GV	Executive Director, Centre for Sustainable Agriculture (CSA)
3	Dr. Renuka Diwan	CEO, BioPrime
4	Dr. Sunder Balakrishnan	General Manager, Natur Tec India
5	Vishal Langote	CEO, LMK Farmer Producer Company Limited

b. Listening circle

#	Name	Organization
1	Dr. Mandira Kochar	Senior Fellow, The Energy and Resources Institute
2	Manoj Kumar Rupa	Co-founder and Managing Director, Capsber Agrisciences
3	Dr. Renuka Diwan	CEO, BioPrime
4	Vishal Langote	CEO, LMK Farmer Producer Company Limited

Know your mitti

India's soil health crisis demands a radical rethink of diagnostics. More than 230 million Soil Health Cards have been distributed, yet fewer than one in five recipient farmers have changed fertilizer practices. The scheme tests only 12 chemical parameters, misses physical and biological indicators entirely, and delivers results months after sowing decisions are made.

Meanwhile, emerging portable technologies, from NIR spectroscopy to electrochemical sensors paired with AI interpretation, offer a path to field-ready, 30-minute soil analysis at a fraction of current costs. The gap between what India's soils need and what its diagnostic infrastructure delivers represents both a crisis and an opportunity: A market valued at INR 9,462 million (USD 114 million) in 2024 and growing, with the potential to reshape input efficiency, yields, and climate resilience for 140 million farm holdings.

India's Soil Health Card scheme: Massive scale, limited impact

The SHC scheme, launched in February 2015, is the world's largest government-led soil testing initiative. Across two completed cycles (2015–17 and 2017–19), approximately 230 million cards have been issued, which target all of India's estimated 141 million operational farm holdings. The scheme operates through roughly 2,500 soil testing labs, which include ~1,395 state government labs, several hundred ICAR/KVK labs, ~400+ private labs, ~429 sanctioned mini-labs, and ~109 mobile testing vans. The combined annual testing capacity stands at approximately 30–35 million samples, though many labs operate below capacity due to staff shortages, reagent supply disruptions, and equipment obsolescence.

The SHC tests 12 chemical parameters: pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), phosphorus (P), potassium (K), sulphur (S), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), and boron (B). This is an exclusively chemical profile. It does not measure physical parameters, such as soil texture, bulk density, water holding capacity, moisture content, infiltration rate, or porosity. The SHC also does not assess biological parameters, such as microbial biomass carbon, soil respiration, enzyme activity (dehydrogenase, phosphatase, urease), or earthworm counts. This chemical-only approach provides an incomplete picture of soil health, which is fundamentally a function of chemical, physical, and biological properties working in tandem.

The scheme's structural limitations are well-documented across evaluations by the NITI Aayog, the CAG, and parliamentary standing committees. Soil samples are collected on a grid basis: One sample per 2.5 hectares for irrigated land and one per 10 hectares for rainfed areas. This means individual farm plots are not tested separately. A farmer with a 1-acre plot receives the same recommendation as all neighboring plots within the grid. The turnaround from sample collection to card delivery is designed to take weeks. Yet, it runs 3 to 6 months and sometimes exceeds a year, which means cards frequently arrive after sowing decisions have been finalized. The CAG audit flagged this timing disconnect as a severe constraint on scheme effectiveness.

Usability for farmers presents another critical barrier. SHCs are printed documents with technical terminology, such as NPK values in kg/ha, micronutrient levels in ppm, which are largely incomprehensible to farmers with limited formal education or extension support. The NCAER evaluation, commissioned by the Department of Agriculture, found that while ~60% of recipients were aware of their SHC, only 10–12% could correctly interpret the recommendations. Inter-laboratory proficiency testing by ICAR has also revealed significant variation in accuracy across

labs, which raises concerns about quality assurance. The government reimburses approximately INR 190–300 (USD 2.29–3.61) per sample for the full 12-parameter analysis, with total per-card costs, including collection, transport, analysis, printing, and distribution, estimated at INR 250–400 (USD 3.01–4.82). Annual scheme budgets have ranged from INR 4–6 billion (USD 48.2–72.3 million).

The most sobering finding concerns adoption. Multiple independent evaluations by the NCAER, IFPRI, J-PAL South Asia, and various academic institutions consistently find that only 8–20% of farmers who received SHCs actually changed their fertilizer application practices. The IFPRI study by Fishman et al. concluded that “information alone is insufficient to change input use behavior.” India’s macro-level fertilizer consumption patterns confirm this: Urea consumption has continued to rise despite the scheme, and the national N:P:K application ratio remains severely skewed at approximately 6.7:2.4:1 against an ideal of 4:2:1, driven largely by distortions in urea subsidy.

Why comprehensive soil diagnostics are a precondition for climate-resilient agriculture

The evidence that links soil testing to improved agricultural outcomes is strong when testing is paired with actionable advisory. The ICAR’s All India Coordinated Research Project on Soil Test Crop Response (AICRP-STCR) has been running since 1967 across 30+ centers. It has consistently shown that soil-test-based targeted yield approaches deliver 15–25% higher yields than general recommended fertilizer doses and 20–30% higher yields than farmers’ practice, with fertilizer savings of 10–20%. The ICRISAT-led Bhoochetana program in Karnataka (2009–2014), which covered 5.5 million hectares across 30 districts, demonstrated 20–66% yield improvements in rainfed crops when soil-test-based micronutrient supplementation was paired with village-level advisory. The program achieved a benefit-to-cost ratio of 3.7:1 to 6.2:1.

India’s soils are in crisis. An analysis of more than 50 million soil samples collected between 2015 and 2019 revealed that 85% are deficient in organic carbon, 97% in available nitrogen, 83% in phosphorus, and 71% in potassium. Average soil organic carbon stands at just 0.3% against a healthy threshold of 1.5–2%. While estimates vary by methodology, approximately 96–147 million hectares are classified as degraded, with 3.6 million hectares of cropland abandoned annually due to poor fertility. The economic cost of soil degradation is estimated at ~2.54% of the GDP annually. India’s nitrogen use efficiency of 30–35% ranks among the lowest globally, with the global average at ~42%. This implies that most of the applied nitrogen is wasted and pollutes groundwater, emits nitrous oxide, and costs farmers money.

Chemical-only testing misses critical dimensions. Physical soil properties, such as texture, bulk density, and water holding capacity, explain 40–60% of crop productivity variation in many regions, often more than chemical fertility alone. Compacted soils with a bulk density greater than 1.6 g/cm³ can reduce root growth by 40–60% and yields by 15–30%. Soils with low water-holding capacity require 30–50% more irrigation frequency, which is a critical consideration for the 55% of India’s net sown area that is rainfed.

Biological parameters serve as early warning systems: Microbial biomass carbon and enzyme activity decline 3–5 years before chemical degradation becomes measurable, which enables preventive intervention. Every 1% increase in soil organic matter can increase water-holding capacity by approximately 20,000 liters per hectare. Comprehensive soil health indices that combine physical, chemical, and biological parameters explain 70–85% of yield variability, compared with just 30–45% for chemical parameters alone.

Global benchmarks underscore India's diagnostic gap. The Cornell Comprehensive Assessment of Soil Health (CASH) in the United States tests 15+ indicators. These span physical (available water capacity, aggregate stability, surface hardness), biological (active carbon, soil respiration, soil protein, organic matter), and chemical categories. The test costs ~ INR 7,055–8,300 (USD 85–100) per sample, with a 2–4 week turnaround time. The Haney Soil Health Test, developed by USDA-ARS, costs USD 50–65 INR 4,150–5,395 (USD 50–65) and measures biologically available nutrients through organic acid extraction. Even routine US soil testing at land-grant university labs costs INR 1,245–2,905 (USD 15–35), and returns results in 1–2 weeks.

The EU's proposed Soil Monitoring Law mandates member states to monitor soil health using standardized physical, chemical, and biological indicators every 5 years. The Netherlands' Eurofins Agro offers comprehensive soil health checks that include nematode analysis and microbial activity for EUR 100–150 with a 5–10 day turnaround. Meanwhile, Australia recommends testing every 3–5 years with deep sampling (0–60 cm) as standard. India's SHC, by contrast, tests only chemical parameters, costs INR 190 (~USD 2.30) at government rates, and takes 3–6 months, which makes it the cheapest yet slowest major national program globally.

The emerging landscape of portable diagnostics technology

Six core technologies underpin the next generation of field-ready soil diagnostics. NIR/Vis-NIR spectroscopy measures reflectance across 350–2,500 nm wavelengths to correlate organic bond absorption patterns with soil organic carbon, moisture, nitrogen, clay content, and texture. It delivers results in seconds without reagents. Electrochemical sensors that use ion-selective electrodes measure dissolved nutrient concentrations (NO_3^- , K^+ , NH_4^+ , pH) in soil extracts at lower hardware costs but with limited parameter range.

Capacitance measurements excel at soil moisture and salinity but cannot measure individual chemical nutrients. ATR (attenuated total reflectance) spectroscopy offers mineralogy and organic compound analysis with minimal sample preparation. AI/ML-based interpretation, which uses partial least squares regression, random forests, and neural networks trained on soil spectral libraries, is what makes all spectroscopy-based devices functional; model quality hinges on training dataset diversity across soil types.

The critical challenge for India is that models trained on Western soils often fail on Indian soils (tropical, alluvial, black cotton, red laterite), which makes an Indian soil spectral library essential.

An INR-114-million market with a 100-million-test gap

India's soil testing equipment market was valued at approximately INR 9,462 million (USD 114 million) in 2024 (per TechSci Research) and is projected to grow at a CAGR of 7–9% to reach INR 14,110–16,600 million (USD 170–200 million) by 2030. Laboratory-based equipment dominates at around 55–60% of the market. However, portable or handheld testing kits (~25–30%) represent the fastest-growing segment. The global precision agriculture market is valued at INR 996–1,245 billion (USD 12–15 billion) (2024) and is growing at 12–14% CAGR, while the global soil sensor market alone is valued at USD 350–450 million and growing at 14–16% CAGR.

The testing volume gap is staggering. India has ~140 million operational farm holdings and ~140 million hectares of net sown area. At the minimum recommended 3-year testing cycle, the country needs approximately 47–50 million tests annually. The current capacity delivers only 20–30 million tests. At the ideal annual frequency for intensive cropping areas, the gap balloons to 100+ million

tests. Even the existing capacity is quality-constrained: Many SHC labs test only basic parameters, and comprehensive testing, including micronutrients, physical properties, and biological indicators, is virtually nonexistent at scale.

The per-test economics tell a compelling story for portable deployment. Government lab testing under SHC costs USD 2.29–3.61 (INR 190–300) per sample (subsidized), but with 3–6 month turnaround. Private labs charge INR 500–800 (USD 6.02–9.64) with 1–3 week turnaround. A mid-range portable device at INR 100,000–300,000 (USD 1,205–3,614, amortized more than 2,000 tests across 3 years, brings the per-test cost to INR 25–150 (USD 0.30–1.81) with same-day results, which makes it competitive on cost and transformative on speed. The aspirational target specification for the Decode Mitti Challenge sets the bar at \leq INR 50,000 (USD 535) per unit. It amortizes to \sim INR 25 per test (USD 0.30 per test), achieves \geq 90% agreement with reference labs, generates geo-tagged plot-level results within 30 minutes, and measures chemical, physical, and biological indicators.

The “missing middle” between soil data and farmer decisions

The most critical lesson from the SHC scheme is that diagnostics without actionable advisory are ineffective. The IFPRI study by Fishman et al. found that providing soil testing information alone had “no statistically significant change” in fertilizer use compared to control groups. Adoption improved significantly only when farmers received simplified, actionable recommendations: What to apply, how much, and when.

The ICRISAT Bhoochetana program’s success (20–66% yield gains) was driven not by testing alone but by the human advisory layer: Trained village-level knowledge workers who explained results in Kannada and demonstrated micronutrient application. Similarly, Precision Development (PxD) RCTs in Odisha showed that digital advisory messages paired with soil test results led to 15–20% higher adoption than the SHC alone.

AI-powered advisory platforms are emerging to bridge this gap. The Microsoft-ICRISAT collaboration on AI sowing advisory, launched in Andhra Pradesh in 2016, combines soil data with weather forecasts and historical crop performance to deliver SMS-based recommendations. It reached approximately 4 million farmers and demonstrated 30% higher yields for participants.

Bihar-based DeHaat serves 2+ million farmers across 15 states with AI-powered recommendations that combine soil data, weather, and crop stage, delivered in Hindi and Bhojpuri through 10,000+ rural microentrepreneurs. Krishitantra integrates its portable testing hardware with cloud-based crop-specific advisory in four Indian languages. Government platforms, such as mKisan (60 million registered farmers) and IFFCO Kisan (11 languages), provide broadcast advisories but lack the personalization that soil-test-linked recommendations demand.

The delivery channel infrastructure exists but is underused. India has 12,000–15,000 registered FPOs, with a government target of 10,000 new FPOs by 2027–28. Each FPO aggregates 300–1,000 farmers and serves as a natural demand aggregation point that enables a single portable device to serve the entire membership and reduces per-test costs to INR 10–50.

An estimated 280,000–300,000 licensed agri-input dealers represent the most trusted information source for 40–60% of farmers, and models, such as Krishitantra’s dealer deployment, already place mini-labs at dealer points. The 731 KVKs (Krishi Vigyan Kendras) each have mandated soil-testing facilities, though their combined capacity is only 2–3 million samples per year, while needs exceed 30 million. The 530,000 Common Service Centers under Digital India already deliver 400+ government services and could serve as sample collection and result delivery points.

Structural barriers demand systemic solutions, not incremental fixes

Six interconnected barriers constrain the adoption of better soil diagnostics at scale. Cost is the most immediate. 86% of Indian farmers are small or marginal with less than 2 hectares in holdings and an average annual household income of approximately INR 122,000 (~USD 1,460).

For such households, individual purchase of even an INR 50,000 (USD 535) device is economically unviable. The only realistic path is FPO or community-level deployment models that spread costs across hundreds of farmers.

Digital literacy in rural India stands at an estimated 25–35%, with smartphone penetration at 40–45% of rural households. However, regular internet usage is lower at 30–35%. The gender gap is stark, with female rural digital literacy at just 15–20%. India's 22 scheduled languages and hundreds of dialects mean that most AgriTech interfaces in English or Hindi exclude large farmer populations, and technical terminology on SHCs remains inaccessible even in regional languages.

Moreover, lack of trust and behavioral inertia run deep. Multiple studies document that farmers rely strongly on traditional practices and local dealer advice rather than scientific test results. Furthermore, the urea subsidy is distorted, as urea costs ~ INR 266 (USD 3.20) per 45 kg bag, whereas its economic cost is INR 1,600–2,000 (USD 19.3–24.1). This disparity actively incentivizes the over-application of nitrogen regardless of soil test recommendations. Infrastructure constraints persist despite progress. While Saubhagya claimed 100% household electrification by 2019, rural areas in states, such as UP, Bihar, and Jharkhand still experience 8–14 hours of power cuts daily, and only 35–40% of rural India has reliable broadband. Cloud-dependent soil testing solutions face real connectivity barriers, which make edge computing and offline-first architecture essential but cost-additive.

Perhaps most critically, no national standard or certification framework is available for portable agricultural soil testing devices. BIS standards cover laboratory methods (ISO 2720 series), and ICAR protocols govern analytical procedures, but mandatory certification, type-approval process, or calibration framework for portable devices are unavailable. This regulatory vacuum simultaneously allows low-quality devices to proliferate and denies validated devices the formal credibility that would accelerate institutional adoption. A national calibration framework that benchmarks portable devices against reference laboratory methods across India's diverse soil types would be transformative.

From diagnosis to decision at the speed of agriculture

India's soil health crisis is quantifiable: 85% of soils are deficient in organic carbon, degradation costs 2.54% of the GDP, while a testing gap exceeds 100 million samples annually. The SHC scheme proved that scale without usability, speed, and advisory integration yields negligible behavioral change. The technology to deliver portable, multi-parameter soil diagnostics is available in the form of NIR spectroscopy, electrochemical sensing, and AI interpretation, which have all been demonstrated in Indian field conditions. Yet, but no single device meets the combined requirements of \leq INR 50,000 cost (USD 602), 30-minute turnaround, 90%+ accuracy across Indian soil types, and chemical-physical-biological parameter coverage. The devices closest to this specification (Bhu Parikshak at INR 50–80K, Proximal Soilsens at INR 30,000–60,000 (USD 361–723) test only chemical parameters. Those that test comprehensively, such as ChrysaLabs at INR 300,000–500,000 (USD 3,614–6,024), exceed the cost threshold by an order of magnitude.

decode mitti challenge

why diagnosis must precede the cure

the big bet

<p>The opportunity</p>	<p>India's soils are increasingly depleted, yet most farmers still make input decisions without reliable, plot-level soil data. The Soil Health Card scheme has expanded coverage, yet testing remains lab-led, slow, and largely limited to chemical nutrients. Grid-based sampling often misses field-specific variations, and results arrive too late to guide the current season.</p> <p>This creates a clear opportunity for portable soil diagnostics that FPO staff or trained farmers can use directly in the field. If testing becomes quick, low-cost, and covers core chemical, physical, and biological indicators, farmers can detect nutrient and carbon gaps early, improve fertilizer-use efficiency, avoid yield losses, and rebuild long-term soil health.</p>
<p>Choke points</p>	<ul style="list-style-type: none"> ▪ Lab turnaround is slow, and results often take weeks or months, which misses the sowing and top-dressing window. ▪ Even when results arrive, they are hard to interpret without extension support and rarely translate into simple, practical actions for smallholders. ▪ Current testing is narrow, focuses mostly on a few chemical parameters, and misses key physical and biological indicators of true soil health. ▪ Portable devices that can test chemical, physical, and biological indicators in the farm remain expensive and are offered by only a handful of global players. This keeps timely, plot-specific diagnostics out of reach for most farmers.
<p>Solution space</p>	<p>Portable, field-ready soil health diagnostics that deliver near-real-time, plot-level measurement of key chemical, physical, and biological indicators, paired with simple, farmer-ready recommendations. Advances in in-field sensing (e.g., spectroscopy and rapid electro-chemical methods) and AI-based interpretation make this increasingly feasible.</p>
<p>Target output(s)</p>	<ul style="list-style-type: none"> ▪ Generate geo-tagged results at plot level within 30 minutes of testing. ▪ Hardware cost \leq INR 50,000 (USD 602) per unit (Assumption from POV of a FPO: at ~2,000 tests over 3 years, this amortizes to ~INR 25 (USD 0.30) per test). ▪ Achieve $\geq 90\%$ agreement with reference lab tests across major Indian soil types. ▪ Measure a core set of chemical, physical, and biological indicators* required for actionable soil health decisions.

The big bet

Portable, smallholder-ready soil diagnostics should be developed. Farmers should be able to use it in the field to measure core chemical, physical, and biological soil-health indicators at plot level. The system should deliver results within 30 minutes, match laboratory accuracy within $\geq 90\%$, and provide clear, easy-to-act recommendations for farmers.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Partha Ghosh	Program Lead, Social Alpha
2	Dr. Ramanjaneyulu GV	Executive Director, Centre for Sustainable Agriculture (CSA)
3	Dr. Renuka Diwan	CEO, BioPrime
4	Vishal Langote	CEO, LMK Farmer Producer Company Limited

b. Listening circle

#	Name	Organization
1	Dr. Mandira Kochar	Senior Fellow, The Energy and Resources Institute
2	Manoj Kumar Rupa	Co-founder and Managing Director, Capsber Agrisciences
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4.1.2 Crop health

Pests, diseases, and weeds are threatening India's crops

If degraded soil represents the slow erosion of Indian agriculture's foundation, then pests, diseases, and weeds represent an active, relentless siege on whatever crops farmers manage to grow. Each season, India's 126 million smallholder households battle an extraordinary range of biotic threats that collectively destroy a staggering share of the country's agricultural output before it ever reaches market. Government estimates place annual crop losses from all biotic stresses, that is, damage caused by living organisms or pests, such as insects, diseases, and weeds, at approximately 33% of the total production, with weeds accounting for 12.5%, insect pests 9.5%, diseases 6.5%, and other pests 4.5% ([ICAR, 2023](#)).

For smallholder farmers who already operate on thin margins, a single pest outbreak, weed infestation, or disease epidemic can wipe out months of labor and investment, and push vulnerable families deeper into poverty. What makes this crisis particularly alarming is that it is accelerating: Climate change has been expanding pest ranges and shortening pathogen life cycles, labor shortages are making traditional weed management untenable, and over-reliance on herbicide and pesticide chemistries is driving the emergence of resistance.

Weeds

While insect pests and diseases tend to dominate public attention and policy discourse, weeds are the single largest cause of biotic crop losses in India—a reality that remains critically under-recognized. As per a study commissioned by the Federation of Seed Industry of India (FSII), weeds are responsible for approximately 25-26% of yield losses in kharif (monsoon) crops and 18-25% in rabi (winter) ([The Hindu, 2024](#)). In absolute terms, the total economic damage from weeds across just 10 major field crops amounts to approximately USD 11 billion annually ([Gharde et al., 2018](#)).

Weeds reduce yields by competing with crops for nutrients, water, sunlight, and space, particularly during early growth stages when crops are most vulnerable. Many weed species grow faster and are more resilient than cultivated plants, which allows them to gradually outcompete crops. However, unlike insects or diseases that cause visible symptoms, such as leaf damage or discoloration, weed-related losses build up slowly and often go unnoticed until harvest. Because the impact is gradual and less visually distinct, farmers may struggle to identify and address weed pressure in time.

Crops that suffer the most

As per estimates from the Government of India's All India Coordinated Research Project on Weed Management (AICRP-WM), weed-induced yield losses are the highest in oilseeds and pulses. In particular, the most affected are groundnut (35.8%), soybean (31.4%), green gram (30.8%) and black gram (30.7%). Substantial losses are also reported in coarse cereals, such as pearl millet (27.6%), maize (25.3%), and sorghum (25.1%). Even staple crops are significantly affected. Direct-seeded rice loses 21.4% and wheat 18.6% of yield to weeds.

These crops are especially vulnerable because many pulses and oilseeds have slow early growth and open canopies, which allows weeds to outcompete them for sunlight, water and nutrients during critical early stages, while intensive cereal systems and direct seeding often lead to strong competition between crops and weeds at the early stages.

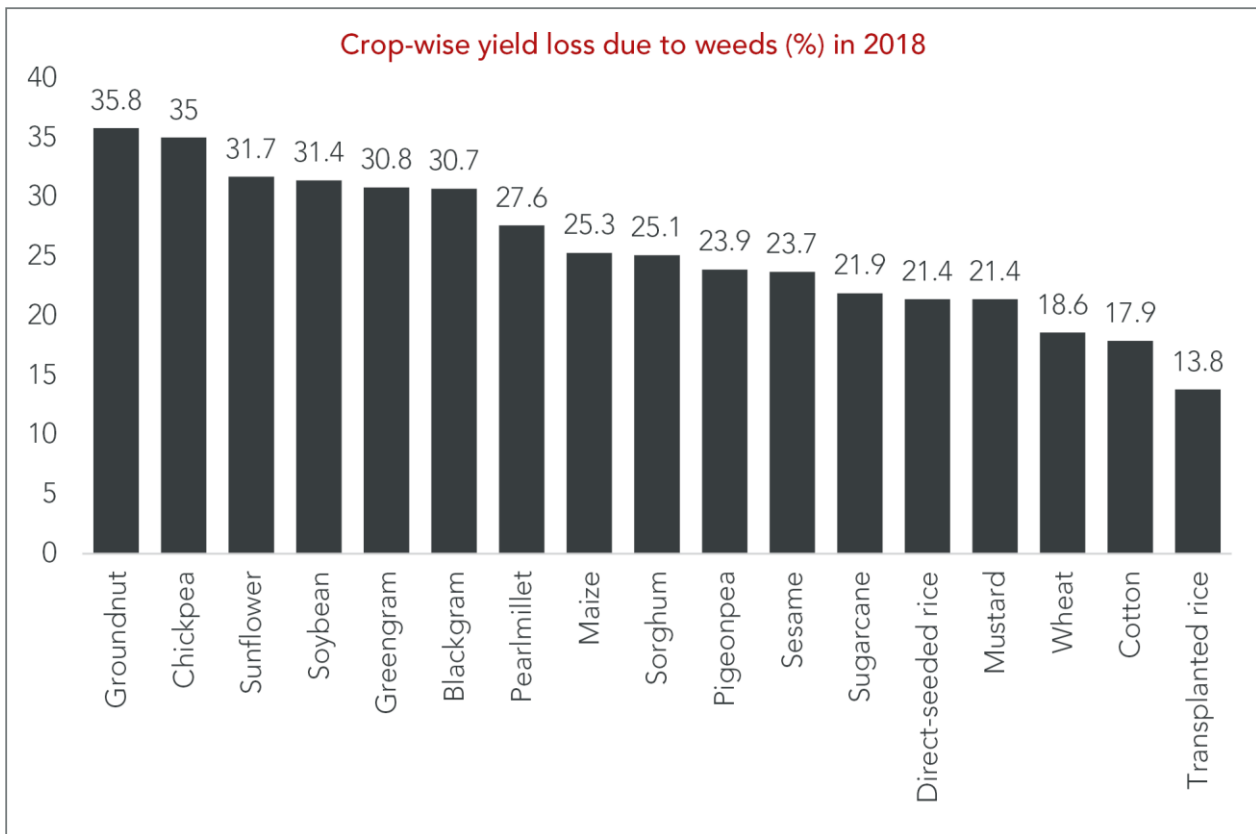


Figure 7: Average yield losses (%) due to weeds in major field crops of India, based on on-farm trials conducted under the All India Coordinated Research Project on Weed Management (AICRP-WM). Source: [ICAR-Directorate of Weed Research](#).

The labor crisis fueling the weed problem

Weed management in India has traditionally been a manual and enormously labor-intensive exercise that requires an estimated 20 person-days per hectare. At the national scale, manual weeding alone requires approximately 5 billion person-days of labor annually ([Rao et al., 2018](#)).

As rural India urbanizes and agricultural labor migrates to non-farm employment, manual weeding is becoming increasingly unaffordable for smallholders. This has fueled rapidly growing demand for herbicides, which are now the fastest-growing segment of India's crop protection market at approximately 10-11% CAGR ([Indian Express, 2025](#)). Herbicide use, however, has ushered in its own crisis.

The herbicide resistance threat

Globally, herbicide resistance has emerged as one of the most serious long-term threats to modern crop production, with more than 260 resistant weed species and 500-plus documented resistance cases across 71 countries ([Shekhawat et al., 2021](#)). As Indian agriculture shifts from labor-intensive manual weeding toward greater chemical dependence, similar risks are intensifying domestically, particularly in high-intensity systems such as the rice-wheat belt of the Indo-Gangetic Plains.

The repeated use of the same herbicides, such as glyphosate, over multiple seasons has already led to confirmed resistance in key weed species and steadily eroded the effectiveness of products

that were once dependable. As control failures increase, farmers are compelled to spray more frequently, combine products, or adopt newer and costlier chemistries, which drives up cultivation costs and reduces predictability of the efficacy of herbicides.

“

Herbicide resistance is a major concern for crop productivity in India. Farmers often lack awareness, yet still prefer traditional weeding methods over herbicides, and the effectiveness of available herbicides varies widely across crops and regions, leading to significant productivity losses.

- Naveen Ranjan - Zonal Demand Generation Lead, Corteva Agriscience

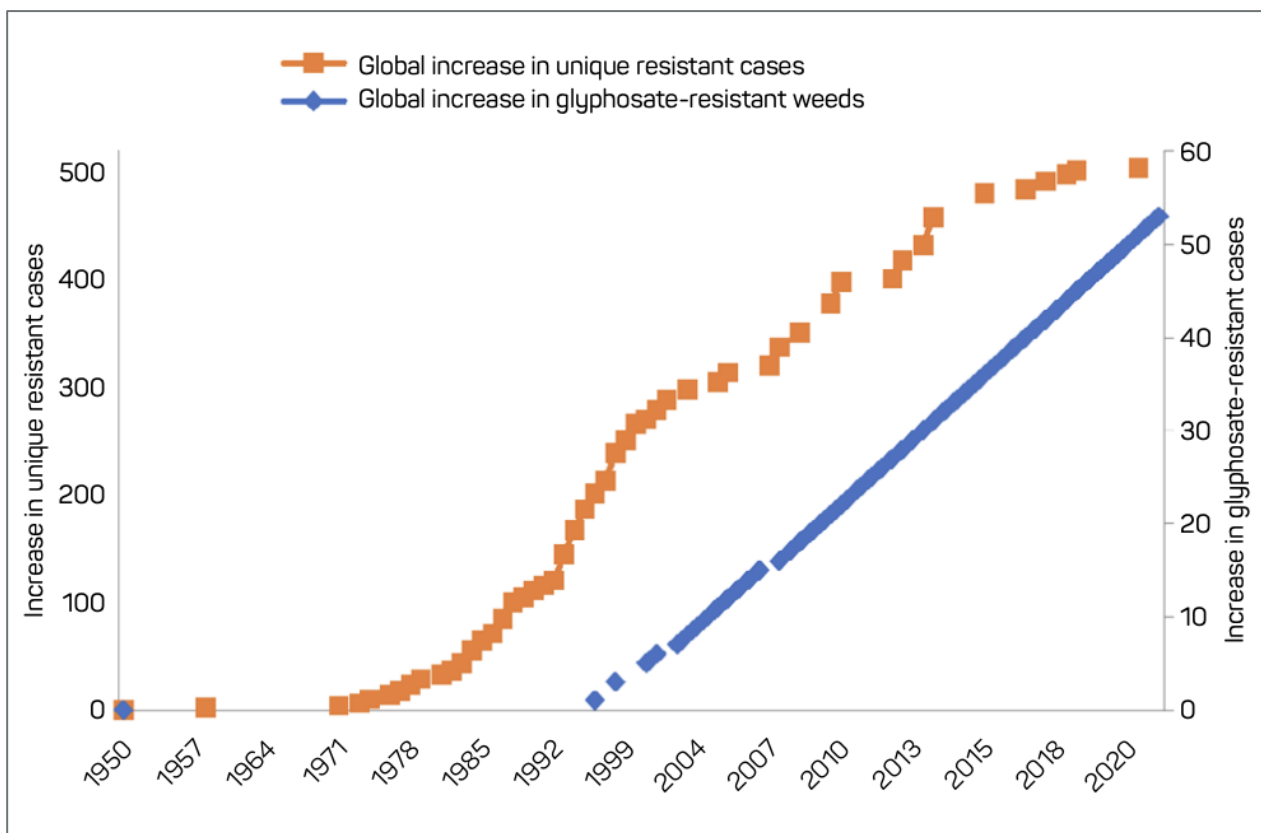


Figure 8: Global increase in documented herbicide-resistant weed cases. The number of confirmed resistance cases has risen steadily since the 1970s. The parallel rise in glyphosate-resistant weeds highlights the risks associated with repeated use of a narrow set of herbicide modes of action. Source: (Shekhawat et al., 2021)

Insects

Insects are the second-largest cause of biotic crop losses in India, responsible for an estimated 9.5% of total production losses annually (ICAR, 2023). In monetary terms, insect-led damage amounts to approximately INR 863.88 billion (USD 10.41 billion) per year (Dhaliwal et al., 2010). What makes India’s insect pest challenge particularly difficult is its sheer diversity. India’s tropical and subtropical climate supports a vast range of pest species active year-round, many of which are polyphagous, which means they can move across multiple crops in a single season.

Unlike temperate countries where cold winters suppress pest populations, Indian agriculture faces near-continuous pest pressure, compounded in recent years by the arrival of destructive invasive species, the breakdown of genetically engineered crop defenses, and the paradoxical effects of the very pesticides used to fight them.

Crops that suffer the most

Among India’s field crops, cotton has historically borne the heaviest burden of insect pests. This is largely because cotton has soft, nutrient-rich bolls that provide an ideal environment for insects, such as the American bollworm and the pink bollworm, to feed and breed in. The crop’s long growing season further compounds its vulnerability and gives multiple pest generations ample time to establish and multiply. At its peak, India’s expenditure on bollworm-targeted pesticides alone was estimated at INR 21,912 million (USD 264 million) per year ([Manjunath, 2004](#)).

Cereal crops face a distinct set of exposures. Rice, typically cultivated in warm, waterlogged conditions, creates a highly favorable habitat for sap-feeding insects, such as the brown plant hopper, which has emerged as a serious threat in key rice-producing states ([PreventionWeb, 2019](#)). Maize, with its dense canopy and large ears, is especially susceptible to the fall armyworm, an invasive species that spread across more than 90% of India’s maize-growing areas within roughly 16 months of its first detection in 2018 ([Shylesha et al., 2018](#)).

Similarly, pulses, such as pigeon pea and chickpea, which are cultivated extensively under rainfed conditions, are exposed to pod borers that thrive in the absence of robust pest management systems. Compounding all of these pressures, periodic desert locust swarms, which can consume food equivalent to the daily intake of 35,000 people, have swept across Rajasthan and Gujarat and devastated more than 50,000 hectares of wheat, mustard, and cumin crops ([Al Jazeera, 2020](#)).

In many respects, horticultural crops are the most structurally vulnerable of all. Fruits, such as mangoes, guavas, and melons, are inherently attractive to pests because of their high sugar content, thin or soft skin, and high moisture levels. These characteristics make them particularly accessible to fruit flies, of which more than 200 species have been documented in India ([Jha et al., 2015](#)). In certain crops, such as muskmelon, fruit fly infestations have been recorded at levels approaching total crop failure in affected districts.

Vegetables, such as brinjal, okra, and cabbage, share a similar exposure profile. Their tender tissues and rapid growth cycles offer favorable conditions for pests, such as shoot and fruit borers and the diamondback moth, whose populations have intensified appreciably as rising temperatures shorten breeding intervals and expand their geographic reach ([Dhaliwal et al., 2018](#)). Unlike large-scale commodity crops, fruits and vegetables are also highly perishable, which implies that even moderate pest damage can make an entire harvest unmarketable.

Crop	Pest	Yield loss (%)
Brinjal	Shoot and fruit borer	70–75%
Cabbage	Diamondback moth	52%
	Cabbage butterfly	40%
Cowpea	Spotted pod borer	36%

Crop	Pest	Yield loss (%)
	Hadda beetle	13–88%
Okra	Shoot and fruit borer	35%
	Red spider mite	7–48%
Tomato	Tomato fruit borer	50–80%
	South American pinworm	50–100%
Cucumber	Cucumber moth	23%
Pointed gourd	Fruit fly	30%
Watermelon		28.55%
Bottle gourd		30–100%
Bitter gourd		41–89%
Chili		Black thrips
	Chili thrips and yellow mite	50%

Table 8: Yield losses due to major, invasive, and emerging insect pests in vegetable crops

The invasive species crisis

India has witnessed a sharp acceleration in the arrival of alien invasive insect pests. While roughly 10 invasive insect species were recorded over an entire century between 1889 and 1989, more than 15 new species have entered the country in just the last decade alone (Kaur et al., 2025). These pests, once established, often thrive precisely because they arrive without the natural predators, parasitoids, and pathogens that kept them in check in their regions of origin.

Globalized trade, India’s extensive and porous borders with neighboring countries, and the sheer diversity of crops grown across the subcontinent all create pathways for introduction and establishment. The fall armyworm, the cotton mealybug, the coconut mite, and the serpentine leaf miner are all examples of pests that arrived from abroad and rapidly became entrenched threats (Indian Journal of Entomology, 2018). India’s existing quarantine and regulatory framework, while present on paper, has struggled to prevent these incursions in practice.

Insects are adapting faster than our ability to control them

Insecticides account for approximately 72% of India’s total pesticide market (Mordor Intelligence, 2024). But heavy, repeated use is driving widespread resistance. Pink bollworm has overcome genetically engineered Bt proteins. Rice planthoppers show declining susceptibility to conventional insecticides. Whitefly populations proved effectively immune to intensive spraying during the 2015 Punjab cotton crisis. As pests develop tolerance, farmers spray more frequently and shift to costlier products, which drives up costs while pest pressure persists.

Diseases

Plant diseases and nematodes together constitute the third major category of biotic crop losses in India. Diseases alone are responsible for an estimated 6.5% of total production losses annually (ICAR, 2023). Meanwhile, plant-parasitic nematodes, often grouped separately due to their distinct biology, cause an additional average yield reduction of 21.3% across the 30 major crops assessed. This amounts to approximately INR 131.14 billion (USD 1.58 billion) in annual losses (Kumar et al., 2020).

While neither category commands the same public attention as weeds or insect pests, their combined impact is immense. What makes them particularly insidious is that both tend to operate out of sight. Fungal, bacterial, and viral pathogens attack internal plant tissues, while nematodes feed beneath the soil surface, which means by the time visible symptoms appear, the damage is often already severe and largely irreversible.

India's tropical and subtropical climate, with its prolonged monsoon seasons and high relative humidity, creates conditions inherently conducive to the proliferation of both pathogens and nematodes. Of the approximately 30,000 plant diseases recorded worldwide, around 5,000 occur in India, and fungal infections alone are estimated to reduce crop yields in the country by roughly 5 million tons per year (Sharma & Karthikeyan, 2022).

Crops that suffer the most from diseases

Among cereals, rice and wheat are India's two most critical staple grains and are particularly under pressure from disease. Rice, cultivated predominantly in warm, waterlogged environments with high humidity, provides near-ideal conditions for fungal pathogens. Rice blast is the most destructive of these. It affects the crop at virtually every growth stage and causes yield losses estimated to be sufficient to feed approximately 60 million people annually (Kumar et al., 2021). Upland and rainfed rice ecosystems, which account for millions of hectares in eastern India, are especially vulnerable because they lack the controlled water management and input access that partially mitigate disease in irrigated systems.

By contrast, wheat is most exposed to rust diseases that thrive under cooler, moist conditions and have historically caused devastating epidemics across the Indo-Gangetic Plains. Globally, wheat rust fungi are responsible for an estimated INR 356.9–415.0 billion (USD 4.3–5.0 billion) in annual losses. India's vast, contiguous wheat belt remains highly susceptible to the rapid wind-borne spread of new rust species (Figueroa et al., 2018). The emergence of wheat blast, a fungal disease already established in neighboring Bangladesh, represents an additional frontier threat. Researchers warn of its potential to spread into Indian wheat-growing regions under warming climate conditions (Islam et al., 2019).

Pulses, which serve as the primary source of dietary protein for hundreds of millions of Indian vegetarians, face an especially damaging disease burden. Fusarium wilt is a soil-borne fungal disease that is among the most economically significant. It attacks both chickpea and pigeon pea with yield losses that range from 10–30% in a typical year, but can escalate to total crop failure under favorable conditions for the pathogen (Sunkad et al., 2019).

What makes pulses structurally vulnerable is a combination of factors. They are overwhelmingly cultivated under rainfed conditions with limited irrigation infrastructure, grown on marginal soils

where stress weakens plant defenses, and frequently sown in continuous rotations that allow soil-borne pathogens, such as *Fusarium*, to accumulate over successive seasons.

Diseases, such as Ascochyta blight, dry root rot, sterility mosaic, and Phytophthora stem blight, further compound the challenge. This collectively reduces pulse productivity well below its potential and contributes to India's chronic shortfall in domestic pulse production ([Springer, 2024](#)).

Horticultural crops are no less exposed. Vegetables, such as tomato, potato, brinjal, and chili, are highly susceptible to a range of fungal and bacterial diseases. This is largely because their high moisture content, dense planting, and rapid growth cycles create microclimates that favor pathogen establishment ([Tripathi et al., 2024](#)). Late blight of potato and tomato, which was responsible for the Irish Potato Famine, remains one of the most feared crop diseases globally and continues to cause significant losses in Indian production.

Post-harvest disease losses in vegetables are particularly severe, estimated at 30–40% of produce. This is because the perishable and high-moisture nature of these crops makes them vulnerable to fungal spoilage during storage and transport. For smallholder vegetable growers who operate without cold chain infrastructure or reliable market access, a disease outbreak at or after harvest can render an entire season's investment worthless.

The insect–disease nexus

A critical and often underappreciated dimension of India's crop disease challenge is the role of insects as disease vectors. The most damaging viral diseases include yellow mosaic virus in pulses and soybeans, leaf curl virus in tomato and chili, and various mosaic and mottle viruses in vegetables. Many of these are transmitted by sap-sucking insects, such as whiteflies, aphids, and thrips.

This creates a compounding effect. As rising temperatures accelerate insect reproduction and expand their geographic range, as discussed in the preceding section, they simultaneously increase the transmission and spread of the viral pathogens they carry ([Singh et al., 2023](#)). This means that the insect and disease crises are not independent problems but deeply interconnected ones. Failure to control vector populations has cascading consequences that extend well beyond direct crop damage.

Compounding the crisis: Cross-cutting challenges

Beyond the specific biotic threats, a set of structural and systemic challenges cuts across all three categories: Weeds, insects, and diseases. These make crop health management exceptionally difficult for Indian smallholders. The challenges interact and reinforce one another to create cycles of vulnerability that are extremely difficult to break.

Climate change is accelerating every threat simultaneously

Climate change does not merely add to India's existing pest, disease, and weed burden. It fundamentally reshapes the dynamics of all three. Rising temperatures accelerate insect metabolism and reproduction. This enables pests to produce more generations per season, expand into previously inhospitable higher altitudes and latitudes, and survive winters that once suppressed their populations ([Lehmann et al., 2020](#)). The fall armyworm's rapid colonization of Indian maize, which spread across 90% of growing areas within 16 months, is precisely the kind of explosive invasion that warming conditions facilitate.

For diseases, elevated temperatures and humidity extend the window for pathogen proliferation, while shifting monsoon patterns create the unpredictable wet-dry cycles in which fungal outbreaks thrive. Researchers have warned that climate change will alter plant–pathogen interactions, enable diseases to establish in new regions, and give rise to entirely new pathogenic strains ([Singh et al., 2023](#)).

Weeds, too, are direct beneficiaries. Elevated CO₂ boosts the growth of C3 weeds, many of which are among the most aggressive species in Indian agriculture, while warmer soils extend germination windows and accelerate weed establishment ([USDA Climate Hubs, 2021](#)). Critically, these effects are not independent. Warmer conditions simultaneously increase insect vector populations and the viral diseases they transmit, while drought-stressed crops become more susceptible to both pest feeding and pathogen infection.

The result is a compounding cycle in which climate change does not simply increase the severity of individual threats but intensifies their interactions, precisely the scenario that India's fragmented, chemical-dependent crop protection system is least equipped to handle.

Counterfeit and substandard pesticides

Even when farmers do invest in chemical crop protection, there is no guarantee that what they purchase will work. An estimated 25% of India's pesticide market consists of counterfeit, spurious, or substandard products ([FICCI, 2019](#)). These products range from diluted formulations to entirely inert substances sold in branded packaging. They fail to deliver pest control, yet still expose farmers, consumers, and the environment to chemical residues of unknown composition. The knock-on cost is high.

As per a report by the Indian Chamber of Commerce, the use of ineffective and illegal products results in the loss of 10.6 million tons of food per year. Meanwhile, exporters fear that the use of counterfeits will threaten India's position as one of the world's leading grain exporters, valued at USD 26 billion a year, due to traces of illegal products found in shipments ([CropLife International, 2023](#)).

For smallholders, the damage is doubly cruel: They bear the upfront cost of purchasing products that do not work, only to suffer crop losses afterward. The prevalence of counterfeits also erodes farmer confidence in legitimate crop protection products and undermines the scientific basis of pest management. This drives many to default to heavier, more frequent spraying, which further accelerates the resistance treadmill described in the preceding sections.

Gaps in early warning, monitoring, and extension

India's ability to detect and respond to pest and disease outbreaks before they escalate remains critically underdeveloped. Traditional pest monitoring relies on manual field scouting, which is a reactive and labor-intensive process, as visible symptoms typically appear only after significant crop damage has already occurred ([ScienceDirect, 2025](#)).

The public agricultural extension system, which should serve as the primary conduit between research institutions and farm-level practice, is severely overstretched. India has approximately 120,000 government extension workers responsible for more than 140 million operational farm holdings. This translates to an effective ratio of roughly 1:1,162, far below the FAO-recommended standard of 1:400 ([GSMA, 2025](#); [Gulati et al., 2018](#)).

In practice, extension services reach only an estimated 6.8% of Indian farmers (FAO, 2012). As a result, most smallholders have no access to prompt pest advisories, economic threshold guidance, or diagnostic support. When faced with unfamiliar symptoms, most rely on local pesticide dealers for advice, whose commercial incentives do not align with judicious pest management. This surveillance vacuum means that outbreaks, whether of fall armyworm, whitefly, or wheat blast, are typically detected only after they have already become widespread, by which point the response options are limited and far more costly.

The path forward: Opportunities to transform crop health management

The scale and complexity of India's crisis in crop health demand a fundamental shift from the current model of reactive, chemical-first pest control toward a system built on prevention, precision, and ecological intelligence. Two interconnected strategies hold the greatest promise for achieving this transition at scale: The nationwide adoption of integrated pest management (IPM) as the foundation of crop protection, and the deployment of digital technologies to close the monitoring and advisory gaps that currently leave millions of farmers without timely support.

Scaling integrated pest management across India

Integrated pest management (IPM) is an ecological approach to crop protection. It combines cultural practices, such as crop rotation, resistant varieties, and intercropping; biological control, such as deploying natural enemies of pests and biopesticides; mechanical methods, such as trapping and physical removal; and the targeted, need-based use of chemical pesticides only as a last resort.

IPM does not attempt to eliminate pests entirely. Instead, its goal is to keep pest populations below economically damaging thresholds to reduce crop losses, cut input costs, and preserve beneficial organisms and soil health. The evidence base for IPM's effectiveness is substantial. Field validation trials conducted by the ICAR's National Centre for Integrated Pest Management (NCIPM) across multiple crops show that IPM technology increases yields by approximately 20% on average compared to conventional practices and reduces production costs by around 10% through decreased pesticide use (CEEW, 2023).

In basmati rice, IPM adoption has been shown to reduce pesticide application by as much as 82% while simultaneously increasing yields by 8–17% compared to farmer practice (ICAR-NCIPM, 2024). Globally, an analysis of 85 IPM projects across Asia and Africa found a mean yield increase of 40.9% and a decline in pesticide use to just 30.7% of baseline levels, with a third of all crop combinations transitioning to zero pesticide use (Pretty & Bharucha, 2015).

Despite these demonstrated benefits, the adoption of IPM in India remains alarmingly low. Only an estimated 3.2% of Indian farmers, or approximately 3.7 million out of more than 140 million, currently practice IPM and cover just 3–5% of the country's cultivated area (CEEW, 2023). The Government of India has promoted IPM as the cardinal principle of plant protection since 1985 and operates 36 Central Integrated Pest Management Centres (CIPMCs) across 28 states. These conduct pest surveillance, produce biocontrol agents, and train farmers through farmer field schools. Yet the program has trained only 574,600 farmers since its inception, a fraction of what is required in a country of 140 million farming households.

A fundamentally different delivery model will be needed if IPM is to be scaled to reach the tens of millions of smallholders who currently lack access to it. This model has to move beyond centralized

government demonstration plots toward decentralized, farmer-led knowledge networks supported by digital extension tools, private-sector participation, and policy incentives that reward reduced pesticide dependence and not subsidize chemical inputs.

Digital technologies for early detection and precision advisory

Technology offers a powerful means of bridging the gap between India's limited extension infrastructure and the vast, dispersed population of smallholders who need real-time pest management support. Smartphone-based diagnostic tools have already demonstrated this potential at scale.

Plantix is a mobile application developed by the German AgriTech company PEAT GmbH in partnership with ICRISAT and Indian state agricultural universities. It uses artificial intelligence to identify crop pests, diseases, and nutrient deficiencies from a photograph taken by the farmer's smartphone. The app provides instant diagnostic results along with both chemical and biological treatment recommendations to effectively put a crop doctor in the farmer's pocket. Plantix has been downloaded more than 10 million times globally, with India accounting for the overwhelming majority of its user base, and has responded to more than 100 million crop-related queries ([Plantix, 2025](#); [CGIAR, 2020](#)).

Critically, because every image uploaded to the platform is geo-tagged and time-stamped, the aggregated data also functions as a real-time crowdsourced surveillance system that enables the tracking of pest and disease outbreaks as they spread. The platform demonstrated this capability during the fall armyworm invasion, when Plantix data mapped the pest's geographic spread across India using more than 100,000 farmer-submitted data points ([GSMA, 2025](#)).

Beyond farm-level diagnostics, satellite-based remote sensing and geospatial intelligence (GIS) represent what may be the most transformative, albeit nascent, frontier for crop health management. Today, a growing ecosystem of private-sector AgriTech companies shows that satellite imagery combined with AI and machine learning can detect crop stress, predict pest and disease outbreaks, and deliver plot-level advisories at a scale and speed unmatched by ground-based extension systems.

Bengaluru-based CropIn has deployed its AI-powered platform across more than 100 countries and 30 million acres. It serves agribusinesses, governments, and development agencies with tools, which include a disease early warning system (EWS). This system can predict disease occurrence at the individual plot level within a 7-day window using weather parameters and satellite-derived crop health indices ([CropIn, 2025](#)). CropIn's models are trained on what the company describes as the world's most extensive crop knowledge grid that covers more than 400 crops and 10,000 varieties. These models have been deployed through partnerships with PepsiCo, Walmart, the World Bank, and the Government of Maharashtra, among others ([CropIn, 2025](#); [NITI Aayog, 2025](#)).

Globally, Planet Labs operates a constellation of more than 200 satellites that image the entire Earth's surface daily at 3–5 meter resolution, sufficient to detect crop health anomalies, pest damage, and irrigation stress at the field level. It supplies this data to agricultural platforms worldwide ([Planet Labs, 2026](#)).

The critical question for Indian agriculture is whether these capabilities can be made affordable and accessible enough to directly benefit smallholder farmers. CropIn and similar platforms increasingly reach smallholders not through direct farmer subscriptions. Their reach is indirect, through agribusinesses that contract with farmer networks, banks that use satellite data to

underwrite crop loans, and insurers that verify claims remotely. The cost is absorbed into the value chain rather than borne by the farmer.

Yet, significant barriers remain. These include rural connectivity gaps, the digital divide among women and marginal farmers, the challenge of training AI models for India's extraordinary crop diversity, and the fundamental need for farmers to trust algorithmic recommendations over generational experience.

fasal protect challenge

next-generation herbicides for sustainable &
resilient agriculture

the big bet

The opportunity	Weeds are India’s most damaging category of farm pests. They are estimated to reduce yields in major crops by 20% to 30% and cause annual productivity losses of around INR 92,000 billion (~USD 11 billion). Smallholder farmers are especially vulnerable to the rise in labor costs and shortages, which makes manual weeding increasingly unsustainable. Therefore, they rely heavily on low-cost, broad-spectrum herbicides, such as glyphosate and 2,4-D. But years of repeated use and limited rotations of modes of action (MOAs) are driving herbicide resistance. This creates a clear innovation gap, wherein farmers demand low-cost, high-efficacy solutions that overcome resistant weeds, protect yields, as well as are safe for humans, crops, and the environment.
Choke points	<ul style="list-style-type: none"> ▪ High cost and seasonal shortages have made manual weeding unsustainable. ▪ Fear of toxicity and residue among farmers has resulted in high hesitancy to use herbicides. ▪ Over-reliance on low-cost herbicides, such as glyphosate, atrazine, and 2,4-D, has accelerated the emergence and spread of resistant weed populations. ▪ High cost and limited access in India have restricted the use of newer herbicide mixtures containing 2–3 active ingredients, which multinational firms primarily supply. ▪ Low awareness and weak guidance on dose, timing, application method have led to low efficacy.
Solution space	Low-cost, high-efficacy herbicide formulations are needed that are residue-safe, human- and eco-friendly, and effective against resistant weed species. Solutions may include bio-herbicides or multi-mode formulations designed to provide sustained weed control and long-term safety for smallholder farmers and the environment.
Target output(s)	<ol style="list-style-type: none"> 1. Low-cost: ≤ INR 2,000 (USD 21.4) per hectare per season 2. Deliver ≥ 90% weed control efficacy on major weeds of principal food crops(such as rice, wheat, maize, soyabean, and cotton) 3. Non-toxic (LD50 >5,000 mg/kg) to humans, animals, and soil organisms and meets FSSAI residue limits (<0.01 mg/kg) 4. Incorporate 2-3 MoA chemistry or biological mechanisms to delay resistance buildup 5. Easy to apply through calibrated knapsack sprayers or precision delivery devices suited to fragmented smallholder plots

The big bet

Innovate herbicides that deliver ≥90% weed control across principal food crops, including resistant and hard-to-control species, and must minimize resistance development. They must meet FSSAI residue limits (≤0.01 mg/kg), ensure human and environmental safety (LD50 >5,000 mg/kg), and cost less than INR 2,000 (USD 21.4) per hectare per season.

List of experts consulted across different stages of research

#	Name	Organization
1	Gitanjali Rajamani	Director, The/Nudge Institute
2	Hemendra Mathur	Co-founder, ThinkAg
3	Naveen Ranjan	Zonal Demand Generation Lead, Corteva-agrisciences
4	Dr. Samunder Singh	President, International Weed Science Society
5	Sandeep Gholkar	Corporate General Manager, Gharda Chemicals
6	Dr. Shobha Sondia	Principal Scientist, ICAR-Directorate of Weed Research
7	Surbhi Katoch	New Commercialization Lead, Corteva-agrisciences
8	Venky Ramachandran	Founder, Krishi.System

4.2 Livestock

4.2.1 Dairy

For more than 80 million rural households in India that depend on dairy farming (PIB, 2024), prosperity flows from a simple equation in which healthy animals that reproduce on schedule produce milk and generates income. In a sector where 95% of milk producers have herd sizes of just one to five animals (USDA GAIN, 2022), even small disruptions to this equation can be devastating. Yet across rural India, both sides of this equation are failing simultaneously. Animals suffer from diseases and disorders that drain their productivity, while Artificial insemination (AI) breeding programs meant to improve genetics and ensure regular calving succeed barely one-third of the time (PIB, 2025). These twin crises cost Indian dairy farmers more than USD 12 billion annually, more than any other country in the world (Rasmussen et al., 2024). Those least able to bear the costs suffer the most.

	Breed and reproduction systems	Feed and nutrition management	Animal health and disease management	Housing and welfare	Post harvest
Core functions	<ul style="list-style-type: none"> ▪ Detect heat on time ▪ Deliver AI within the breeding window ▪ Maintain regular calving intervals ▪ Improve herd genetics 	<ul style="list-style-type: none"> ▪ Provide fodder, concentrates, minerals, and water for optimal health and milk production ▪ Balance ration by animal stage ▪ Sustain milk yield and fertility 	<ul style="list-style-type: none"> ▪ Prevent major diseases ▪ Detect illness early ▪ Ensure timely treatment and vaccination ▪ Reduce production losses 	<ul style="list-style-type: none"> ▪ Provide shade, ventilation, drainage, and resting space ▪ Ensure water access and cooling ▪ Reduce stress and injury 	<ul style="list-style-type: none"> ▪ Store milk under optimal conditions immediately after collection ▪ Chill milk rapidly to reduce spoilage risk ▪ Test fat and SNF (Solids-Not-Fat) ▪ Preserve quality during storage and transport
Key risks	<ul style="list-style-type: none"> ▪ Heat detection is often missed ▪ AI is often performed at the wrong window period ▪ Buffaloes often show silent heat ▪ Access to breeding and veterinary 	<ul style="list-style-type: none"> ▪ Green fodder is seasonal and scarce ▪ Dry fodder is often of low quality ▪ Concentrates are unaffordable for many farmers 	<ul style="list-style-type: none"> ▪ Mastitis is often detected late ▪ Diseases that were once endemic are transitioning into widespread epidemics ▪ Access to veterinary 	<ul style="list-style-type: none"> ▪ Many shelters are non-durable or open ▪ Floors stay wet and unhygienic ▪ Ventilation is poor ▪ Animals are often tethered continuously 	<ul style="list-style-type: none"> ▪ Large volumes of milk still move through unrefrigerated channels ▪ Quality testing is inconsistent outside formal systems ▪ Rural power outages disrupt chilling

	Breed and reproduction systems	Feed and nutrition management	Animal health and disease management	Housing and welfare	Post harvest
	services are limited	<ul style="list-style-type: none"> Mineral use is irregular 	services is limited <ul style="list-style-type: none"> Farmers struggle to spot early symptoms of diseases and disorders 	<ul style="list-style-type: none"> Cooling provision is usually absent 	<ul style="list-style-type: none"> Collection infrastructure is uneven
Climate impact	<ul style="list-style-type: none"> Rising temperatures and longer heat waves weaken estrus signs More frequent heat stress lowers conception rates Temperature extremes increase early embryonic loss Climate stress lengthens calving intervals 	<ul style="list-style-type: none"> Droughts and erratic monsoons reduce fodder availability and quality. Feed prices increase during periods of scarcity. Heat stress reduces feed intake in cattle. Production losses worsen when inadequate nutrition and heat stress occur together. 	<ul style="list-style-type: none"> Rising temperatures and heat stress can weaken immune function in cattle, making them more vulnerable to infections. Hot and humid conditions can increase the incidence of mastitis and other climate-sensitive diseases. The health burden on cattle is aggravated when disease detection, treatment, and veterinary care are delayed or inadequate. 	<ul style="list-style-type: none"> High temperatures intensify thermal stress Poor housing worsens disease and lameness risk Buffaloes are especially vulnerable to heat stress without sufficient water sources for wallowing or cooling 	<ul style="list-style-type: none"> High ambient temperatures during summer months speed up microbial growth in milk

Table 9: Climate-linked risks and impacts across the dairy value chain

The twin crises: When health fails and breeding falters

The disease burden

India's dairy animals contend with a relentless burden of endemic diseases. Mastitis (inflammation of the udder) affects nearly half of all dairy cattle in its subclinical form. In this form, it silently

reduces milk production without visible symptoms until significant damage has occurred. Meta-analysis across Indian studies carried out during 1995–2019 reveals subclinical mastitis prevalence of 43-46%, with the clinical form affecting approximately 18% of dairy animals ([Krishnamoorthy et al., 2021](#)). The estimated annual economic loss due to both subclinical and clinical mastitis in India reaches INR 71.65 billion (USD 0.86 billion) ([Bansal and Gupta, 2009](#)). For a smallholder dairy farmer with two animals, mastitis alone can erase a significant portion of annual dairy income, often from a condition they do not even know exists.

Foot-and-mouth disease remains endemic despite decades of vaccination efforts, causing annual estimated losses of INR 200 billion (USD 214 million) ([Das et al., 2023](#)) annually through reduced milk yields, weight loss, mortality, and trade restrictions. Brucellosis, a bacterial infection causing abortion and infertility, inflicts losses worth INR 282.2 billion (USD 3.4 billion) across India's livestock sector, with cattle and buffalo accounting for more than 95% of the damage ([Singh et al., 2025](#)). The 2022-2023 lumpy skin disease outbreak demonstrated how quickly an emerging disease can devastate the sector, causing an estimated INR 202.52 billion (USD 2.44 billion) in losses within two years ([Nature, 2025](#)).

These diseases share a troubling pattern. By the time farmers recognize something is wrong, substantial damage has already occurred, leading to significant losses in India.

The breeding failure

Alongside the health crisis, dairy systems also face a serious breakdown in reproduction. AI, the primary pathway for genetic improvement in Indian dairy system, fails roughly two-thirds of the time. India's overall AI conception rate hovers around 35%, compared to 60% or higher in dairy systems across developed countries ([ScienceDirect, 2016](#)). This means that of the approximately 80 million inseminations performed annually across 71,000 AI centers, about 52 million fail to result in pregnancy.

Each failure carries a steep cost. When conception does not occur, the farmer must wait at least 21 days for the animal's next heat cycle, if that cycle is detected at all. Research estimates that in Indian states the cost of reproductive problems was INR 2,424.9 (USD 36.1) per dairy animal per year, with extended calving intervals accounting for 46.1% of total costs ([MDPI, 2021](#)). A cow that should calve every 12-13 months may instead calve every 16-18 months, for farmers operating on thin margins, these delays can mean the difference between modest prosperity and chronic debt.

The roots of this breeding failure lies in poor heat detection. AI must be performed within 6-24 hours of estrus onset, yet farmers often cannot reliably identify this window. When cows are inseminated correctly at the right time, 50-60% may conceive on first service, but this drops dramatically when timing is poor ([Merck Veterinary Manual, 2024](#)).

The detection gap: Why problems go unseen

The health and breeding crises appear distinct, but they share a common root cause. Both depend on detecting subtle, time-sensitive changes that the current system cannot reliably identify. This detection gap, the space between what farmers need to see and what they actually can see, is where billions of dollars in losses accumulate.

The limits of human observation

Successful dairy management depends on early detection across multiple areas. Mastitis must be identified in its early, treatable stages by recognizing changes in milk consistency or udder texture before visible swelling or fever appear. Heat detection relies on observing behavioral changes, namely restlessness, mounting activity, and mucus discharge. This may last only 12-18 hours and often occur overnight. Similarly, metabolic disorders require attention to subtle shifts in feeding patterns or rumination before the animal becomes visibly ill.

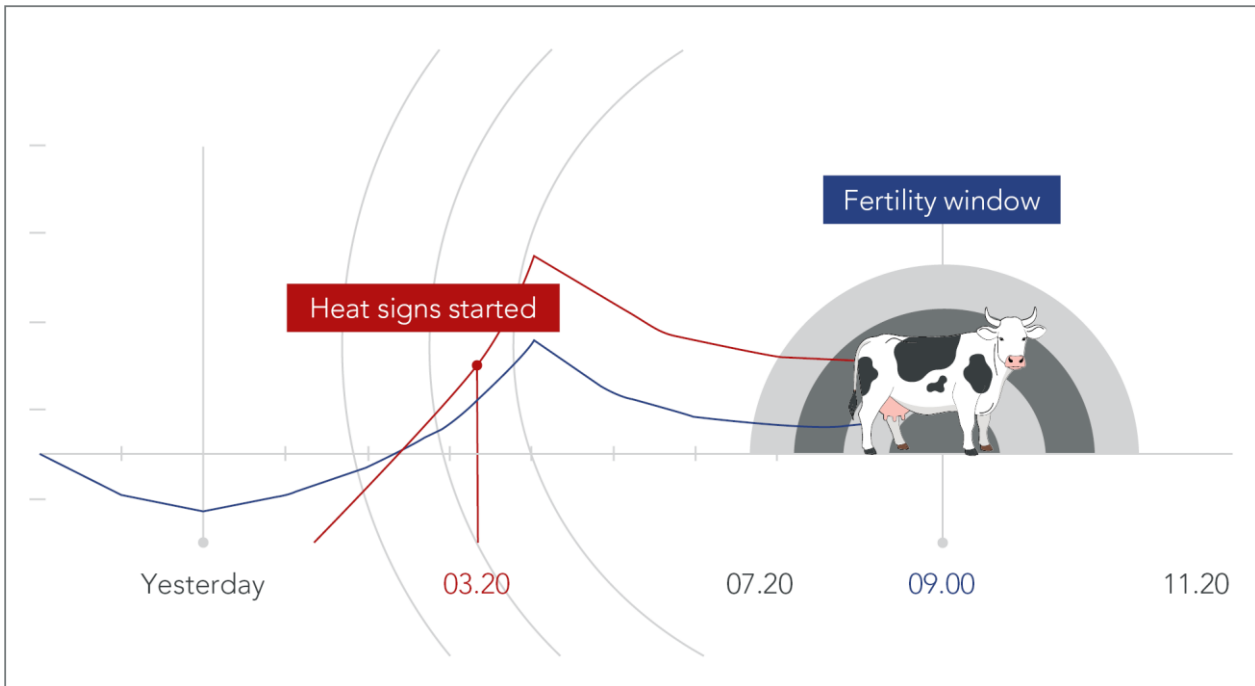


Figure 9: Heat detection and fertility window in dairy cattle ([Afimilk](#))

These detection tasks are not impossible, but they demand near-constant, expert observation. A farmer managing a small herd alongside crop cultivation, household responsibilities, and other livelihood activities cannot maintain round-the-clock vigilance. Even attentive farmers systematically miss critical events. Research indicates that visual observation alone detects only 50-60% of heat events under intensive management conditions ([Wisconsin Extension, 2024](#)). Detection rates in India are generally considered to be low, particularly among smallholders managing animals alongside multiple other demands.

Buffaloes present particular challenges. Unlike cattle, which typically display obvious mounting behavior during estrus, buffaloes are notorious for silent heat or ovulating with weak or absent behavioral signs. They demonstrate inconsistent periods of mounting acceptance ranging from 6 to 48 hours, and behavioral signs of estrus are less pronounced and often expressed at night ([Frontiers, 2025](#)). For farmers who depend on buffalo, which produce the majority of India's marketed milk, this silent heat problem represents a fundamental barrier to ensuring reproductive success.

The veterinary vacuum

Dairy systems in developed countries, veterinarians supplement farmer observation with regular herd health check-ups, reproductive examinations, and diagnostic testing. In India, smallholders rarely have this support. With approximately one veterinarian per 5,000 animals, India falls 10 times below the World Organization for Animal Health's recommended ratio of one per 500 ([Daily Excelsior, 2025](#)). Only 30% of rural households in India have access to veterinary services leading to inadequate animal health management ([Ken Research, 2025](#)).

This shortage compels farmers to rely on their own judgment. A smallholder in rural Bihar or Odisha may live hours from the nearest veterinary facility. By the time the cost and distance feel justified, the animal may have suffered irreversible damage or the breeding window may have closed. Detection is critical, but the infrastructure for it does not exist.

The cost of delay

Every missed detection carries a measurable price. Untreated mastitis progresses to chronic infection, permanently damaging the udder and eventually forcing culling. Foot-and-mouth disease spreads through a herd before visible symptoms appear, turning a single infection into an outbreak. A heat cycle missed by 12 hours means waiting 21 more days; a cycle missed entirely means waiting 42 days.

These delays compound. As per research cows with multiple failed inseminations on average have more than 126 "days open" (the gap between calving and next conception) against the optimal target of 60-85 days ([BMC Veterinary Research, 2022](#)). Extended calving intervals mean fewer calves born, less milk, and genetic improvement programs that stagnate instead of advancing herd quality across generations.

Climate change: A crisis accelerating

If the detection gap is a chronic weakness in India's dairy system, climate change is an acute threat that exploits and widens it. Rising temperatures and erratic weather worsen animal health, suppress reproductive performance, and make detection harder.

When heat becomes the enemy

Dairy animals thrive within a thermoneutral zone of 16-25°C. Beyond this range, heat stress diverts energy from production toward cooling the body. The impacts are severe and well-documented. Studies have shown that dry matter intake decreases from 40% to 48%, which, in turn, reduces milk yields from 25% to 53% relative to animals in thermoneutral environments ([Frontiers, 2023](#)). At the national-level, heat stress costs India more than INR 26 billion annually, with milk production losses of up to 30% during summer months ([IJFMR, 2025](#)).

Heat stress also suppresses immune function and renders animals more susceptible to the diseases already endemic in Indian herds. Studies have reported a 30-40% increase in clinical and subclinical mastitis cases in India during summer, directly correlated with high temperature-humidity index ([IJFMR, 2025](#)). Metabolic disorders increase as animals reduce feed intake to lower body heat. A disease burden that already costs billions grows heavier as temperatures climb.

Reproduction under siege

The reproductive impacts of heat stress are equally devastating. Elevated body temperatures impair follicular development, reduce egg quality, and compromise early embryo survival. Conception rates during summer can fall to 20-30%, compared to 40-50% during cooler seasons ([Springer, 2007](#)). Heat stress during the first week after conception causes early embryonic death, meaning that even apparently successful breeding may fail silently.

However, heat stress attacks the detection system itself. Animals under thermal discomfort reduce their physical activity, including the mounting and restlessness behaviors that signal estrus. Heat-stressed cattle display fewer standing events, shorter heat duration, and weaker behavioral signs. For farmers who rely on visual observation for heat detection, climate change is making an already difficult task nearly impossible during the hottest months.

A worsening trajectory

Climate projections offers little comfort. It is estimated that heat stress days will increase substantially across India's dairy regions. A Lancet Planetary Health study projected nearly 25% decline in milk production per animal in India's arid and semi-arid regions by century's end under high-emissions scenarios ([Lancet, 2022](#)). According to the National Dairy Research Centre, heat stress in Punjab, Haryana and western Uttar Pradesh could cause milk production losses to rise to 339,000 tonnes during 2020-2029 and 629,000 tonnes during the next decade ([Mongabay, 2022](#)).

The smallholder farmers with one to four animals, limited capital, and no access to cooling infrastructure will bear the heaviest burden as they are least equipped to adapt. Climate change does not create new problems so much as intensify existing ones, widening the detection gap and accelerating the losses that already drain India's dairy sector.

Big bet needed: Closing the detection gap

Our analysis shows India must close the detection gap to solve bovine the health and breeding crises. Farmers require technology to identify heat events and health issues. This equipment should also track physiological changes that people often miss. Effective tools must work works continuously, accurately, and affordably to help these farmers succeed.

What technology can offer

Modern livestock wearables use accelerometers, temperature sensors, and other instruments to continuously monitor animal behavior and physiology. These devices include ear tags, neck collars, or leg bands. They detect the increased activity and restlessness during estrus and identify rumination changes that signal digestive problems. These tools measure body temperature variations to find fever or metabolic stress and track patterns that human observation inevitably misses.

Machine learning algorithms process this data stream to generate actionable alerts. International systems show strong performance. Devices, such as CowManager, achieve more than 90% heat detection accuracy. Other systems report sensitivity rates of 94-97% estrus identification ([MDPI, 2022](#)). These technologies alert farmers to events they might miss. They enable precise insemination timing and flag health problems 24-48 hours before visible symptoms appear. This early window makes intervention most effective.

Indian solutions emerging

Indian companies now adapt wearable technology for domestic conditions. Stellapps Technologies deployed its mooON device across nearly 450,000 animals. This leg-worn activity monitor uses accelerometer data to detect health and estrus events ([CNN, 2022](#)). The company reports that proper use can increase milk yields by 20% and reduce health expenses by up to 50% through early intervention. Prompt Equipments developed BovSmart in partnership with IIT Mumbai. This wearable belt uses AI and IoT to monitor cattle activity. It claims 90% heat detection accuracy ([IBEF, 2021](#)).

“

Wearable technologies need to be adapted to India's tied animal systems, and we must develop affordable pen side diagnostic kits under INR 350 (USD 4.29) to enable faster, accurate disease treatment and reduce drug misuse. While vaccination efforts have reduced disease spread, sporadic outbreaks continue to occur, highlighting the need for better monitoring. Affordable, rapid diagnostics are not an alternative to wearables—they complement them to improve animal health outcomes.

- Dr. Sachin Joshi, Chief Thematic Programme Executive, BAIF

These early efforts demonstrate technical feasibility. But scaling to India's 80 million smallholder households requires solving unaddressed challenges. Monitoring devices are often prohibitively expensive for farmers with small herds. Battery life and accuracy present additional barriers. Most bovines in India are tied and connectivity in rural areas with intermittent network coverage present additional barriers.

India's dairy feed and nutrition crisis

India produces more milk than any other country on earth, yet the animals responsible for this achievement are chronically underfed. Feed and fodder account for 60-70% of the milk production cost ([DAHD, 2024](#)), making nutrition the single largest determinant of both productivity and profitability. India faces a national deficit of 11.24% in green fodder, 23.4% in dry fodder, and 28.9% in concentrate feed ingredients, according to the Indian Grassland and Fodder Research Institute (IGFRI) ([Down to Earth, 2025](#)). The Indian Grassland and Fodder Research Institute (IGFRI) has noted that this shortage keeps milk productivity in India 20-60% below the global average ([The Print, 2020](#)). In a sector where 80 million rural households depend on dairy as a primary income source ([PIB, 2024](#)), this feeding crisis suppresses milk output and limits income potential.

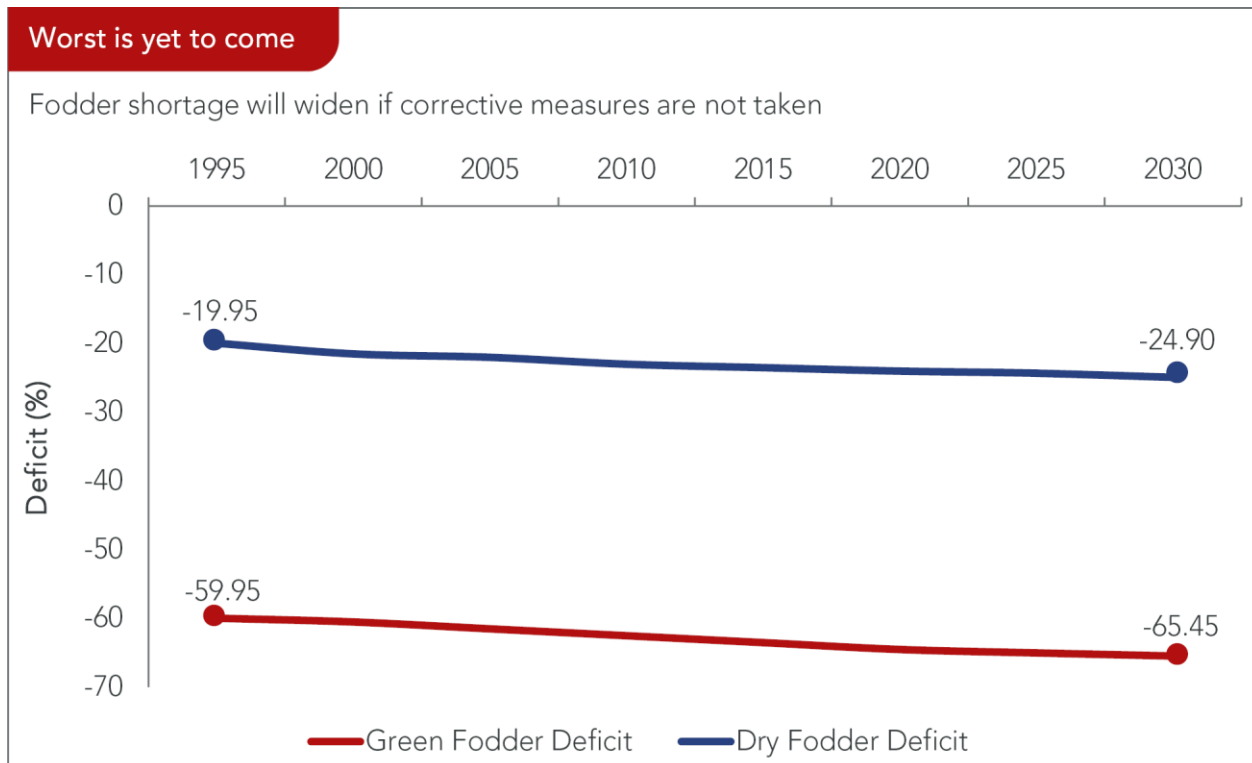


Figure 10: Green and dry fodder shortage in India. Source: DownToEarth

Source: Indian Grassland and Fodder Institute

The nutrition deficit

A productive dairy cow requires a balanced ration of green fodder for energy and protein, dry fodder for fiber, concentrates for supplementary nutrition, daily mineral mixtures, and adequate clean water. Indian smallholders typically feed their animals an inverted balance. Green fodder, the most nutritionally valuable component, is often available only seasonally and comprises low-quality grass instead of protein-rich legumes. Dry fodder, primarily untreated paddy or wheat straw with poor digestibility, dominates the diet.

Farmers limit concentrates based on affordability and usually opt for wheat bran or oil cakes. Mineral mixtures, which should be provided daily, are rarely or irregularly used ([ADRTC, 2021](#)). These nutritional gaps create a cascading negative effect. Protein deficiency suppresses milk synthesis. Excess low-quality fiber fills the rumen without delivering nutrients. Widespread mineral deficiencies in calcium, phosphorus, copper, and zinc impair fertility and reduce milk fat. These factors increase susceptibility to diseases.

This feeding deficit reflects a structural challenge rooted in competing land-use incentives. Fodder cultivation competes directly with food and cash crops for farmland. Farmers dedicate less than 5% of total cropped area to green fodder because wheat, rice, and vegetables offer better immediate returns. Meanwhile, feed prices have risen sharply and squeezed smallholder profit margins who already operate on thin profits. Most farmers follow traditional feeding practices and rarely adjust for individual animals at different stages of lactation, pregnancy, or growth ([NDDB, 2025](#)).

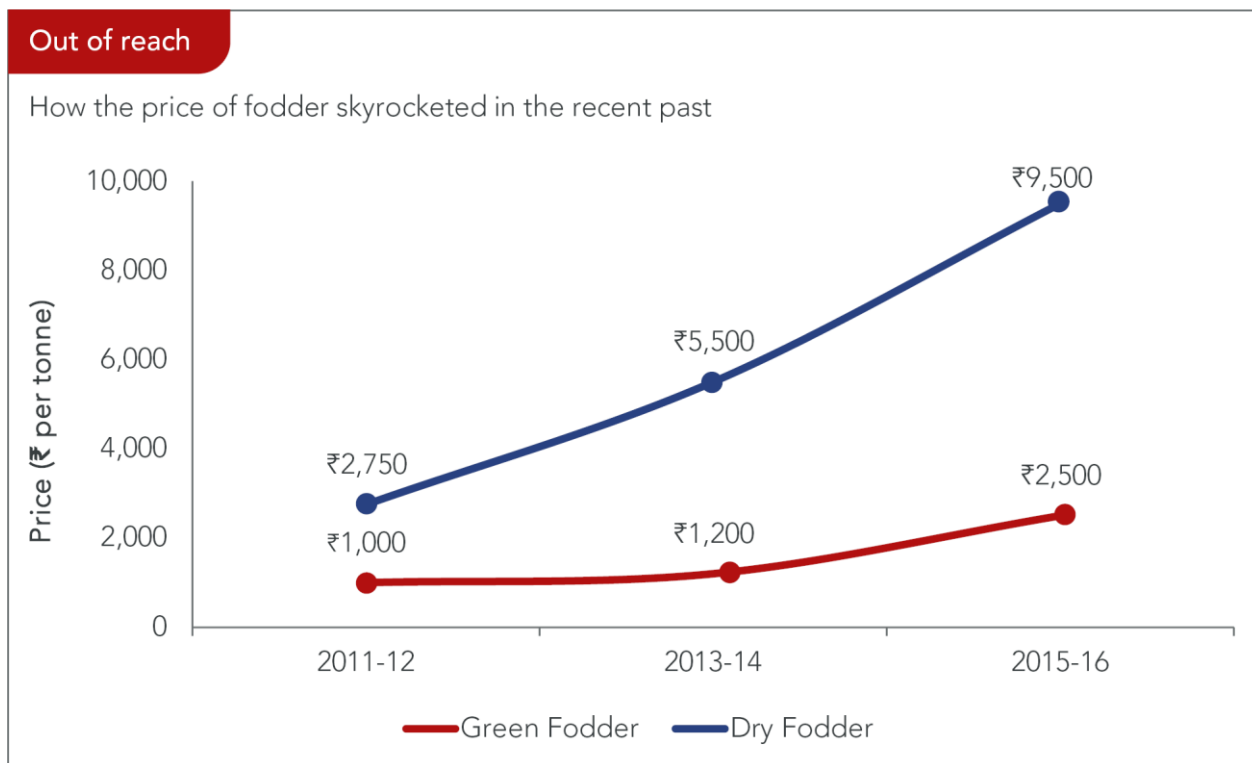


Figure 11: Rise in fodder prices (2011-16) in India. Source: DownToEarth

Source: Based on field work by Vikas Kumar, scientist (agricultural economics), IGFR

The scale of wasted potential is striking. The National Dairy Development Board’s Ration Balancing Programme found that simply rebalancing existing rations using locally available feed ingredients increased net daily income. The program is implemented across 33,374 villages covering 2.86 million dairy animals. It is found that the net daily income increased by INR 25.5 (USD 0.26) per animal and extended lactation by an average of 26 days for cows and 50 days for buffaloes. The program also found that rebalancing reduced enteric methane emissions by 13.7% per kilogram of milk (NDDB, 2024). The productivity potential locked inside India’s existing herds is immense, if only the animals could be fed properly.

A crisis deepening: Climate change and the shrinking fodder base

If the feeding deficit is a chronic condition, climate change is transforming it into an acute emergency. Fodder production in India is overwhelmingly rain-fed and seasonal, making it acutely vulnerable to monsoon disruption. Prolonged droughts, erratic monsoons, and rising temperatures have severely affected seasonal fodder crops, such as berseem and maize (Down to Earth, 2025). India’s green fodder deficit is projected to widen to 65.5% by 2030 if current trends continue, with the cost of green fodder already tripling between 2011 and 2016 in some regions (Down to Earth, 2016).

Heat stress compounds this nutritional crisis. As discussed in the preceding section on health and breeding, heat-stressed animals reduce their feed intake by 10-30% to lower body heat generation (NADIS, 2012). The combined effect of heat and poor nutrition is devastating. Milk yield drops significantly more than either factor alone would predict alone. For smallholders without access to cooling infrastructure or irrigated fodder plots, rising input costs and falling output create a grim

financial reality. Shrinking margins that push households toward distress sales of their animals and this threatens their livelihood security.

Pathways forward: Investments for a better-fed herd

Targeted investments help bridge India's dairy feed gap without capital-intensive global models. Solutions must work within the constraints that smallholders households face. Both market-based and public interventions offer pathways to fix this deficit.

Market-based interventions

- **Hydroponic fodder systems:** Some of the examples of low-cost units include Hydrogreens' Kambala. This specific unit was developed by Hydrogreens in partnership with ICAR-NIANP and was priced at INR 30,000 (USD 320). It produces 25-30 kg (55 to 66 lbs) of fresh green fodder daily on just 50 liters of water every three days. Such units offer a commercially scalable answer to the green fodder deficit ([ICAR, 2020](#)). The fodder-as-a-service model deploys community fodder stations at dairy cooperatives and removes high upfront costs for farmers while turning green fodder into a predictable daily input rather than a seasonal gamble ([Mongabay, 2024](#)).
- **Densified total mixed ration (TMR) blocks:** Crop-residue-based TMR blocks compress straw, concentrates, minerals, and vitamins into balanced feed. They transform low-value agricultural waste into a storable, ready-to-feed product customized by lactation stage. Research shows TMR block can increase daily milk yields by 10-15% and reduce feeding labor by 30-40% ([IndiaDairy, 2021](#)). Manufactured at cooperative-level feed plants and distributed through village societies, TMR blocks represent a market-ready product that converts what farmers already have into what their animals actually need ([NDDB, 2024](#)).
- **Commercial silage production:** Smallholder often lack means to preserve surplus monsoon fodder for lean months when prices spike. High-quality silage can meet up to half of a dairy cow's energy requirements ([SR Publications, 2025](#)). Cooperative-managed community silage units and subsidized baling equipment could create viable microenterprises while bridging the seasonal gap that currently devastates lean-season productivity ([Pashudhan Praharee, 2022](#)).

Non-market interventions

- **Azolla cultivation through extension networks:** Azolla is an aquatic fern with 25-30% crude protein. Farmers can grow it in backyard pits at near-zero recurring cost. It can replace 15-20% of commercial concentrates while boosting milk yield by 15-20% ([Bulletin of the National Research Centre, 2022](#)). Field trials in Karnataka, India, reported a cost-benefit ratio of 1:3.97 ([Patil et al., 2014](#)). Yet adoption remains limited by awareness, making azolla a classic case where public extension investment can unlock a commercially self-sustaining practice.

Shelter

Whether an animal can rest adequately, stay cool, remain dry during monsoons, or avoid the injuries and infections that erode productivity depends fundamentally on how it is housed. Yet, the vast majority of India's dairy cattle and buffaloes live in inadequate housing. For a sector where 95% of producers own herds of just one to five animals, the shelter question is not about building

modern barns. It is about whether animals that already face disease, breeding failure, and nutritional deficits are housed in conditions that make each of those problems worse.

How smallholders actually shelter their animals

An assessment of Indian dairy housing conditions by the Federation of Indian Animal Protection Organisations (FIAPO) across 10 states found significant gaps. More than 25% of dairies had no proper shelter arrangements. They housed animals under thatch roofs, roadside overhangs, or in open areas. Further, more than 78% of dairies provided no access to soft ground. This same percentage of dairies kept animals permanently tethered on short ropes. Additionally, 32% lacked proper lighting at night. Consequently, 57% of dairies had animals under visible stress or illness and more than 64% had animals with injuries ranging from bruises to tumors and fractures (FIAPO, 2017).

Regional studies reinforce this picture of inadequate shelter. In coastal South Gujarat, more than 54% of dairy housing was kutchha (non-durable, earthen) type and 90% of farmers kept animals inside both day and night. Revery shed had bare earthen floors and thatched roofing predominated at more than 70% (Patel et al., 2017). A welfare assessment of dairy farms in Kerala found that all cows observed were close-tied on ropes under one meter. Water was available on only 22% of farms and food access averaged just 4.3 hours per day. Further, on half the farms, cattle were tied indoors for the entire 24-hour day (Mullan et al., 2020).

Across these studies, a consistent set of structural deficiencies emerges. Earthen floors without drainage become saturated with dung and urine. These environments create conditions for pathogen proliferation. Low roofs with no designed ventilation trap heat and ammonia. Permanent tethering on short ropes prevents animals from a comfortable rest. It also stops grooming and natural behaviors. This includes the estrus signs that farmers need for breeding decisions.

The absence of adequate water access, in a country where summer temperatures routinely exceed 40°C, leaves animals chronically stressed and dehydrated during peak heat months. Furthermore, the near-total absence of any cooling provision, such as shade trees, fans, water for sprinkling or wallowing, leaves both cattle and buffaloes fully exposed to thermal stress.

For buffaloes, which produce nearly half of India's milk (USDA GAIN, 2022), the housing situation carries an additional dimension. Buffaloes have fewer sweat glands and darker skin than cattle, making them inherently less efficient at dissipating heat through sweating (Yadav et al., 2016). Their primary natural thermoregulatory mechanism is submerging in water or mud to cool the body through conduction, also known as wallowing. When prevented from engaging in this adaptive behavior, as they are in most tethered smallholder systems, buffaloes become particularly vulnerable to heat stress.

How poor shelter affects productivity

The health consequences of inadequate housing are well documented. The most direct pathway to losses runs through flooring and hygiene. In India, lameness prevalence in crossbred dairy cattle ranges from 8% to 30.5%. This makes it the third most economically important disease after infertility and mastitis (Mishra et al., 2017). A study across six Indian states confirmed that lameness was significantly associated with absence of bedding and steep floor gradients (Sharma et al., 2019).

The relationship between housing and mastitis follows a similar pattern. Bacterial counts at the teat end rise in dirty, wet environments (Farm Health Online, 2024). For a cow or buffalo that rest on a damp earthen floor contaminated with waste face higher risk of subclinical mastitis, a

condition that is already affecting 43–46% of Indian dairy cattle. A welfare assessment held in Kerala identified poor hygiene and mastitis risk as significant concerns in tie-stall systems. Nearly 69% of cows exhibited hair loss, lesions, or swelling attributable to their housing environment (Mullan et al., 2020).

The second major pathway is heat stress. Properly designed housing mitigates thermal load through shade and ventilation. Most Indian smallholder shelters achieve the opposite effect. A study in Tamil Nadu found that shelters with cement-sheet roofing recorded the highest interior temperatures and humidity indices among all housing types tested, while thatched roofing performed best for thermal comfort (Sivakumar et al., 2017). A separate study in Goa showed that well-ventilated, east–west oriented sheds with adequate space produced significantly more milk than those in poorly ventilated structures. Orientation and false-ceiling insulation further enhance these outcomes (Journal of Animal Research, 2015).

For buffaloes, the heat stress impact of poor shelter is particularly pronounced. Research on lactating Murrah buffaloes show that wallowing was significantly more effective than misting at maintaining milk yield. This is especially true during the hot-humid period when evaporative cooling from misting becomes less efficient (Yadav et al., 2016). A comprehensive review of buffalo heat stress responses confirmed that among all cooling strategies evaluated, such as shade, fans, sprinklers, and pools, wallowing produced the strongest improvements in production, reproduction, and overall animal welfare (Fusaro et al., 2023). A recent CEEW survey of more than 7,300 cattle-rearing households found that climate-related factors affected more than 54% of buffalo rearers. Increased disease incidence and behavioral stress were among the most commonly reported impacts (Down to Earth, 2026).

Climate change: Widening the shelter gap

Climate change transforms inadequate shelter from a chronic constraint into an intensifying crisis. Heat stress already causes national-level economic losses estimated at more than INR 26 billion (USD 278.2 million) annually, with milk production reductions of up to 30% during summer months (IJFMR, 2025). In the North Indian Plains, which is country's dairy heartland, the projected annual milk losses due to heat stress reached approximately 361,000 tonnes under current climate trajectories (Choudhary et al., 2022). At a global level, a Lancet Planetary Health study projects cattle production losses of INR 1,245–3,320 billion (USD 15–40 billion) annually by mid- to end-century, with South Asia among the most affected regions (Lancet, 2022).

The compounding effects underscore why shelter matters. Heat-stressed animals reduce feed intake to lower metabolic heat generation. When the feed they consume is already nutritionally deficient, the combined impact on milk yield exceeds what either factor alone would predict. Poor shelter amplifies the feed crisis. An animal that might tolerate a suboptimal ration under comfortable housing conditions experiences sharper productivity declines when housed in an unventilated, heat-trapping structure.

Pathway forward: Affordable interventions

The closure of the shelter gap does not require replication of the capital-intensive dairy infrastructure of developed nations. It requires targeted, low-cost interventions that work within the constraints of farmers owning one to eight animals on thin margins.

The simplest intervention is improved shed design at the time of construction. An east–west orientation for sheds maximizes shade during peak heat hours. This zero-cost design choice provides has a minimum roof height of 3 meters with ridge ventilation that allows natural hot-air exhaust. Farmers can replace dark metal sheets with whitewashed cement sheets or thatch-over-bamboo to reduces interior temperatures by 3–5°C ([Sivakumar et al., 2017](#)). Extension services can disseminate these principles through demonstration sheds at dairy cooperative collection centers and require no new technology.

For flooring, farmers must replace bare earth with brick-on-edge or stabilized-earth surfaces that incorporate a 2–3% drainage gradient to lower standing moisture, bacterial load, and hoof injury risk. At a slightly higher investment level, cement-plastered floors with rubber mat inserts at lying areas address both hygiene and comfort.

The NABARD Dairy Entrepreneurship Development Scheme provides subsidies of 25–33% for dairy infrastructure, including shed construction, with unit financing of up to INR 0.5 million (USD 5370) available through commercial banks ([Just Agriculture, 2024](#)). State-level schemes in dairy-intensive states offer additional cattle shed subsidies, particularly for SC/ST beneficiaries ([DAHD Maharashtra, 2023](#)). However, uptake among the smallest producers remains limited, indicating that awareness and access, rather than scheme availability, are primary constraints.

For buffaloes, the single highest-impact intervention is a direct path to wallowing. Research on Murrah buffaloes has demonstrated that wallowing outperforms misting and sprinkler systems. This practice maintains milk yield and reduces physiological stress indicators, particularly during hot-humid months ([Yadav et al., 2016](#)). A simple wallowing pit is a shallow, lined depression of approximately 3×2 meters filled with water. Farmers can construct it at minimal cost and can be shared by neighboring households. For smallholders without space for a dedicated pit, daily hosing or access to a nearby pond during peak heat hours provides measurable benefits.

Additional low-cost measures include the placement of shade trees around existing shelters, the installation of jute-curtain evaporative cooling, and the setup of shared fogger/misting systems using community-level investments through cooperatives. Crossbred cattle are more heat-sensitive than indigenous breeds and lack the buffalo’s wallowing adaptation. For these animals shade-plus-sprinkler combinations represent the most practical cooling approach within smallholder budgets.

The shelter gap is, at its core, a knowledge and investment gap. The design principles for effective and low-cost dairy housing are well established. Financial support mechanisms exist. What remains absent is the systematic extension effort to connect smallholder farmers with shelter designs appropriate to their species, climate zone, and budget. It also requires the recognition that housing quality is not peripheral to dairy productivity. Instead, proper shelter is foundational to the success of the sector.

Post-harvest losses

Government-commissioned assessments consistently report very low quantitative post-harvest losses for milk in India. The ICAR-CIPHET national assessment estimated total losses at 0.92% in 2015. Later, MoFPI-commissioned NABCONS study implies a total loss of about 0.87% during 2020–2022, comprising 0.54% at farm operations and 0.33% at market level ([PIB, 2022](#)). By comparison, fruits and vegetables suffer losses exceeding 10% and fish between 5% and 10%. On the surface, milk appears to be a post-harvest success story.

This aggregate figure, however, obscures a deeper structural divide. The data must be read in relation to the specific value chain. Not all milk produced in India enters the market. Approximately 37% of total production is retained at the producer level. Farming households consume this milk or sell it locally within villages. Of the remaining marketable surplus (67 percent), roughly 32% flows through the organized sector, comprising dairy cooperatives and registered private processors. The unorganized sector comprising traditional vendors, small-scale processors, and direct-sale channels handles the majority share of 68% (PIB, 2025).

These two channels differ fundamentally in their infrastructure and regulatory oversight. The organized sector operates with established cold-chain systems, standardized quality testing, and pasteurization protocols. By contrast, the unorganized sector functions largely without refrigeration, systematic quality monitoring, or formal regulatory supervision. The majority of India’s milk circulates through the unorganized channel. This specific segment likely experiences the most significant post-harvest losses. Yet, because losses in the informal segment remain largely unmeasured, national aggregates conceal more than they reveal.

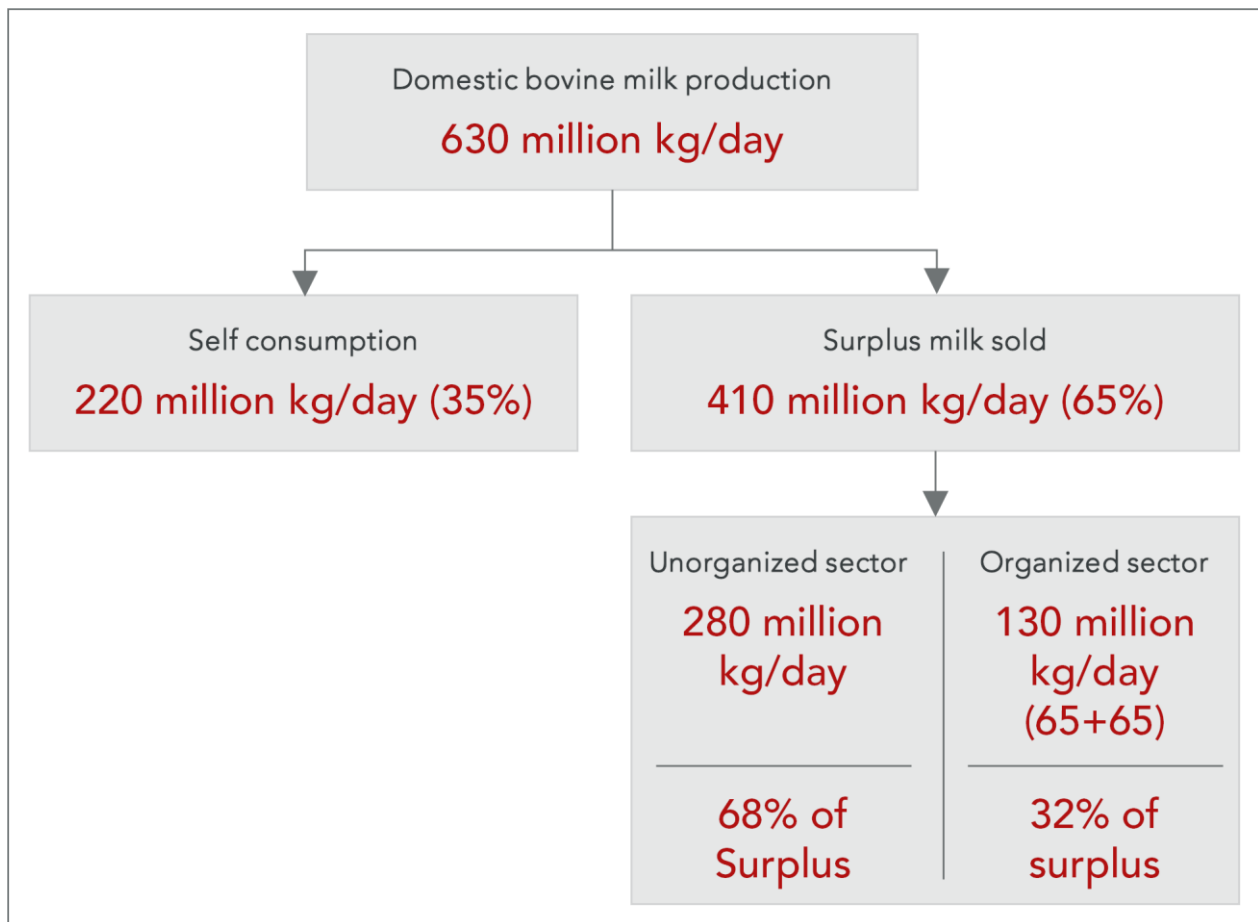


Figure 12: Milk supply to various channels in India

Two value chains, two realities

Milk is highly perishable. It leaves the udder at roughly body temperature of around 37°C, which supports rapid microbial growth. Under favorable conditions, bacterial populations can double in as little as 20 minutes. Rapid cooling is therefore the single most important intervention. Chilling milk quickly to around 4°C or lower slows microbial multiplication dramatically and extends usable

life from hours to days, although some cold-tolerant organisms can still grow slowly. A commonly cited rule of thumb is that small increases in storage temperature can sharply shorten shelf life. For example, a 2°C rise in temperature has been reported to reduce the shelf life of milk by about 50% (Stellapps, 2019).

The organized dairy sector comprises cooperatives, such as Amul, Mother Dairy, and Nandini, as well as private processors such as Hatsun, Heritage, and Parag. They typically operate a structured procurement and cold chain system. Milk is collected at village-level collection points; tested for key quality parameters, including fat and solids-not-fat; and chilled using bulk milk coolers (BMCs).

Chilled milk is then moved in insulated tankers to processing plants for pasteurization, packaging, and conversion into value-added products. Such structured procurement and cold-chain operations are sustained by a vast cooperative institutional framework rooted in the White Revolution (Operation Flood). Over time, this framework has expanded into a nationwide network of 22 state milk federations, 241 district cooperative unions, 28 marketing dairies, and 25 milk producer organizations (MPOs).

Together, they extend across nearly 235,000 villages and integrate 17.2 million dairy farmers into formal dairy value chains (PIB, 2025). Within this structured chain, post-harvest physical losses are genuinely minimal. Milk reaches cooling facilities within 3.5 hours of milking, and cold chain continuity is maintained through to the consumer (Energypedia).

The unorganized sector operates under fundamentally different conditions. Here, traditional vendors (*dudhiyas*) and other informal intermediaries procure “loose” milk from dispersed smallholder households. These collectors often conduct early-morning and evening rounds and aggregate it for rapid resale in nearby towns and peri-urban markets. Milk is typically transported in cans on bicycles, motorcycles, or small vehicles, and is sold the same day to households; tea stalls; hotels; sweet shops, also known as *halwais*; and small private processors.

Quality assessment in these channels is uneven and highly variable. Instead of standardized testing and traceable records, transactions often rely on visual inspection, rudimentary density checks, or trust-based relationships built through repeated exchange and localized credit arrangements.

The chain is time-sensitive and largely unrefrigerated. Vendors frequently manage spoilage risk through quick turnover and partial processing, such as converting milk into paneer. Sometimes they add substances to delay souring. This operating model keeps costs low and ensures last-mile availability. However, it also concentrates food-safety and loss risks in the least monitored part of the system. The quality of vendor-supplied milk is not guaranteed and the loose-milk trade is vulnerable to adulteration and irregular enforcement. Inspection and oversight are difficult across this highly fragmented network of micro-actors (FAO, 2002).

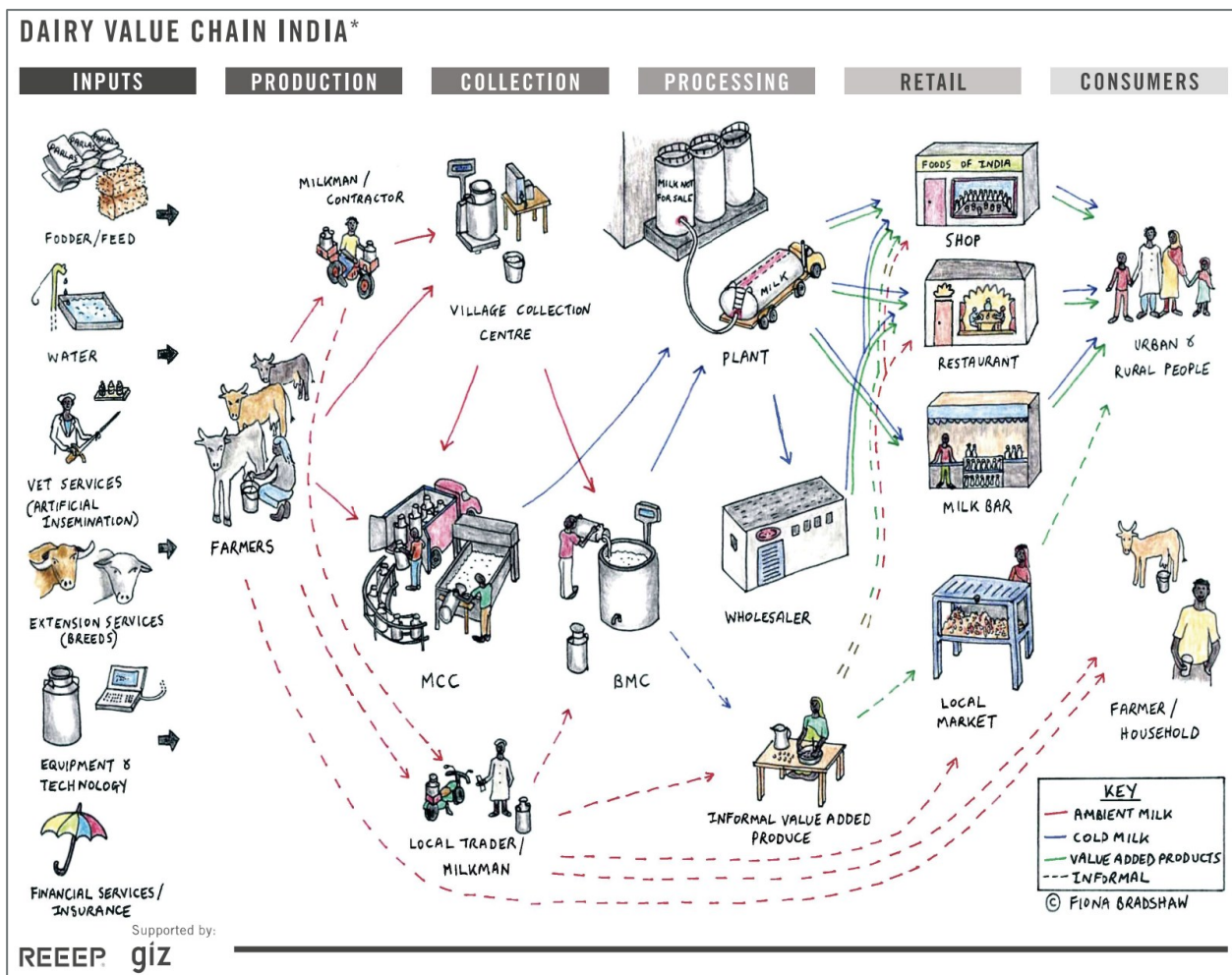


Figure 13: Overview of the formal and informal dairy value chain in India.

Source: REEEP

The quality gap

The distinction between these two channels has implications beyond simple spoilage. In the organized system, quality-based pricing incentivizes producers to maintain milk hygiene because fat and SNF content directly determine the price they receive. In the unorganized system, no such mechanism operates.

Pricing is typically based on volume alone, which creates perverse incentives for vendors. Individuals who deliver milk directly to households commonly dilute it with water to increase volume and margins. This dilution necessitates the addition of thickening agents, such as starch, flour, glucose, urea, or salt, to mask the reduced solids content and restore the expected consistency.

Perishability poses an additional challenge for informal vendors. They lack access to cold chain infrastructure, particularly during summer months. Therefore, they sometimes resort to chemical preservatives such as hydrogen peroxide, sodium bicarbonate, or sodium hydroxide to extend shelf life and neutralize acidity from bacterial growth (Grover et al., 2022).

In the organized sector, by contrast, every liter of milk passes through electronic testing at collection. This process includes chilling at the village or district level and pasteurization at processing. Non-compliant milk is rejected or its price is discounted, which creates a continuous incentive for quality maintenance.

The informality of unorganized channels also means there is no reliable measurement of total production volumes, wastage, or quality failures in this segment. The government's sub-1% post-harvest loss figure for milk is necessarily derived from the parts of the supply chain that are visible and accessible. This quality gap between organized and unorganized channels is substantial and losses in the informal sector take the form of quality degradation, health costs from unsafe consumption, and systematic value erosion across the chain.

Why the unorganized sector persists

The persistence of the unorganized sector is a simple failure of infrastructure. It reflects rational choices by both producers and consumers. For smallholder farmers, selling to a local vendor offers immediate cash payment, no quality rejection risk, and no requirement to travel to a collection center that may be kilometers away. The cooperative model, while offering better long-term returns and institutional support, requires registration, twice-daily delivery at fixed time, and acceptance of quality-based pricing that can penalize farmers with low-yielding animals or poor feed and health practices.

On the consumer side, many households prefer to buy loose milk from a trusted local vendor over packaged milk from organized processors. The perception of freshness, the lower price point (since informal milk avoids pasteurization and packaging costs), and long-standing vendor relationships all sustain demand for unorganized-sector milk (FAO, 2002). In rural and peri-urban areas where organized retail penetration is limited, informal channels may be the only available option.

The geographic dimension compounds the problem. Dairy cooperative coverage varies dramatically across states. Gujarat, Maharashtra, Kerala, and Karnataka have extensive cooperative networks, while states, such as West Bengal, the northeastern states, and parts of Uttar Pradesh have cooperative coverage below 10–20% (Vajirao & Ravi, 2025). In underserved regions, the absence of organized procurement infrastructure means that even farmers willing to participate in formal channels have no channel to participate in. Their milk enters the unorganized value chain by default, with all the quality and loss implications that entails.

Pathway forward: Expanding the organized value chain

The most effective intervention to reduce post-harvest loss and quality degradation in India's milk value chain is the rise in the share of milk that flows through organized, cold-chain-equipped channels. The government's recognition of this priority is reflected in the recently launched White Revolution 2.0 initiative, which aims to increase milk procurement by dairy cooperatives by 50% by 2028–2029. It targets a rise from 66 million kg per day to 100.7 million kg per day. The program proposes the establishment of 75,000 new dairy cooperative societies in uncovered areas. It also seeks the strengthening of 46,422 existing ones, with infrastructure support, including automatic milk collection units, electronic testing equipment, and bulk milk coolers (NDDB, 2023-24).

The centerpiece of this expansion at the village level is the bulk milk cooler. A BMC installed at a village collection center enables milk to be chilled from its initial temperature of 35–37°C to the

safe storage temperature of 4°C within hours of milking. This arrests bacterial growth and extends shelf life. Each 2°C increase in storage temperature reduces milk shelf life by approximately 50%, which makes rapid chilling the single most important quality-preservation intervention ([Stellapps, 2019](#)).

Nationally, there are approximately 26,000 BMCs that operate across dairy companies, but coverage remains inadequate in many regions. Approximately INR 2.5 million (USD 26,870) is required for complete BMC installation, including chilling equipment, site preparation, and backup power. This is a significant investment that individual smallholders cannot finance but cooperatives and producer organizations can ([Stellapps, 2019](#)).

The high operating costs of BMCs in rural India has prompted innovation in renewable energy solutions. Frequent power outages in rural villages mean that diesel generators have traditionally served as backup power for milk chillers, which increases both costs and emissions. WWF-India's Energy Transition in Dairy Cold Chain project has worked with dairy cooperatives and farmer-producer organizations to install 101 solar-powered instant milk chillers in Uttar Pradesh, Rajasthan, Gujarat, Karnataka, and Maharashtra. These equipment have a combined chilling capacity of 50,000 liters per day and total solar capacity of 851 kW ([WWF India, 2024](#)). In Rajasthan, the Asha Mahila dairy cooperative reported that solar-powered chillers eliminated previous quality degradation. This improvement is vital during the summer months when ambient temperatures reach 45–50°C. Extreme heat triggers rapid bacterial proliferation in nonchilled milk ([The Better India, 2025](#)).

Beyond cold chain expansion, the collection center model offers additional benefits that address quality problems in the unorganized sector. Automated milk collection units equipped with electronic fat and SNF analyzers enable quality-based pricing, which directly incentivizes producers to maintain milk hygiene and avoid dilution. Transparent, data-recorded transactions reduce the scope for intermediary exploitation. And the cooperative structure provides a platform to deliver veterinary services and feed supplements. The platform also offers extension advice based on inputs that, as documented in earlier sections of this report, are essential to improve both animal productivity and the quality of milk at source.

The scale of the remaining gap is substantial. Dairy cooperatives currently cover approximately 30% of India's villages and procure roughly 16% of the country's marketable milk surplus ([NDDB, 2025](#)). Reaching the remaining 70% of villages, particularly in states with minimal cooperative or private player presence, will require not only infrastructure investment but sustained engagement with farmers who have long operated outside formal systems. The post-harvest challenge in India's dairy sector is not primarily one of physical spoilage but of institutional reach.

cattle.ai challenge

enhancing productivity and animal welfare through early,
affordable disease and estrus detection

the big bet

<p>The opportunity</p>	<p>India's 80 + million smallholder dairy households own more than 300 million bovines but lose more than INR 996 billion (USD 12 billion) annually due to undetected diseases and missed heats. Climate change makes these challenges worse. Heat stress suppresses estrus expression, which makes detection harder. Changes in rainfall, frequent floods, droughts, and heatwaves alter the transmission of infectious diseases and increase outbreak frequency. Sub-clinical mastitis alone infects 50% of bovines in India, which causes a loss of INR 7,165 (USD 86.3) per animal per year.</p> <p>Each missed heat costs INR 4,000–6,000 (USD 48.2–72.3) due to delayed conception and lost milk production. With only one veterinarian available per 4,600 animals, approximately, and less than 15% village coverage by mobile units, timely detection is often unfeasible. However, studies show that advances in IoT sensors, artificial intelligence, and machine learning make it possible to monitor animal health and estrus affordably, with accuracies exceeding 90%.</p>
<p>Choke points</p>	<ol style="list-style-type: none"> 1. The lack of sufficient veterinarians limits effective disease and disorder identification and management. Only one vet is available per 4,600 bovines. 2. Manual methods used for heat detection are often inaccurate, which leads to high losses due to open days and a low artificial insemination success rate of approximately 30-35%. 3. High device cost and limited affordability: Wearable sensors are typically prohibitively expensive for India's dairy smallholder farmers. These technologies are mostly designed for and adopted in developed countries with large herd sizes. 4. Limited transparency and validation: Current solutions provide little clarity on which diseases or disorders they can detect, how early they can flag them, their actual detection accuracy, and how it would translate in Indian field conditions. 5. Low usability for rural farmers: Solutions need to be paired with user-friendly, local-language mobile applications that can simplify alerts, heat cycle tracking, and intervention recommendations for non-tech-savvy smallholder dairy farmers in India.
<p>Solution space</p>	<p>The proposed solution will develop a low-cost (\leq INR 3,000 (USD 35) per animal) wearable heat and health monitoring system capable of \geq 85% estrus detection accuracy and 24 to 48 hours advance alerts for detectable diseases and disorders with \geq 80% accuracy.</p>

Target output(s)

1. Demonstrate $\geq 85\%$ estrus detection accuracy and $\geq 80\%$ accuracy in early identification of detectable disorders and diseases
2. Deliver 24 to 48-hour advance alerts before visible symptoms
3. Achieve a total ownership cost \leq INR 3,000 (USD 35) per animal (which will include hardware and software)
4. Ensure offline or low-network functionality and develop a user-friendly app with local-language support

The big bet

Innovate affordable, high-accuracy, and farmer-friendly estrus and health monitoring solutions that achieve $\geq 85\%$ estrus detection accuracy and $\geq 80\%$ disease/disorder detection accuracy, providing 24–48-hour advance health alerts at \leq INR 3,000 (USD 35) per animal.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Ravindra Goyal	Consultant, National Rural Livelihoods Mission
2	Shashi Kumar	CEO, Akshayakalpa Organic
3	Vamseedhar	Senior Vice President Operations, Sid's Farm

b. Listening circle

#	Name	Organization
1	Divyesh Butala	Product Manager, Prompt DairyTech
2	Madhu Kumar	Product Expert, Stellapps
3	Ravindra Goyal	Consultant, National Rural Livelihoods Mission
4	Dr. Sachin Joshi	Chief Thematic Program Executive, BAIF
5	Vamseedhar	Senior Vice President Operations, Sid's Farm

4.2.2 Goatery

Goatery: A climate-critical livelihood for 30 million Indian households

How climate change is turning one of India’s most resilient livestock systems into a growing livelihood risk for landless and smallholder farmers

Goats are among the most resilient and adaptable livestock species globally. They are often described as the “poor person’s cow” due to their ability to survive and generate value under resource-constrained conditions. Goats are biologically suited to arid, semi-arid, and climatically variable regions. They can thrive on diverse and low-quality forage, browse shrubs, and crop residues, and tolerate heat and water stress better than most ruminants. This hardiness has made goats a cornerstone of livestock systems across the Global South.

India is home to one of the world’s largest goat populations, with 148.88 (DAHD, 2023) million goats as per the 2019 Livestock Census. This accounts for roughly 17% of the global goat population. The sector has shown steady growth, and goat numbers have increased by around 10% between 2012 and 2019. This reflects their rising importance in smallholder livelihood systems (DAHD, 2023).

	Breed and reproduction systems	Feed and grazing	Disease management	Housing	Production and herd performance	Market access and aggregation
Core functions	<ul style="list-style-type: none"> ▪ Maintain herd reproduction ▪ Improve genetic productivity ▪ Enable trait transmission ▪ Support herd replacement 	<ul style="list-style-type: none"> ▪ Provide daily animal nutrition ▪ Sustain body maintenance needs 	<ul style="list-style-type: none"> ▪ Prevent disease outbreaks ▪ Maintain herd immunity levels ▪ Support survival and recovery 	<ul style="list-style-type: none"> ▪ Protect animals from weather ▪ Provide safe resting spaces 	<ul style="list-style-type: none"> ▪ Convert feed into output ▪ Generate meat and milk ▪ Enable herd growth cycles 	<ul style="list-style-type: none"> ▪ Enable livestock monetization ▪ Facilitate price discovery ▪ Aggregate saleable volumes to buyers
Key risks	<ul style="list-style-type: none"> ▪ High non-descript breed presence leads to genetic dilution ▪ Limited access to artificial insemination services reduces genetic diversity 	<ul style="list-style-type: none"> ▪ Shrinking common lands reduces access to food ▪ Rising purchased feed costs causes additional burden ▪ Water scarcity constraints 	<ul style="list-style-type: none"> ▪ Low vaccination coverage ▪ Parasite and outbreak surge ▪ Limited last-mile services available for preventive and curative treatment ▪ Weak biosecurity awareness 	<ul style="list-style-type: none"> ▪ Heatwave exposure ▪ Flood and cold stress ▪ Waterlogging in shelters ▪ Poor ventilation design 	<ul style="list-style-type: none"> ▪ Nutritional stress cycles ▪ Delayed breeding intervals ▪ Low growth efficiency ▪ Young stock vulnerability 	<ul style="list-style-type: none"> ▪ Distress sale pressure ▪ Weak farmer aggregation ▪ Market price volatility

	Breed and reproduction systems	Feed and grazing	Disease management	Housing	Production and herd performance	Market access and aggregation
	<ul style="list-style-type: none"> Weak extension outreach reduces conception and survival rates when conceived 					
Climate impact	<ul style="list-style-type: none"> Declining fertility rates due to reduced conception during peak reproductive period Non-descript breeds have reduced growth potential Extreme temperatures lower kid survival 	<ul style="list-style-type: none"> Reduced feed intake due to the lack of availability of nutritious food Increased production costs due to higher dependence on purchased feed Reduced weight gain due to reduced consumption 	<ul style="list-style-type: none"> Frequent and more widespread disease shocks cause higher mortality in goats Reduced herd performance due to diseases, which reduces the output 	<ul style="list-style-type: none"> Higher exposure to extreme temperature reduces productivity in terms of meat and milk Increased disease incidence due to high exposure to extreme events and resulting higher seasonal mortality 	<ul style="list-style-type: none"> Slower weight gain due to extreme temperatures increases turnaround time to reach market weight Reduced productivity leads to declining household income 	<ul style="list-style-type: none"> Lack of access to organized markets reduces price realization Extreme temperature induces distress sales and thus causes income instability cycles Market exclusion risks

Table 10: Climate-linked risks and impacts across the goaterly value

A quiet economic engine in India's livestock economy

Economically, goats contribute significantly to agricultural output through meat, milk, skin, and manure. In 2023, the total value of goat-based products in India was estimated at approximately INR 11.9 trillion (USD 127.5 billion), which contributes about 8.4% to the country's livestock GDP (DAHD, 2023). Goats contribute only around 3.36% of total milk production due to lower per-animal yields at an average of 0.48 kg per day. However, their role in meat production is far more prominent, which accounts for nearly 15.5% of national meat output (DAHD, 2023).

Beyond aggregate GDP contributions, goats play a critical livelihood role. They are highly liquid assets, reproduce quickly, and require low initial investment, which makes them especially important for landless households, women, and marginal farmers. Currently, more than 30 million households are dependent on goat farming. Approximately 83% of goats (Tamilarasan, 2024) in India belong to landless small-scale farmers.

Resilient animals, fragile systems

Despite this scale and resilience, productivity in the sector remains structurally constrained. More than 85% (Singh, 2018) of goats are reared under extensive, low-input, or zero-input systems. Despite more than 39 registered breeds, nearly 65% of India's goats are nondescript and lack defined genetic potential (Singh, 2018). This combination of poor genetics, inadequate nutrition, limited healthcare, and weak market linkages results in productivity levels estimated to be 75–100% below achievable potential. (Singh, 2018)

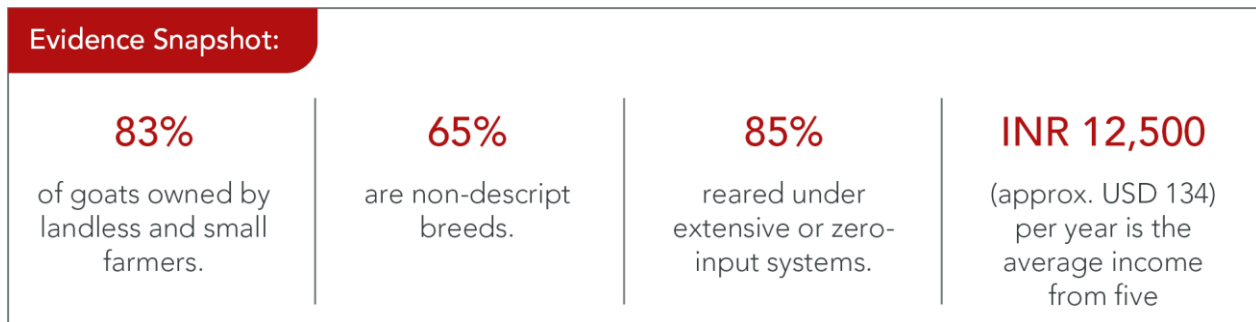


Figure 14: Data at a glance

Most smallholder goat farmers maintain 3–10 animals (Tamilarasan, 2024), where around five goats earn approximately INR 12,500 (approx. USD 134) (Singh, 2018) annually under low-input conditions. Evidence from the ICAR and ILRI pilots shows that modest shifts toward higher input practices, such as improved fodder, mineral supplementation, housing, and vaccination, can double farmer incomes by as they will improve survival and quality of produce.

Climate change as a stress test for smallholder goatery

Taken together, the scale of the goat economy, the high livelihood dependence of smallholders, and the dominance of extensive rearing systems create a clear climate vulnerability profile. Climate change is steadily eroding the foundations on which smallholders operate through declining fodder biomass, heat stress, water scarcity, and shifting disease ecologies. With limited savings, insurance, or access to inputs, smallholders have little capacity to absorb productivity shocks, which makes even modest impacts economically destabilizing.

Currently, the impacts of climate change are evident across the entire goatery value chain. Livelihoods dependent on goat rearing face heightened risks of income and productivity loss. In extreme cases, the risk of exiting the activity altogether also exists. How these impacts manifest, along with the corresponding solution pathways, are summarized below:

1. Feed	2. Disease	3. Housing	4. Breeding
Shrinking common property resources → higher feed costs due to purchased feed	Heat and humidity → increased parasite and outbreak surge reducing mortality.	Heat, floods and cold → lower productivity and higher mortality	Unstructured mating → falling fertility and genetic dilution.

Figure 15: How climate risk manifests in the goat supply chain: its core problem areas

We will now detail each of these problem areas and possible solution pathways. Solving emerging problems can stabilize the income of millions of goat farmers and generate new livelihood opportunities in rural areas.

1. Collapse of commons

How climate change is breaking smallholder feed systems

Feed availability has emerged as a critical climate-sensitive constraint in smallholder goat systems, as both ecological conditions and access arrangements that historically supported extensive rearing are undergoing change. Extensive goat rearing underpins the livelihoods of a large share of low-income households and has traditionally relied on common property resources (CPRs), including grazing lands, fallows, shrubs, and fodder trees, which provided low-cost, low-input feed across rural and peri-urban contexts.

Under these systems, adult goats primarily meet their nutritional needs through natural grazing, supplemented with crop residues and limited concentrates, and have access to clean drinking water, which supports maintenance, milk, and meat production.

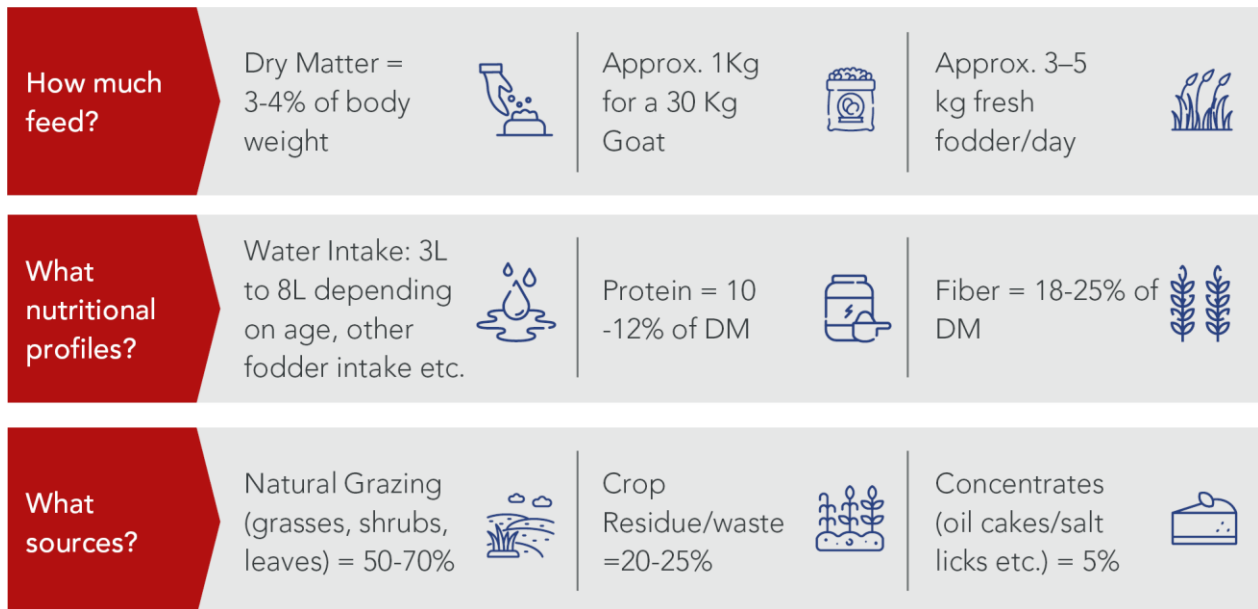


Figure 16: Snapshot of the daily feed needs of an adult goat

Why the old system no longer works

The existing feeding pattern assumes consistent availability of grazing biomass of adequate quantity and quality across seasons, which climate change is disrupting. FAO projections and the International Panel on Climate Change (IPCC) have recognized the decline of feed availability due to rising temperature, especially in the tropics, at up to 60% (IPCC, 2014). At the national level, India faces a net fodder deficit of approximately 35.6% (Narayan, 2022), which spans green fodder, dry fodder, and concentrate feed ingredients.

As common property resources shrink due to climate stress and land-use change, extensive systems struggle to meet even maintenance nutrition needs. This lack forces a shift toward purchased feed and higher input costs. Farmers moving out of a no-input system spend as much as 60% of their total costs on feed.

What are farmers experiencing on the ground?

Field evidence confirms this shift. A 2025 study of 120 goat farmers in Lalitpur district in Bundelkhand, Uttar Pradesh, found that 85% of farmers identified shrinkage of grazing land as their most critical feeding constraint, followed by non-availability of green fodder at 80% and price fluctuations in feed and fodder by 76.66% (Sonu, 2025). These constraints were ranked above issues related to farmer knowledge or feeding practices, which indicated that feed stress is driven primarily by loss of access and rising market dependence.



Figure 17: Data at a glance

How should feed access be stabilized at the right scale?

The collapse of common property resources points to a systemic failure that has not been replaced by an alternative mechanism capable of ensuring a sustained feed supply under climate vulnerability. This calls for an ecosystem-level intervention, such as a community fodder bank, which addresses feed stress at the scale at which it is generated. A community fodder bank would function as a shared, locally managed feed access system at the village or cluster level. Self-help groups can support their day-to-day operations, and panchayats can provide oversight and governance.

External agencies, such as non-profits, can play a catalytic role in facilitating establishment and capacity building, while ownership and management remain with the community. The fodder bank aggregates both demand and supply. This reduces farmers' dependence on volatile markets and stabilizes feed access during lean periods.

Community fodder banks can stabilize feed access, generate local livelihoods through fodder production and management, and strengthen income security for existing goat-rearing households at the same time.

When prevention fails

How climate stress drives disease incidence and income loss

Goats are affected by viral diseases, such as peste des petits ruminants (PPR), goat pox, and foot-and-mouth disease (FMD), along with bacterial and parasitic infections. All these reduce productivity and income. For smallholders, the loss of one goat in a herd of five implies a 25% loss of productive assets. Mortality is the highest among young animals. A nine-year hospital-based study from Punjab found that nearly half of all disease cases occurred in goats under one year of age, while female goats accounted for more than 60% of reported illness (Kumar, 2025).

Disease incidence peaks during the monsoon and is increasingly intensified by climate change. This is because rising temperatures, humidity, and erratic rainfall enable pathogens to persist longer, expand geographically, and interact with nutritionally stressed animals, which turns episodic outbreaks into recurring productivity shocks.

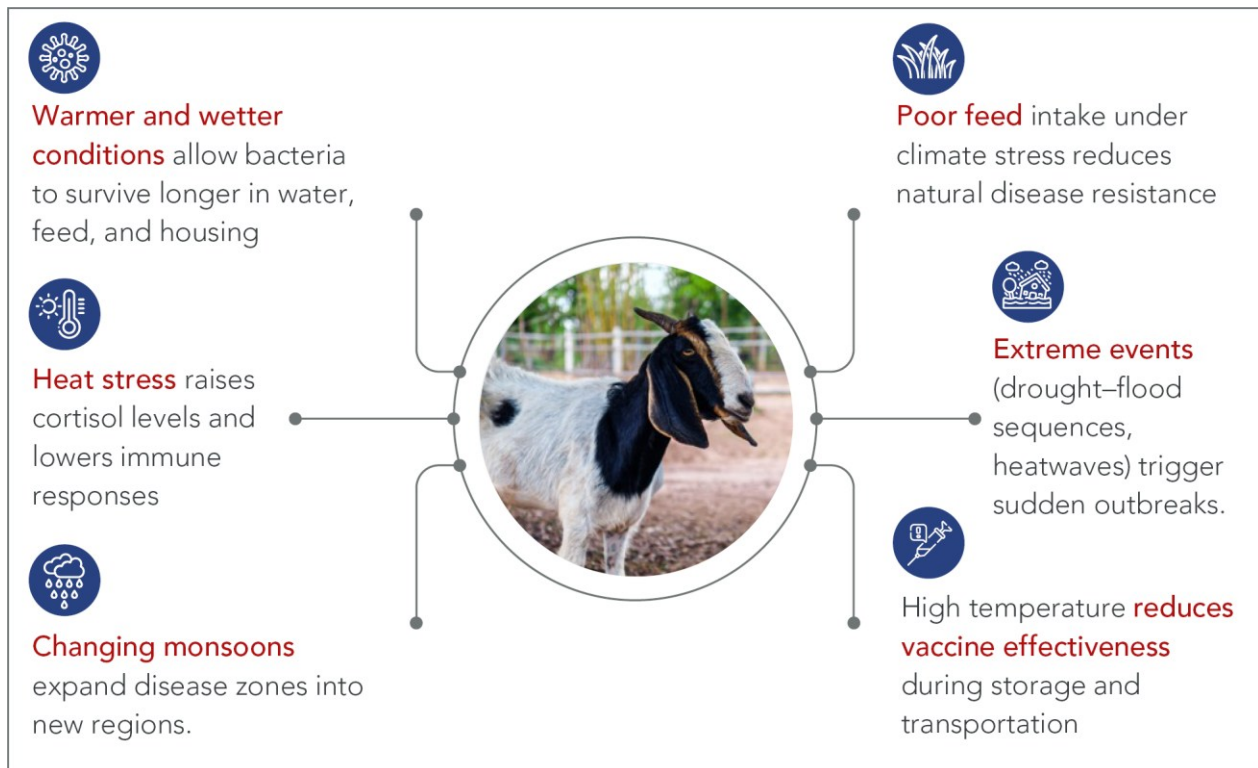


Figure 18: Double impact of climate change on disease burden in the form of increased pathogens and decreased immunity

Prevention works, but coverage remains thin

Preventive measures, such as vaccination, deworming, and basic biosecurity, are effective but underutilized. A field study showed deworming coverage remains below 50%. More than 40% is self-administered, while vaccination coverage is only 30–35% (Kumar, 2021), far below herd immunity thresholds. Large-scale evidence suggests that if preventive coverage increased to 70–80%, it can halve kid mortality and stabilize household incomes, especially when deworming is undertaken before the monsoon.

Public programs are scaling, but last-mile gaps persist

The gaps in prevention are recognized by ecosystem actors who support goat-based livelihoods. The government has expanded public investment in small ruminant health through large-scale programs. The National Animal Disease Control Program (NADCP), launched in 2019, seeks to eliminate foot-and-mouth disease (FMD) and brucellosis through universal vaccination of cattle, buffalo, sheep, and goats (DAHD, 2024). In parallel, the PPR Eradication Program (PPR-EP) targets nationwide elimination of PPR by 2030 through mass vaccination. These efforts are complemented by non-profit actors, who, through *Pashu Sakhi* models and community mobilization, have worked to strengthen last-mile delivery of preventive care and basic treatment.

Despite these efforts, significant disease management challenges persist in India's goat systems, particularly among smallholders who operate extensive, low-input models. In 2023, PPR accounted for 86 outbreaks that affected more than 7,000 goats, with mortality exceeding 50% (DAHD, 2024). Seroprevalence studies also show that only about 44% of goats in northern regions carry PPR antibodies, which falls well below the approximately 70% coverage required for herd immunity (Balamurugan, 2020).

Preventive care remains constrained by access and delivery gaps. Vaccination and deworming are largely episodic and campaign-driven, which many smallholders miss due to migration, distance from camps, or lack of timely information. These challenges are compounded by behavioral and information gaps, alongside fragmented service delivery. This leads farmers to rely on traditional practices and self-medication even when services are available.

Strengthening systems: From campaigns to continuous care

A shift is needed from campaign-based approaches to accessible, scalable, and inclusive delivery models to address existing constraints. Community-level animal health workers, such as *Pashu Sakhi*, should be strengthened and scaled to institutionalize routine vaccination, deworming, and basic disease surveillance at the village level. The adoption of thermostable vaccines can further address last-mile cold-chain constraints. In parallel, large-scale behavior change interventions, implemented through trusted community institutions, can improve uptake of preventive care. Proven models under the NRLM and livestock-focused FPOs offer replicable pathways to scale these solutions across regions.

Housing, exposure to extreme temperatures, and survival in smallholder goat systems

One of the most critical impacts of climate change on livestock systems is the rising frequency and intensity of extreme temperature events, which lead to both heat and cold stress. While goats are widely recognized as more climate-resilient than cattle, the current escalation in temperature extremes is increasingly pushing even goat systems beyond their coping limits.

Why temperature extremes threaten goat productivity

Goats thrive best within a thermoneutral temperature range of approximately 12–24 °C, where they can maintain body temperature without diverting energy from production. Compared to cattle, in which production losses begin when the temperature–humidity index (THI) exceeds 72–75, goats generally maintain productivity up to a THI of approximately 80 (V. Bhatshwar, 2022). However, beyond this threshold, especially under prolonged exposure, goats also experience measurable stress. Heat stress typically begins above 35°C, while cold stress sets in below 5°C (Das, 2025), particularly when accompanied by wind, damp floors, or poor bedding.

Once exposed to heat stress, goats reduce feed intake to limit metabolic heat production, which leads to declines in weight gain, milk yield, and reproductive performance. Cold stress similarly increases maintenance energy requirements, suppresses immunity, and raises the incidence of pneumonia and diarrheal diseases, particularly among kids. Across studies and field observations, combined heat and cold stress can result in 10–35% productivity losses, based on duration and management conditions (Das, 2025).

Evidence from the field: Why current housing fails under climate stress

Field reports from arid regions, such as Rajasthan, indicate higher kid mortality, reduced milk yield, and slower growth during extreme summer heatwaves (Waiz, 2018). Conversely, harsher winters and flood events in northern and eastern India have led to displacement and livestock losses where shelters collapse or remain waterlogged. This vulnerability is worsened by the fact that most smallholder goats are housed in thatched or *kutchha* structures, often without proper ventilation, raised flooring, or dry bedding. There is little protection against temperature extremes.

What climate-resilient housing changes

Well-established evidence suggests that well-designed, climate-resilient housing can reduce heat load by 30–50% (Das, 2025). These can significantly improve animal comfort and productivity. Raised and slatted flooring systems can help mitigate flood and waterlogging risks. Non-profits, such as SEEDS India (The Better India, 2023), have demonstrated the feasibility of these designs through SHG-linked, aggregated implementation models, which lower the upfront costs for individual farmers. Such housing interventions can combine partial cost-sharing, use of local materials, and community-level oversight to protect animals from dampness, flooding, and temperature stress. These also improve adoption, maintenance, and long-term sustainability.

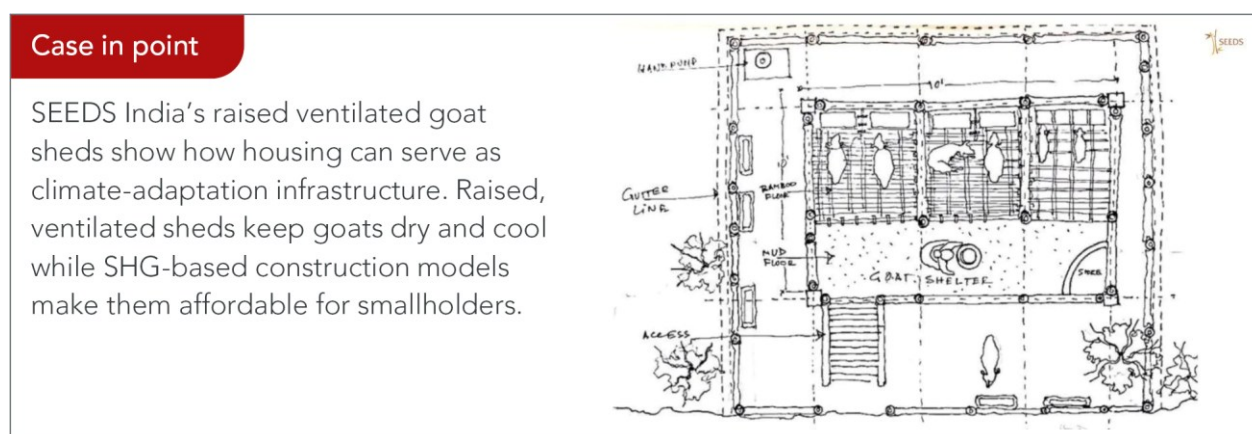


Figure 19: Example of climate-resilient housing for smallholders

Source: SEEDS

Breeding constraints in a changing climate

How unstructured systems erode genetic potential and productivity

Goat breeding in India is largely unstructured and dependent on non-descript or locally adapted populations, with natural breeding dominating across regions. Field studies show that most farmers use either their own buck or a community buck for breeding, as more than 70% in a Rajasthan study (Bagri, 2024) and 96.7% in a Gujarat study reported this practice and (Siyak, 2024). A large section of them also showed repeated use of the same male over multiple breeding cycles.

Over generations, this practice increases inbreeding and genetic dilution. This results in the gradual erosion of desirable traits in recognized breeds, such as the Black Bengal for its meat quality and Surti for its milk yield. Inbreeding reduces fertility, growth rates, and kid survival, which contributes to inferior herd performance.

Climate stress disrupts reproductive cues

Most farmers also continue to rely on traditional knowledge to detect heat and pregnancy. While this approach has historically worked under stable climatic conditions, climate change disrupts reproductive cues (DK Bagri, 2024). Recent climate research highlights that climate-induced heat stress and altered seasonal patterns can mask traditional heat signals and delay estrus, which complicates timely breeding under changing climate regimes. It also directly impairs reproductive efficiency in goats through physiological stress in both males and females. This reduces semen quality, conception rates, and embryo survival, and stresses an already exhausted system.

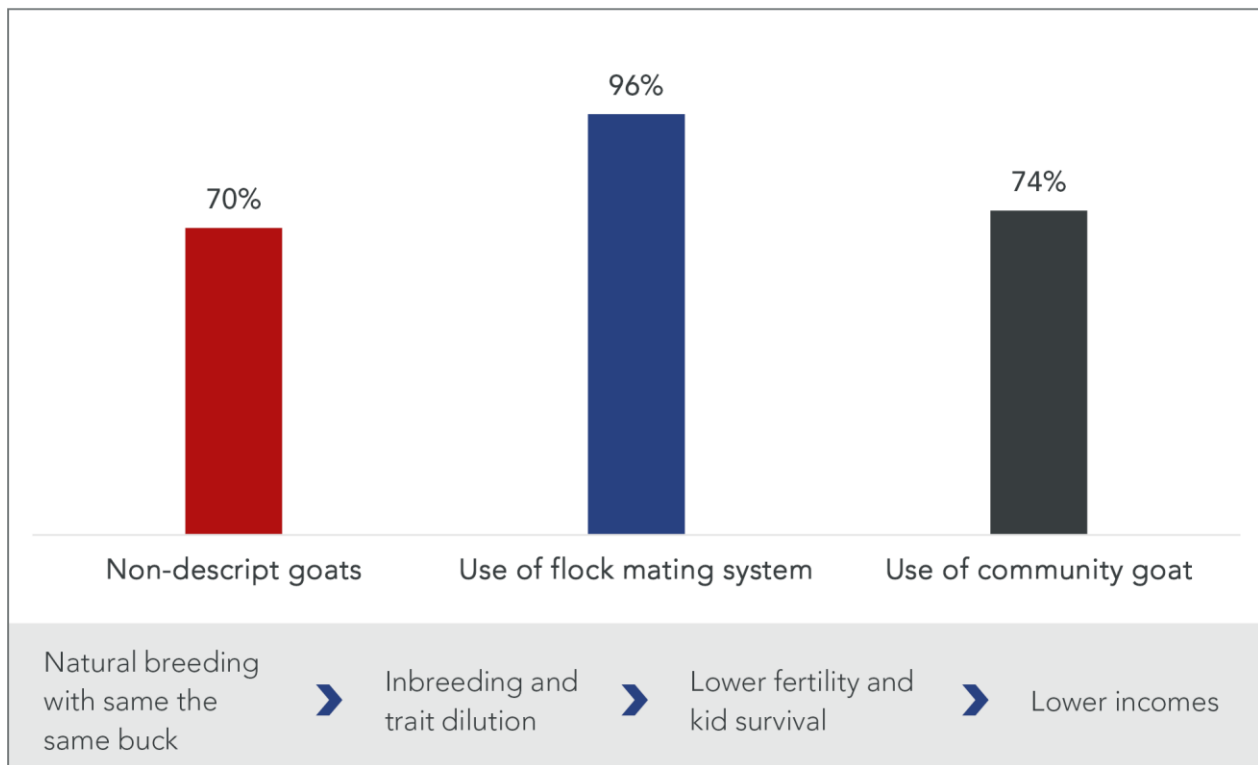


Figure 20: Status of breeding in smallholder goat farmers and why natural breeding is harmful

Green shoots of genetic improvement through artificial insemination

A scientific approach to goat breeding is urgently needed. While artificial insemination (AI) has made major strides in cattle, similar progress has not occurred in goats. AI success depends on trained inseminators, reliable semen logistics, accurate heat detection, and strong extension support. These areas remain underdeveloped for small ruminants.

Evidence from field studies reports conception rates of 45–55% in goats under managed AI conditions (ICAR, 2026), comparable to natural service when adequate technical support is available. However, such successes remain confined to small pilots. Investment is therefore required to scale technician training, semen supply systems, and community-based delivery models. This will ensure a larger share of goats can access improved genetics and reduce inbreeding under increasing climate stress.

Constraints in feed, disease management, housing, and breeding are closely interlinked and mutually reinforcing within smallholder goat systems. Climate change intensifies each of these pressures and converts previously manageable risks into recurring productivity and income losses.

Importantly, the preceding sections indicate that responses are already emerging across these domains, which range from collective feed infrastructure and last-mile animal health delivery to climate-resilient housing and improved breeding services. However, the effectiveness of these approaches depends on their ability to operate at scale and align with smallholder realities. Without such system-level adaptation, climate stress will continue to erode the viability of goat rearing as a stable livelihood for vulnerable households.

Pathways forward: Scaling what already works

Across feed, disease, housing, and breeding, the binding constraints are not technological but scale and buying power. Community fodder banks, vaccination, climate-resilient sheds, and improved breeding services are all proven. But smallholders who manage 3–10 goats lack the capital, credit, and volume to adopt them on their own. Climate resilience cannot be built household by household. It requires institutions that aggregate farmers into investable units.

Farmer-producer organizations (FPOs), SHG federations, and livestock cooperatives provide this missing infrastructure. They enable bulk procurement of feed and minerals, community-level preventive care through *Pashu Sakhi*, shared housing investments, and organized breeding services. Just as importantly, aggregation improves price realization as it allows farmers to sell healthier, higher-quality animals in larger, more predictable volumes.

Livestock FPOs remain rare because they are capital-intensive, service-heavy, and risky to operate. Unlike crop FPOs, goat-based FPOs must manage feed stocks, health delivery, mortality risk, and working capital across the year. This makes them difficult to finance and slow to scale. Without patient capital, technical support, and long-term institution building, most never move beyond pilots. Stakeholders need to treat livestock FPOs as critical rural infrastructure to unlock climate resilience in goateries. They need to enable livestock FPOs to operate across the value chain and build collective buying power that smallholders cannot achieve on their own.

List of people consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Chetan Dubey	Thematic Program Executive, BAIF
2	Dr. Krishnakumar Singh	Chief Program Coordinator, BAIF

4.2.3 Poultry

India's poultry economy

High-growth protein system powers rural incomes but are increasingly constrained by climate change and market fragility

Poultry is India's fastest-growing livestock sector, driven by rising demand for affordable animal protein, short production cycles, and low land requirements. Unlike cattle or small ruminants, poultry converts feed into meat and eggs with exceptionally high biological efficiency. This makes it particularly attractive for smallholders, women, and land-constrained households.

A broiler reaches market weight in just 35–40 days, while a layer begins to produce eggs within 18–20 weeks. This enables multiple income cycles per year and rapid capital turnover. This speed makes poultry one of the most scalable and income-intensive forms of livestock in rural India. But it also makes it highly sensitive to shocks, since even a single failed cycle can wipe out a household’s working capital.

	Breed and reproduction systems	Feed and nutrition systems	Disease and hygiene	Housing and thermal environment	Production and flock performance	Market access and aggregation
Core functions	<ul style="list-style-type: none"> Supply day-old chicks Enable genetic productivity Support flock replacement cycles 	<ul style="list-style-type: none"> Provide balanced bird nutrition Enable rapid weight gain and egg production Support feed conversion efficiency 	<ul style="list-style-type: none"> Prevent infectious disease spread Maintain flock immunity levels Enable rapid outbreak response 	<ul style="list-style-type: none"> Regulate shed micro-climate Protect birds from heat stress Maintain ventilation and hygiene Support stable productivity levels 	<ul style="list-style-type: none"> Convert feed into output Generate meat and milk Enable herd growth cycles 	<ul style="list-style-type: none"> Enable bird and egg sales Facilitate price transmission Aggregate farmer production Connect farms to value chains to buyers
Key risks	<ul style="list-style-type: none"> Dependence on commercial strains of birds and integrators where smallholders have less bargaining power Weak backyard breed improvement Limited quality chick access 	<ul style="list-style-type: none"> High maize-soy dependence Rising grain price volatility Feed quality deterioration Limited smallholder procurement power 	<ul style="list-style-type: none"> Weak last-mile vaccination access Poor farm-level biosecurity High pathogen transmission rates 	<ul style="list-style-type: none"> Low-cost, poorly insulated sheds Limited cooling infrastructure High humidity and ammonia build-up Inefficient housing increases flood and heatwave exposure 	<ul style="list-style-type: none"> High input cost sensitivity Thin farmer production margins Working capital dependence Cycle failure income shocks 	<ul style="list-style-type: none"> Commodity price fluctuations Integrator bargaining power Weak smallholder aggregation Transport and cold-chain gaps
Climate impact	<ul style="list-style-type: none"> Rising temperatures and heatwaves reduce hatchability and chick survival Greater variability in 	<ul style="list-style-type: none"> Crop yield variability (droughts, erratic rainfall) reduces feed availability and quality Heat stress lowers feed intake and 	<ul style="list-style-type: none"> Warmer and more humid conditions accelerate pathogen growth and disease spread Increased frequency of 	<ul style="list-style-type: none"> Heatwaves and rising average temperatures increase thermal stress in poultry sheds Climate conditions 	<ul style="list-style-type: none"> Heat stress reduces growth rates, egg production, and feed efficiency. Greater climate variability 	<ul style="list-style-type: none"> Climate shocks disrupt transport, storage, and cold-chain infrastructure Fluctuations in supply due to climate

	Breed and reproduction systems	Feed and nutrition systems	Disease and hygiene	Housing and thermal environment	Production and flock performance	Market access and aggregation
	seasons disrupts breeding cycles and increases mortality	feed conversion efficiency <ul style="list-style-type: none"> ▪ Rising feed prices due to climate shocks increase production costs 	extreme weather events weakens biosecurity systems <ul style="list-style-type: none"> ▪ Loss of potential income due to higher mortality 	(heat + humidity) increase ammonia build-up, reducing bird health and productivity <ul style="list-style-type: none"> ▪ Mass mortality during heatwaves 	increases production uncertainty and income instability	impacts increase price volatility <ul style="list-style-type: none"> ▪ Reduced and inconsistent production affects farmers' ability to access stable markets

Table 11: Climate-linked risks and impacts across the poultry value chain

Half of India's meat is one of its biggest rural industries

India is now one of the world's largest poultry producers, and ranks second globally in egg production and fifth in poultry meat. In 2023–24, India produced 10.25 million tonnes of meat, of which poultry accounted for nearly 49%, and 142.7 billion eggs. More than 86% of this came from fowl (DAHD, 2024). Poultry production is regionally concentrated, with the broiler industry dominated by southern and western states. The layer industry is led by Andhra Pradesh, Tamil Nadu, and Maharashtra, which together account for almost 60% of national egg output (DAHD, 2024). This geographic clustering has enabled scale and efficiency, but it also concentrates climate and disease risks into a handful of critical production hubs that feed the entire country.

Poultry has evolved into one of India's most dynamic agro-industries. The sector was valued at INR 2,304 billion (approx. USD 25 billion) in 2024 and has been growing rapidly. Chicken meat has expanded at about 9% a year and eggs at around 6% over the past two decades (DAHD, 2023). By 2033, the market is projected to reach INR 8,430 billion (approx. USD 90 billion), growing at a CAGR of 12.6%. Beyond meat and eggs, the poultry economy also supports hatcheries, feed mills, veterinary services, cold chains, transport, and retail, which creates dense employment networks across rural and peri-urban India. With annual revenues of around INR 1.25 trillion (approx. USD 13.38 billion), poultry now contributes 1% to the national GDP and 14% to livestock GDP (DAHD, 2023). This makes it one of the few agricultural sectors that combines scale, speed, and recurring cash flows, which is why poultry has become central to India's food security and rural income strategies.

From backyard to big business

India's poultry system is sharply dualistic and spans both backyard and commercial production. According to the Department of Animal Husbandry and Dairying (DAHD), any flock of fewer than 1,000 birds is classified as backyard poultry, a segment that supports 23.79 million households. Backyard poultry produces 27 billion eggs, which contributes 19.5% of the total output, while commercial systems produce 114.9 billion eggs, or 80.5% of the total. Bird populations are rising fast, with commercial poultry at 534.7 million birds (up by 4.5%) and backyard poultry at 317.1

million birds (up by 45.8%) from the previous Census (DAHD, 2023). Therefore, backyard poultry is not just an industrial food system but one of India’s most widely distributed livelihood assets. It includes households with 10–20 birds and FPO-linked farmers who manage 200–800 birds.

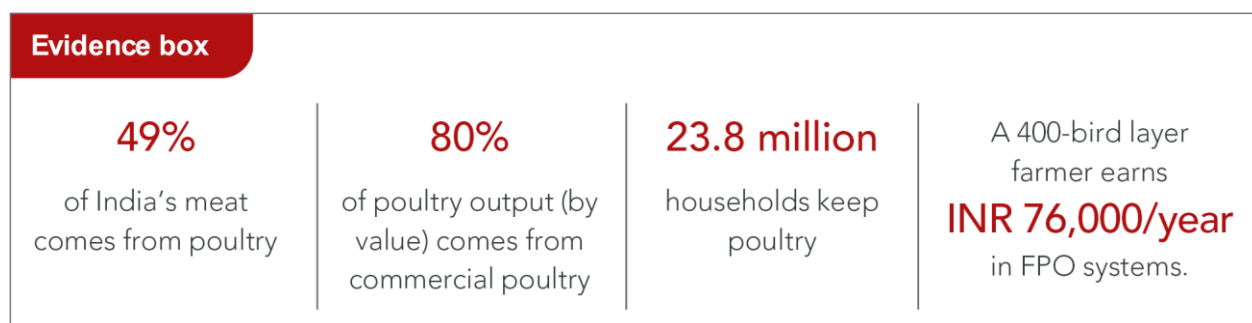


Figure 21: Data at a glance

Within this large and fast-growing sector, three structurally different bird systems shape farmer outcomes

Desi or indigenous birds are climate-resilient and low-input, but have very low productivity of 60–80 eggs per bird per year, which keeps incomes subsistence-level. Commercial or exotic birds are highly productive. Each bird produces 280–320 eggs per year. But, they depend on intensive inputs and operate in commodity markets with thin farmer margins and high climate and disease risk. Between these extremes lie desi–crossbred systems, which combine resilience with productivity at 180–250 eggs per bird per year, and are structurally suited to free-range and premium markets.

	Desi/Indigenous	Crossbred/Improved	Commercial/Exotic
Type of system	Scavenging/extensive (backyard, free-range, low input)	Free-range/semi-intensive (scavenging + partial feed)	Intensive/industrial (cage/deep litter, full feed dependence)
Eggs/bird/year	60–80	180–250	280–320
Input cost/egg	INR 10–11	INR 7	INR 2.5–3.5
Farmer price/egg	INR 15–18	INR 10–12	INR 3.5–4
Margin/egg	INR 5–7	INR 3–5	INR 0.5–1 (very thin)
Market positioning	Local/informal markets	Premium/niche markets	Commodity markets

Table 12: Comparison of desi, crossbred, and commercial poultry birds

Why poultry is profitable

At the household level, poultry offers a strong income potential. A typical 400-bird layer farmer earns about INR 6,000 (approx. USD 64) per month or INR 76,000 (approx. USD 814) per year when part of an FPO system, such as KESLA, under the national smallholder poultry trust. Larger flocks generate substantially higher returns (National Smallholder Poultry Development Trust, 2022-2023). This income is increasingly delivered through contract farming, where hatcheries and integrators supply chicks, feed, and assured market access.

By 2020, nearly 80% of India's poultry output (by value) came from this organized segment, with around 70% of participating farmers being smallholders who operate flocks of 3,000–10,000 birds (DAHD, 2023). There are conflicting accounts of the benefits of contract farming for farmers. Some praise the risk mitigation aspect due to backward and forward linkage, while others are discontent with the returns.

Beneath this growth, however, lies deep vulnerability, especially for smallholder farmers. Feed alone accounts for 60–70% of production costs, which leaves farmers highly exposed to price shocks in maize and soybeans. At the same time, most smallholder and contract farms operate with weak housing, limited temperature control, and poor disease surveillance. As climate variability increases heat stress, humidity, and pathogen pressure, these biological and infrastructural gaps are becoming binding constraints. Without climate-adapted feed, housing, and health systems, poultry can shift from a high-return livelihood to a high-risk enterprise, where a single heatwave or disease outbreak can wipe out an entire production cycle. Here is a summarization of climate impacts on the poultry value chain:

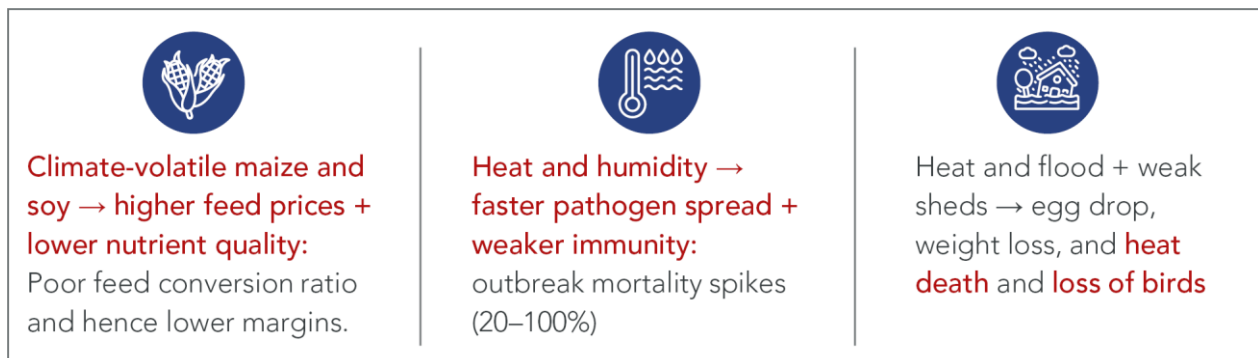


Figure 22: Summary of climate impacts in poultry value chain

Feeding poultry in a changing climate

How feed quality, grain markets, and climate stress jointly shape poultry productivity and profitability

Poultry feed is not just about filling birds' stomachs. It provides the right nutrients in the right balance at the right time. Broilers require high-protein, energy-dense diets, with 18–22% protein to reach market weight in 5–6 weeks (MSD Veterinary Manual, n.d.). Layers need moderate protein (16–18%) and high calcium (4–4.5%) to sustain egg production for 12–15 months (ICAR, 2026). This precision enables poultry to achieve a Feed Conversion Ratio (FCR) of 1.6–1.7. This means 1.6–1.7 kg of feed produces 1 kg of live weight and underpins the biological basis of poultry's profitability (ICAR, 2026).

The maize–soy backbone

More than 80% of this poultry feed comes from maize and soybeans, where maize alone contributes more than 50%. Roughly half of India's maize production (Yes Bank - FICCI, 2023) is absorbed by the animal feed industry. Large integrators, cooperatives, and commercial feed mills have standardized feed formulation. However, smallholders access this system very differently, from kitchen scraps in subsistence systems to pre-mixed bags from local dealers or integrators in semi-commercial farms. For small farmers, feed management involves ways to achieve maximum biological efficiency at the lowest possible cash cost.

Feed costs shape production economics

As the feed accounts for 60–70% of poultry production costs, farmers are extremely vulnerable to grain price volatility. Over the last decade, maize prices have risen at around 6% CAGR, (Statista, 2025) while egg prices have grown only about 4% (National Egg Coordination Committee, 2025), which has steadily squeezed farmer margins. Egg production has expanded at about 5% CAGR, but maize production has lagged at around 3.2%, which tightens supply just as demand rises (Yes Bank - FICCI, 2023; DAHD, 2023). The diversion of maize for ethanol and industrial use further intensifies competition for grain and raises feed costs.



Figure 23: Economics of how feed cost has risen, and eggs have not kept up

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For backyard poultry, feed is the bottleneck. At 60% of costs, without a breakthrough in cheaper, reliable feed, smallholders cannot compete with big integrators, no matter how good the health or shelter tech is.

- Pawan Ojha, Director, The/Nudge Institute

Climate as a new input cost

The added pressure from climate stress is raising prices and eroding feed quality itself. Warmer, more humid conditions encourage fungi, such as *aspergillus* and *fusarium*, to grow in stored grain. These produce toxins, namely aflatoxin and fumonisin, that reduce digestibility and depress feed conversion. Water stress and poor soil moisture lower the protein, fat, and micronutrient content of maize and soybean. As a result, a standard composite feed that should contain 18–22% protein and 2,850–3,100 kcal per kg can fall to 16–20% protein and 2,700–3,000 kcal per kg. This forces birds to eat more feed for less growth (Kelvin Ngongolo, 2024; Goel, 2021; D. Renaudeau, 2012). Broilers take longer to reach market weight, and layers lay smaller eggs with thinner shells, which directly cut farmer incomes.

This, combined with heavy dependence on maize and soybeans, creates a significant risk, as both are highly sensitive to monsoon timing, rainfall intensity, and heat stress. Erratic monsoons reduce yields, disrupt harvests, and increase post-harvest losses, which tightens domestic grain availability. When this happens, feed mills and integrators are forced to compete for smaller volumes of maize and soybeans, which drives up market prices. These shocks are quickly passed down the value chain. This means that even modest climate-driven price rises translate directly into lower margins for farmers.

Pathways to reduce feed system risk

Farmers and firms are exploring two main pathways to escape feed inflation. One pathway involves alternative proteins, such as Black Soldier Fly larvae, worm meal, and other waste-based feeds. These offer 45–55% crude protein (Imen Belhadj Slimen, 2023) and can substitute 10–50% of conventional feed. However, these currently cost INR 90 (USD 1) per kg, approximately, compared to INR 30 (USD 0.3) per kg, approximately, for composite feed (Indiamart, 2025). This makes them inaccessible for most smallholders despite promising pilots by firms like Loopworm. Future-focused studies (Esther Khayanga Sumbule, 2021) also point to its unaffordability as a substitute in the near future.

The second pathway is collective procurement through cooperatives, such as the National Smallholder Poultry Trust, which provides backward linkages, bulk buying power, and a stable supply. Without these institutional buffers, individual farmers remain exposed to climate-driven feed shocks that directly translate into falling productivity and rising debt.

The cost of getting sick

Hotter, wetter conditions are driving faster disease transmission, and why prevention systems are struggling to keep up

Poultry is exposed to a wide range of pathogens, which include viral diseases, such as Newcastle Disease (ND) and avian influenza (AI), bacterial infections, such as Salmonella and Pasteurella. Poultry is also exposed to parasitic infections, such as coccidiosis and worms. These pathogens spread rapidly through direct contact, contaminated feed and water, aerosols, litter, equipment, vectors, and, in some cases, through eggs. Once introduced, infections can escalate within 24–36 hours (MSD Veterinary Manual, 2025) and quickly spread across entire flocks, which makes early detection and rapid response essential.

Speed of spread and scale of loss

After feed-related challenges, disease outbreaks are among the leading causes of production losses in poultry systems, particularly for smallholders. Under routine conditions, major diseases result in 8-15% mortality rates. But during outbreaks, losses can rise sharply to 20–100%. Highly contagious viral diseases, such as ND and avian influenza, can wipe out entire flocks. This results in a complete loss of productive assets and income.

The first line of defense

Prevention remains the most effective strategy for disease control. Biosecurity measures are critical to prevent pathogen entry and spread. These measures include controlled access, sanitation, all-in-all-out management, and litter hygiene. Vaccination is important to protect against major viral diseases, such as ND, IBD, Marek's disease, and fowl pox, with protocols varying by production system and disease prevalence. For high-impact diseases, such as avian influenza, surveillance and early detection are equally important to enable timely containment.

Health services stop before the village

While preventive health management is standard within integrated poultry systems, most smallholder and backyard farmers face significant access constraints. Even when vaccines are free, reaching vaccination points involves time and transport costs, while scattered farm locations and weak last-mile cold-chain infrastructure limit delivery. In many areas, low awareness further reduces uptake of preventive practices.

Climate-driven shifts in disease dynamics

Climate change increases these challenges in two ways. First, warmer and more humid conditions increase pathogen survival and transmission. This expands the geographic and seasonal spread of diseases, such as ND and AI. Second, climate-driven increases in heat stress weaken bird immunity. At sustained temperatures of 32–35°C, antibody responses to vaccination decline by 25–35%, and birds experience significantly higher mortality during outbreaks (Oke, 2024) (Renaudeau, 2012). These effects convert disease risk from an episodic shock into a recurring productivity constraint.

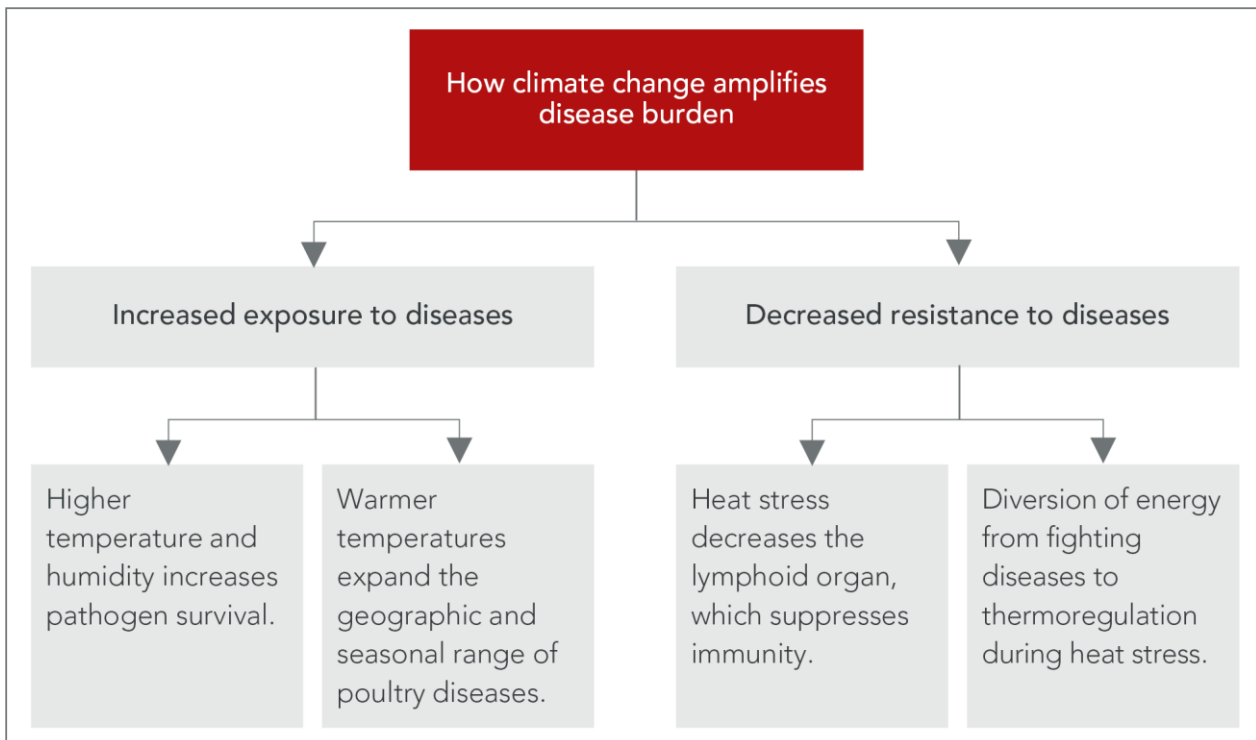


Figure 24: How climate change increases the burden of disease

Building a health system that reaches farms

We need to strengthen last-mile delivery to reduce diseases driven by climate change. Cooperative and integrated value-chain models enable more reliable access to vaccination, surveillance, and advisory services. Investments in local cold-chain infrastructure, combined with sustained awareness efforts and community-based service delivery models, such as *Pashu Sakhi*, can significantly improve preventive coverage and reduce mortality among smallholder poultry producers.

The missing asset

How housing has become the most important and most neglected climate-resilience investment in poultry

Few livestock systems are as tightly bound to their physical environment as poultry. Unlike ruminants, chickens have a limited ability to regulate body temperature and depend heavily on housing to buffer them from heat, humidity, and airflow fluctuations. Poultry perform best within a narrow thermal window of roughly 20–24°C, beyond which energy is diverted from growth and egg formation toward cooling the body.

Once ambient temperatures rise above 28–30°C, both broilers and layers begin to show measurable declines in feed intake, immunity, and productivity (Wasti, 2020). With India warmed by about 0.64 °C century⁻¹ over 1901-2016 (Molina, 2026) and continue to steadily heat up, housing has become one of the most critical determinants of poultry viability under climate change.

The biology of thermal stress and why hotter days mean fewer eggs

Thermal stress sets off a rapid biological cascade. The temperature for the upper critical threshold (UCT) is 30–32°C for layers and 28–30°C for broiler birds. Above these levels, they start to pant to dissipate heat, lose carbon dioxide, and disturb their blood chemistry. This reduces feed intake and weakens the immune response. In layers, egg numbers fall by 10–20%, egg weight drops by 4–8%, and shell breakage rises by 10–15% due to impaired calcium metabolism (Goel, 2021).

In broilers, continuous heat exposure reduces final body weight by 15–25% and worsens feed conversion (Renaudeau, 2012). Mortality also rises sharply. During heat waves, death rates can increase by 50–150% compared to normal periods, and when heat coincides with disease outbreaks, flock losses of 30–60% are common in smallholder systems (Oke, 2024) (Ngongolo, 2024).

Housing built for cost, not climate

Despite this sensitivity, most smallholder poultry in India are housed in thin, low-cost structures of tin, asbestos, or plastic sheets on bamboo or wooden frames, with little insulation or controlled airflow. These sheds trap heat during the day and release it slowly at night, which exposes birds to prolonged thermal load when they are least able to recover. Limited ventilation leads to high humidity, ammonia build-up, and wet litter. This further suppresses immunity and increases susceptibility to respiratory and intestinal infections.

Field evidence confirms how widespread this exposure is. A study from Madhya Pradesh found that only 42% of farmers had well-ventilated or insulated sheds, and just 33% used fans, foggers, or sprinklers during heat waves (Vishwakarma, 2025). This means most flocks face rising temperatures with little protection. This explains the frequent reports of mass mortality during heat waves, floods, and other extreme weather events across poultry-producing regions.

Technology exists, but access does not

Technically, the solutions are well known. Insulated roofs, reflective materials, better ventilation, and evaporative cooling can reduce shed temperatures by 4–12 °C. The lowered temperature can sharply reduce heat stress and stabilize production (Goel, 2021). But costs remain prohibitive as even basic insulated sheds require about INR 90,000 (approx. USD 960). Fully climate-controlled units cost INR 6,00,000 to 7,00,000 (approx. USD 6,400 to 7,500), far beyond what individual smallholders can afford. This makes poultry housing an institutional challenge rather than just a technical one. We need to build community-scale sheds, cooperative models, and subsidized climate-smart designs to turn housing into public climate infrastructure for a critical food and income system.

What it will take to stabilize poultry livelihoods

India's poultry sector is not short of technical solutions. Alternative feed formulations, effective vaccines, cooling systems, and better shed designs are all established. The real barrier is that these inputs are priced and delivered for large integrators, not for households that manage a few hundred birds. For smallholders, the problem is the gap between what exists and what they can realistically access and afford.

Closing this gap requires action on three fronts:

The first is public systems and policy delivery. Climate stress is turning vaccination, disease surveillance, and temperature management into essential services, yet these remain uneven beyond integrated farms. We need to expand cold-chain infrastructure, ensure regular vaccination coverage, and strengthen village-level advisory systems. These are critical to prevent heat and disease from becoming chronic production shocks. At the same time, farmers need practical guidance on nutrition, housing design, and hygiene, so that limited investments translate into healthier flocks.

The second front is economic organization and market access. When farmers act alone, they buy feed at retail prices, sell birds with little bargaining power, and cannot invest in cooling, housing, or health systems. When they operate through FPOs, cooperatives, or producer companies, they can aggregate demand for inputs, run shared services, and negotiate better prices for birds and eggs. This scale also enables private players to serve smallholders by designing low-cost feed, modular housing, vaccine delivery, and service bundles that work at village and cluster levels, rather than only for large integrators. In a climate-exposed poultry economy, it is this combination of collective buying power, last-mile service delivery, and private-sector scale that will determine whether smallholder poultry remains a livelihood or becomes an increasingly risky gamble.

The third is market-based diversification and value capture. Long-term livelihood stability needs market restructuring, not only production resilience. Smallholders remain vulnerable when productivity improvements are absorbed into commodity markets with thin margins. A complementary pathway is therefore market-based diversification. This will enable farmers to shift from low-margin commercial systems and low-productivity backyard systems into desi-crossbred, free-range production models that are structurally linked to premium markets.

Models, such as Akshayakalpa, demonstrate that crossbred birds reared under free-range conditions, with partial self-sourced feed and welfare standards, can access differentiated urban and institutional markets. This allows farmers to move from commodity pricing to premium price capture, which improves incomes through value differentiation rather than volume expansion.

backyard2bazaar challenge

enhancing farmer income through access to specialty markets for organic and free-range eggs, which provides higher returns

the big bet

<p>The opportunity</p>	<p>India's poultry sector is the fastest-growing livestock segment, driven by rising demand for affordable animal protein, short production cycles, and low land requirements. India is the world's second-largest egg producer, with an annual production of ~142.7 billion eggs. Poultry supports nearly 30 million farmers. Backyard systems produce ~27 billion eggs (19.5%), while commercial systems produce the remaining 80.5%.</p> <p>Despite this scale, most smallholder poultry farmers remain trapped in low-margin backyard systems rearing desi birds with minimal productivity (60–80 eggs/year), where climate stress is squeezing already thin incomes. At the same time, urban and institutional demand for cage-free, free-range, and antibiotic-free eggs is on the rise, with global buyers, such as Accor Hotels, Marriott, and Subway, committing to cage-free sourcing by 2028. Indian consumers already pay ~INR 24 (approx. USD 0.26) per egg for certified free-range or organic eggs. Models, such as Akshayakalpa's, show that desi crossbreeds, reared under true free-range conditions (≥ 15 sq ft per bird) with self-sourced feed, can produce 180–250 eggs per bird and access premium markets. However, most smallholders lack the organization, standards, and market access needed to participate, which leaves significant value unrealized.</p>
<p>Choke points</p>	<ol style="list-style-type: none"> 1. Poor productivity: Desi poultry birds in India have low productivity and lay on average only 80 eggs per year, compared to 250+ eggs per year in commercial layer strains. They attain a body weight of about 1.0–1.5 kg at 20–24 weeks, which leads to significantly lower meat and egg output. 2. Low awareness of premium demand and standards: Farmers are largely unaware that organic and free-range certified eggs can fetch prices of INR 24–25 (approx. USD 0.26) per egg, or of the conditions and certifications needed to access these markets. 3. Fragmentation of production: Backyard and smallholder poultry producers operate at sub-scale and in isolation, which prevents aggregation of consistent volumes, standard enforcement, premium market linkages, or collective negotiation for better prices.
<p>Solution space</p>	<p>Novel models are needed that enable backyard poultry farmers to transition to certified free-range, antibiotic-free egg and chicken production, enhance productivity with low to zero external inputs, and improve incomes through access to premium markets.</p>
<p>Target output(s)</p>	<ol style="list-style-type: none"> 1. Free range and welfare: ≥ 15 sq ft per bird, stress-free, antibiotic free and cage-free rearing

2. Low-/no-input: Nutrition should primarily be derived from on-farm scavenging (1–2 acres), crop residues, and kitchen waste
3. Productivity: Consistent production of ≥ 180 eggs per bird per year (desi-cross free-range systems) at standardized shape and quality
4. Farmers must capture $\geq 50\%$ of the final consumer selling price for eggs and chickens

The big bet

Smallholder poultry farmers should be empowered to transition from low-margin backyard to free-range, desi-cross egg production. This can be done by building aggregation, SOPs, and market linkages to allow farmers to reliably realize 50% of the product selling price and meet the growing demand from urban consumers and free-range institutional buyers.

List of people consulted across different stages of the research

a. Expert consultations

#	Name	Organization
1	Dr. Harekrishna Deka	CEO, NSDPT
2	John Paul	Executive Director and Chief Program Officer, The/Nudge Institute
3	Dr. Pankaj Das	COO, National Smallholder Poultry Development Trust
4	Pawan Ojha	Director, The/Nudge Institute
5	Dr. Sandeep Shivana	Head, Dairy and Poultry R&D, Akshyalakalpa
6	T. Sivaram	Product Manager, The/Nudge Institute

4.2.4 Fisheries

Millions at the water’s edge

How climate and market volatility are threatening India’s fishing and fish-farming households

India is the world’s second-largest fish producer. It contributes about 8% of the global output (Press Information Bureau 2025). In 2023–24, the country produced 18.4 million tonnes (PIB, Casting Nets, Catching Success, 2025) of fish, of which more than 70% came from inland fisheries and aquaculture. Marine products exports reached 1.78 million tonnes (Economist Impact, 2025) worth INR 61,554 crore (approx. USD 7.38 billion) (Economist Impact, 2025), led by frozen shrimp. Fisheries contribute 1.1% of national GVA (PIB, 2023) and more than 6.7% of agricultural GVA (Press Information Bureau 2023), making it one of India’s most valuable agri-food sectors.

Production hubs are concentrated in Andhra Pradesh, West Bengal, Gujarat, Odisha, and Tamil Nadu, which together anchor most of India’s aquaculture and seafood exports. The sector is projected to grow from INR 1,79,405 crore (approx. USD 21.5 billion) to INR 2,72,582 crore (approx. USD 32.7 billion) by 2032 at a CAGR of 5.4%, driven by domestic protein demand and global seafood markets (Markets and Data, 2024).

	Hatchery and seed systems	Pond preparation and grow-out	Feed and nutrient management	Pests, diseases and biosecurity	Harvest and post-harvest handling	Market access and aggregation
Core functions	<ul style="list-style-type: none"> Manage broodstock breeding and conditioning Produce quality seed in hatcheries Distribute seed to grow-out farms 	<ul style="list-style-type: none"> Prepare and maintain pond infrastructure Manage water quality and availability Monitor stock growth and health 	<ul style="list-style-type: none"> Procure and transport feed inputs Store feed safely on-farm Apply correct feeding practices 	<ul style="list-style-type: none"> Conduct disease surveillance Manage climate-sensitive outbreaks Enforce biosecurity practices 	<ul style="list-style-type: none"> Schedule harvest at optimal weight Minimize post-harvest losses Apply quality grading standards 	<ul style="list-style-type: none"> Manage transportation to markets Navigate market price volatility Ensure equitable market access
Key risks	<ul style="list-style-type: none"> Spawning depends on narrow temperature ranges Poor seed quality lowers survival rates Hatcheries are high disease-exposure environments 	<ul style="list-style-type: none"> Floods damage earthen pond bunds, dikes, and sluices Heatwaves reduce dissolved oxygen, stressing or killing stock Droughts shrink freshwater 	<ul style="list-style-type: none"> Floods disrupt rural roads and supply routes, delaying deliveries High humidity and flood moisture degrade stored feed Overfeeding during low-oxygen events wastes 	<ul style="list-style-type: none"> Climate variability increases disease frequency and unpredictability Warmer water accelerates pathogen replication and reduces fish immunity Weak farm-level sanitation makes containment difficult 	<ul style="list-style-type: none"> Floods delay harvest timing High humidity causes spoilage without cold chain Lack of climate-resilient grading standards 	<ul style="list-style-type: none"> Floods damage rural roads cutting market access Climate extremes cause simultaneous supply shocks and price volatility Marginalized farmers are the first excluded

	Hatchery and seed systems	Pond preparation and grow-out	Feed and nutrient management	Pests, diseases and biosecurity	Harvest and post-harvest handling	Market access and aggregation
		supply and raise water temperatures	feed and worsens water quality			from resilient supply chains
Climate impact	<ul style="list-style-type: none"> ▪ Temperature variability disrupts spawning ▪ Water quality decline lowers hatch rates ▪ Extreme events damage hatcheries 	<ul style="list-style-type: none"> ▪ Heat reduces dissolved oxygen resulting in fish mortality ▪ Flooding causes stock loss and infrastructure damage ▪ Drought increases salinity and stress 	<ul style="list-style-type: none"> ▪ Floods disrupt feed supply chains ▪ Heat and humidity spoil feed 	<ul style="list-style-type: none"> ▪ Warmer water accelerates pathogen growth ▪ Climate variability increases outbreak frequency ▪ Extreme events weaken biosecurity 	<ul style="list-style-type: none"> ▪ Higher temperatures accelerate spoilage and reduce shelf life ▪ Power disruptions affect cold storage and increase post-harvest losses 	<ul style="list-style-type: none"> ▪ loaded roads delay transport and increase losses ▪ Climate shocks drive price volatility ▪ Market access disruptions for smallholders

Table 13: Climate-linked risks and impacts across the fisheries value chain

A mass livelihood system with fragile incomes

Fisheries support 28 million people directly (Handbook Fisheries Statistics, 2023) and nearly double that number through processing, transport, and trade. Inland fisheries dominate. It employs more than 23 million people, mostly smallholders who operate ponds, tanks, and wetlands. More than 60% of fishers fall in vulnerable income groups and earn on average INR 10,000–11,000 per month (approx. USD 120-132) (Peace 2022; DoF 2023).

Even when fish sell at INR 100/kg (approx. USD 1.1/kg), a typical small pond (0.1–0.4 ha) generates only INR 200,000 – 300,000 (approx. USD 2,398–3,597) in annual revenue,¹ much of which is absorbed by seed, feed, water, electricity, and harvesting costs. As a result, fish farming remains a high-turnover yet low-margin livelihood for most small producers.

Fisheries are further threatened by a range of factors. Rising temperatures, erratic rainfall, floods, droughts, and water pollution are reshaping both marine and inland fisheries. Warmer waters reduce breeding success and push valuable species into cooler zones. Extreme rainfall fragments habitats and disrupts spawning cycles, while low dry-season flows and pollution increase disease and mass fish deaths.

How climate stress translates into fish losses

In river systems, such as the Ganga basin, temperatures have risen 0.2–0.5°C (Das, Debroy, and Chandragou 2026) and rainfall has declined sharply in recent decades, which has directly affected

¹ Expert consultations

fish reproduction and yields. What were once predictable fishing seasons are becoming volatile and uncertain, undermining food supply and income stability.

Temperature and water flow	Water quality and disease
Warmer rivers and seas → fish migrate, breed less, and grow slower → falling catches and unstable stocks	Heat + pollution → higher disease and mass fish kills → sudden pond and river losses
Rainfall extremes	Ecosystem disruption
Floods and droughts → destroyed spawning grounds, unpredictable harvests → volatile incomes	Food-web shifts → native species replaced by hardy, lower-value fish → income and nutrition fall

Three pathways to climate-resilient fish livelihoods

As warming waters, erratic flows, and disease make wild and open-access fisheries increasingly unstable, small fish producers need systems that allow greater control over production and risk. Three models dominate India’s response. Each offers a different pathway to climate resilience.

Pathway	What it does	Why it matters for climate resilience	Limits today
Integrated farming systems (IFS)	Combines fish with crops and livestock	Recycles nutrients, spreads climate risk, cuts feed costs	Complex to manage across enterprises
Aquaponics	Fish + vegetables in closed systems	Very water-efficient and climate-buffered	High capital, technical skill required
Aquaculture (ponds and tanks)	Controlled fish farming	Most scalable, predictable, market-friendly system	Needs feed, seed, water, and extension

Table 11: Pathways to climate-resilient fish livelihoods

Aquaculture offers a more straightforward, lower-risk, and market-friendly entry point for small fish farmers in India. While IFS and aquaponics hold strong appeal for sustainability and resilience, their greater technical and management complexity, coupled with capital requirements, limit their rapid adoption compared to aquaculture’s more accessible model.

The Blue Revolution’s second act: Aquaculture

How managed ponds replaced open waters and how climate risk now threatens this smallholder lifeline

India’s fish economy is no longer driven primarily by rivers and oceans, but by ponds and tanks. With more than 70% of fish production (NABARD, 2018) now coming from inland aquaculture, India has become the world’s second-largest aquaculture producer and the third-largest overall fish producer. This shift has transformed fisheries from a seasonal capture activity into a managed

food production system that supports hatcheries, feed mills, cold chains, processors, and export industries. For smallholders, aquaculture offers something rare in rural livelihoods: The ability to control stocking, feeding, and harvest timing, which has made incomes far more predictable than in open-water fishing.

The economics of a fish crop

The income potential is real. Evidence from Assam shows that polyculture systems (CRIER, 2025) — where carps are grown alongside small indigenous species can raise net returns substantially. Studies have found that in a 0.5-hectare pond, adding *Gudusia chapra* alongside carp generated an additional INR 28,753 (approx. USD 345) in net income beyond standard carp farming (Duarah and Mall 2020). Similar results are reported across eastern India, where diversified stocking improved feed efficiency, reduced risk, and raised cash returns from the same water body.

Yet, most small farmers operate at the fragile end of this spectrum. Indian aquaculture is dominated by extensive and semi-intensive systems that rely heavily on natural pond productivity, with limited aeration, filtration, or disease control. Yields typically range from 1–3 tonnes per acre in extensive systems and 3–8 tonnes in semi-intensive ones, and generate INR 200,000 – 400,000 (approx. USD 2,398–4,796) in gross revenue for a small pond. After paying for seed, feed, labor, electricity, and pond maintenance, which often reach INR 1,50,000–3,00,000 (approx. USD 1,799–3,597) per cycle, net incomes narrow to roughly INR 20,000–100,000 (approx. USD 240–1,199) (PAF 2025), leaving little buffer against shocks.

Climate risk enters through the pond

Aquaculture is not immune to climate risks. Small-scale fish farmers invest upfront in ponds, seed, feed, and labor over a 5–8-month production cycle. When climate shocks hit through heat waves, floods, disease outbreaks, or water contamination, the entire biological and financial system gets exposed at once.

Direct climate shocks	Indirect economic stress
Water quality collapse (oxygen crashes, toxic blooms, fish kills)	Higher feed use and mortality driving up production costs
Disease outbreaks causing rapid or total pond losses	Cash-flow shocks limiting ability to restock or scale

For instance, rising temperatures simultaneously reduce oxygen solubility and increase the metabolic demand of fish, which accelerates oxygen depletion. Similarly, excess nutrients from feed and runoff can trigger eutrophication, which leads to algal blooms that release toxins and further deplete oxygen levels. In coastal and delta systems, saline intrusion alters water chemistry and reduces the survival rates of freshwater species.

Water quality: climate change hits aquaculture at its weakest point

Climate change strikes aquaculture first through water instability. Rising water temperatures reduce oxygen solubility, increasing metabolic demand while depleting the dissolved oxygen fish need to survive — slowing growth and raising mortality rates. Droughts concentrate waste and nutrients, while floods wash in sediments, pollutants, and pathogens, or flush fish out of ponds. These forces destabilize temperature, oxygen, pH, and salinity, which are the core parameters fish

depend on. Even small deviations suppress feeding and growth and force farmers to spend more on aeration and water exchange just to keep fish alive. Unlike field crops, where damage accumulates gradually and partial harvests remain possible, water quality collapse in aquaculture is fast and often total — with little warning and no partial recovery.

In practice, however, water-quality management in smallholder aquaculture remains largely reactive. Farmers rely on visible signal changes in water color, surface scum, or fish gasping, which typically appear only after stress has already crossed critical thresholds. Preventive actions, such as aeration, water exchange, or feed adjustments, are therefore triggered late, which reduces their effectiveness. Advisory support, when available, tends to be periodic and generic rather than pond-specific, which limits its ability to guide timely intervention.

Disease: Heat and pollution turn outbreaks into economic disasters

Warmer, nutrient-rich water also accelerates the spread of bacterial, fungal, and parasitic infections. Heat and low oxygen weaken fish immunity, while crowded ponds allow pathogens to move quickly through stocks. Smallholders usually lack diagnostics or veterinary support, so disease is often detected only after mortality begins.

Climate change worsens the degradation. It increases pathogen survival and pushes fish into chronic stress, which turns outbreaks into full-cycle financial disasters. When a pond crashes, farmers lose not just their fish but their entire season's investment in seed, feed, and labor, and are left with debt instead of harvest.

The absence of early warning systems compounds this challenge. Disease detection is typically based on visible symptoms, by which time the infection has already spread across the pond. Without access to simple, rapid diagnostic tools or risk alerts, farmers are forced to rely on reactive treatment, often with limited effectiveness and higher costs.

Water quality: Climate change hits aquaculture at its weakest point

How warming, pollution, and rainfall shocks destabilize ponds, and why farmers lose fish before they know what is wrong

Aquaculture's success depends on water chemistry. Fish thrive only within narrow ranges of dissolved oxygen (≥ 5 mg/L), temperature (24–30 °C), pH (6.5–8.5), ammonia (< 0.05 mg/L), and clarity (40–60 cm Secchi depth). When these parameters drift, growth slows, immunity weakens, and mortality rises. Climate change makes this balance harder to maintain. Rising temperatures reduce oxygen solubility, while increasing fish metabolism pushes ponds toward oxygen stress. Major carp species in India tolerate 20–37°C but suffer outside this range, whereas species, such as tilapia, collapse below 8°C or above thermal thresholds. In shallow or poorly managed ponds, even short heat waves can trigger rapid oxygen crashes and mass fish deaths.

Why poor water quality leads to rapid economic loss

Beyond temperature, climate change intensifies multiple water-quality pressures at once. Higher rainfall variability and runoffs bring excess nutrients from fertilizers and feed to trigger eutrophication and toxic algal blooms that strip oxygen from ponds. Sea-level rise and saline intrusion alter water chemistry in coastal and delta regions, stressing freshwater species and reducing survival. Droughts and evaporation concentrate waste, raise salinity, and lower pond depth, while floods introduce pesticides, heavy metals, and pathogens. These interacting stresses

make water instability one of the most common causes of crop failure in aquaculture, particularly in major producing states, such as Andhra Pradesh, West Bengal, and Odisha.

The economic impact is large. India's fisheries sector is estimated to lose more than INR 16,680 crore (approx. USD 2 billion) annually due to water pollution and untreated wastewater entering aquatic systems (Business Standard 2025). At the farm level, poor water quality leads to slower growth, higher feed use, disease outbreaks, and emergency treatments that raise costs and cut margins.

Why prevention works, but remains out of reach

The benefits are greater where water is managed actively. Maintaining stable oxygen, temperature, and nutrient levels can raise harvest volumes by 20–35% and sharply reduce disease and mortality. Aeration, controlled water exchange, and waste management prevent toxic buildups and protect fish immunity. This lowers the need for emergency treatments and improves margins. In theory, aquaculture is one of the most controllable forms of farming. In practice, smallholders rarely have the tools to manage their ponds this way.

The constraints are not only affordability but also usability and field readiness. Most real-time monitoring systems are designed for commercial aquaculture and require stable electricity, connectivity, calibration, and technical interpretation. For small-scale farmers who manage extensive or semi-intensive ponds, these requirements are difficult to meet. Even when tools are available, they often generate streams of raw data rather than clear decisions. This places the burden of interpretation on farmers who may lack the time, training, or confidence to act on multiple parameters simultaneously. As a result, technologies intended to enable prevention often end up reinforcing a pattern of delayed, symptom-driven response.

Most farmers lack affordable aeration, real-time water monitoring, and reliable power for pumping and circulation. They depend on visual signs such as gasping fish, water color, and surface scum, which appear only after stress is already severe. By then, the window to intervene has often closed. Climate volatility makes this gap even more damaging: faster environmental swings now outrun human observation. Without continuous information on oxygen, temperature, pH, or ammonia, farmers cannot act early enough to avoid losses. Climate volatility makes this gap even more damaging: Faster environmental swings now outrun human observation.

The missing link: seeing problems before fish start dying

Technologies to manage pond conditions already exist, but their impact depends on whether problems are detected in time. Low-cost water-quality sensors can provide real-time information on oxygen, temperature, and pH, which typically increases yields and reduces losses by 15–18% as they allow farmers to intervene before stress becomes lethal. Simple aeration systems, such as paddle-wheel, wind, or solar aerators, stabilize dissolved oxygen and, in some settings, cut electricity costs by up to 80% (Nafiah, Fikriyadi, and Putri 2024).

More advanced approaches, including biofloc systems and recirculating aquaculture systems (RAS), can raise growth and survival by 15–40% (Farmonaut, 2025) and lower feed and water use, but their higher capital and skill requirements place them beyond the reach of most individual smallholders.

Early detection is also inherently difficult. Key parameters, such as dissolved oxygen, temperature, turbidity, and nutrient levels, begin deteriorating hours to days before visible stress appears, which

creates a narrow but critical window for preventive action. However, these parameters interact in complex ways, and clear action thresholds are often not well understood at the farm level. Without simple indicators or decision rules, farmers cannot distinguish between normal variation and early signs of risk, which leads to delayed or missed interventions.

Disease: heat and pollution turn outbreaks into economic disasters

Why warming water, stressed fish, and weak detection systems are driving catastrophic stock losses

Freshwater aquaculture ponds are ideal environments for pathogens. Warm, nutrient-rich water allows bacteria, fungi, and parasites to multiply rapidly, while dense stocking brings fish into constant contact with contaminated water, waste, and biofilms. Common pathogens, such as *Aeromonas*, *Edwardsiella*, *Saprolegnia*, and parasites, such as *Argulus* and *Ergasilus* persist in pond sediments and on surfaces, which makes reinfection common even after treatment. Poor hatchery hygiene and infected seed further amplify early-stage outbreaks to turn disease into a built-in biological risk for smallholder aquaculture.

How climate and water stress amplify outbreaks

Climate change intensifies this vulnerability. Higher temperatures accelerate pathogen growth and replication and weaken fish immune systems. Fluctuating rainfall, droughts, and water-quality instability create repeated stress shocks that make fish more susceptible to infection. Low oxygen, ammonia spikes, eutrophication, and salinity changes suppress immunity and damage gills and skin. This allows bacteria and fungi to invade more easily. As a result, disease outbreaks that were once episodic are becoming more frequent and more severe.

The scale of economic loss

The financial toll is large. Disease accounts for at least 25% of aquaculture losses in India (The Indian Express 2017), with more than half of these losses caused by bacterial pathogens. The total economic burden is **around INR 20,682 crore** (approx. USD 2.48 billion) annually, nearly 15% of the national aquaculture production value (Patil et al. 2025). Disease outbreaks in Indian freshwater aquaculture cause significant mortality rates of 15-30% in affected stocks, leading to major income losses (Sahoo et al., 2020). Because farmers have already invested in feed, seed, labor, and pond preparation, these losses translate directly into debt and income collapse.

How can losses be mitigated, and why are smallholders still struggling?

Biosecurity measures, rigorous seed quality control, and prophylactic treatments can significantly reduce disease incidence before it takes hold. When early diagnosis is paired with timely treatment, farmers can contain outbreaks, limit mortality, and protect the investments already committed to each production cycle. Emerging tools—such as AI-based disease recognition, low-cost molecular diagnostics, and sensor-linked monitoring systems—can identify infection risks before mortality begins, enabling earlier intervention that can substantially improve productivity and reduce losses.

Yet most smallholders remain far from this standard. Weak extension systems, low awareness, and the absence of insurance or risk-pooling mechanisms mean that farmers absorb the full shock of

disease outbreaks. In the absence of timely diagnostics and advisory support, many resort to unregulated antibiotic use, exacerbating antimicrobial resistance and compounding long-term disease pressure. Although effective technologies exist, they remain largely out of reach—often too costly, too complex, or too dependent on infrastructure that small-scale farmers lack.

Across both water quality and disease management, a consistent pattern emerges: small-scale aquaculture systems are constrained by a mismatch between available technologies and field realities. Existing solutions are not sufficiently adapted to the cost structures, capacity levels, and operational constraints of smallholders. This creates a persistent gap between when risks emerge and when farmers can respond—a gap that is likely to widen further under increasing climate variability.

Pathways forward

Small-scale aquaculture is constrained less by biology than by the ability to anticipate and manage changing pond conditions. Most farmers operate extensive or semi-intensive systems with thin margins and limited working capital, where even short periods of suboptimal conditions—such as low dissolved oxygen, temperature stress, or water quality fluctuations—can reduce growth, increase feed inefficiencies, and trigger disease outbreaks. Yet farmers currently do not have access to affordable, real-time tools that enable early detection of these risks or timely action to prevent avoidable losses.

As a result, pond conditions are often managed reactively. Farmers typically respond only after visible signs of stress—such as reduced feeding, erratic fish behavior, or mortality—by which point productivity losses are already locked in. Existing advisory systems reinforce this pattern: they are infrequent, generic, and not designed to support continuous pond management. While advanced monitoring technologies exist, they are built for intensive systems and require infrastructure, data interpretation, and sustained investment that do not align with smallholder realities.

The core challenge, therefore, is not only about detecting risks early, but about enabling farmers to maintain stable, optimal pond conditions over time. This requires shifting from episodic, symptom-driven responses to continuous, preventive management. Farmers need simple, reliable signals that indicate when pond conditions are moving out of optimal ranges, combined with clear, actionable guidance on how to respond—through adjustments in feeding, aeration, water exchange, or stocking practices.

What is missing is an accessible layer of support that connects early risk detection with everyday pond management decisions. Solutions must move beyond monitoring to actively help farmers stabilize pond environments, reduce variability, and sustain conditions that support consistent fish growth. This means prioritizing tools that are low-cost, low-maintenance, and usable in low-connectivity settings, while translating complex environmental dynamics into intuitive prompts that fit within existing farm practices.

Without this shift, farmers remain locked in reactive cycles, unable to prevent fluctuations that drive productivity losses and disease vulnerability. Bridging this gap—from delayed response to proactive stabilization—is critical to improving yields, reducing input inefficiencies, and building resilience in small-scale aquaculture systems under increasing climate variability.

the aqualife challenge

enhancing smallholder aquaculture productivity through
optimal pond environmental management

the big bet

<p>The opportunity</p>	<p>Small-scale inland fish farmers in India face significant productivity and income losses due to preventable pond-level risks, which include water-quality stress, disease vulnerability, feed inefficiencies, and seasonal environmental variability. These risks often develop gradually and remain unnoticed until fish mortality or growth slowdown occurs.</p> <p>A strong opportunity has emerged to deploy low-cost, preventive solutions that will enable farmers to maintain stable, optimal pond environmental conditions that support fish growth, improve productivity, and enhance farm profitability. Improved pond stability can also help reduce excessive input use and disease vulnerability while improving resilience to climate variability.</p>
<p>Choke points</p>	<ol style="list-style-type: none"> 1. Pond environmental conditions fluctuate rapidly and often become suboptimal before visible stress in fish is observed. 2. Fish farmers typically respond only after fish mortality, disease outbreaks, or growth slowdown occurs. 3. Fish farmers have a limited ability to interpret environmental and biological signals and link them to management decisions, such as feeding, aeration, or water exchange. 4. Monitoring and pond management practices are inconsistent and largely reactive among smallholder farmers. 5. Preventive pond management tools involve high perceived costs, complexity, and effort. 6. Fish farmers depend on electricity, connectivity, and equipment during extreme weather events. 7. Cash-flow constraints and risk aversion delay prompt management interventions. 8. Farmers have limited access to simple and trusted advisory solutions that can optimize growth conditions rather than only detect stress events.
<p>Solution space</p>	<ol style="list-style-type: none"> 1. Low-cost solutions that help farmers maintain optimal pond environmental conditions to support fish growth and survival through early warning signals and clear management thresholds 2. Behaviorally designed decision-support tools that translate monitoring insights into practical management actions, such as feed optimization, aeration, water exchange, or stocking adjustments 3. Advisory models that help farmers understand risk levels and optimize input efficiency and disease prevention practices 4. Modular and scalable solutions that allow farmers to adopt basic interventions and upgrade gradually

	<ol style="list-style-type: none"> 5. Offline or low-connectivity solutions suited to rural aquaculture environments 6. Solutions that build farmer trust and adoption through intuitive design and integration with existing value chains and farm practices
Target outputs	<ul style="list-style-type: none"> ▪ Enable farmers to maintain ponds within optimal environmental and growth conditions for longer durations ▪ Reduce fish mortality and disease incidence by $\geq 25\text{--}30\%$ ▪ Reduce feed, chemical, and input costs by $10\text{--}15\%$ ▪ Improve yield stability and overall pond productivity across production cycles ▪ Increase the adoption of preventive and science-based pond management practices ▪ Deliver measurable farmer benefits at $\leq \text{INR } 4,000$ (approx. USD 43) per pond per year

The big bet

Small-scale inland fish farmers should be empowered to maintain optimal pond environmental conditions that improve fish growth, reduce input inefficiencies, and prevent production risks. To do this, they should be able to use intuitive, reliable, and affordable solutions within INR 2,000–4,000 (approx. USD 21–43) per pond per year to significantly reduce avoidable fish losses and income shocks.

List of people consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Aatish Khan	COO and Co-founder, NatureDots
2	Neelkanth Mishra	CEO and founder, Jal Jeevika
3	Dr. N. Sridhar	Former Principal Scientist, ICAR- Central Inland Fisheries Research Institute (CIFRI)
4	Rabindra Sahoo	Community Expert, Gram Uthaan

b. Listening circle

#	Name	Organization
1	Aatish Khan	COO and Co-founder, NatureDots
2	Ajay Gopi	Founder, Hasiru Aqua
3	Jyoti Matoli	Head of Aquatic Sciences and Fisheries, NatureDots
4	Pranav Kay	Co-founder, Hasiru Aqua
5	Snehal Verma	CEO and Co-founder, NatureDots

4.3 Forestry

A foundational pillar of livelihoods, ecological stability, and climate resilience

Forests are a critical pillar of India's rural livelihood economy, ecological stability, and climate resilience. Beyond their role in biodiversity conservation and carbon sequestration, forest ecosystems underpin the subsistence and income needs of millions of vulnerable households, particularly indigenous peoples, Scheduled Tribes, and forest-fringe communities. Forest-based livelihoods in India are deeply intertwined with the collection, processing, and trade of non-timber forest products (NTFPs), which provide food, fuel, medicine, and cash income. For many households, these resources function as informal safety nets during agricultural lean seasons and periods of climatic or economic stress.

As of 2019, an estimated 300-plus million people in India (PIB, 2023) depended on forests for primary or supplementary livelihoods through NTFP collection and trade, while approximately 125 million people (Haque, 2020) lived in and around forest areas and were directly reliant on forest ecosystems for subsistence and livelihood security. This dependence is particularly pronounced among tribal and forest-dwelling communities, for whom forest resources remain one of the few accessible, culturally embedded, and locally governed livelihood options.

At the household level, forest-based livelihoods are typically collective in nature, with income accrued and managed at the family rather than individual level. Evidence from forest-dominated states underscores both the economic significance of forests and the structural vulnerability of these livelihoods. In Madhya Pradesh, the average annual income of a forest-dweller household is estimated at INR 73,900 (approx. USD 794) (PRADAN, 2022). In Chhattisgarh, it is approximately INR 53,610 (approx. USD 576) (PRADAN, 2022). In Jharkhand, it is approximately INR 75,378 (approx. USD 810) (PRADAN, 2021). In Odisha, the average annual income is INR 61,263 (approx. USD 658) (PRADAN, 2021).

These differences reflect regional variation in forest productivity, market access, and institutional support. Within this broader income mix, forest-dwelling households typically earn INR 5,000 to 10,000 (approx. USD 54 to 108) per year and sometimes up to INR 15,000 (approx. USD 161) from NTFP collection and sale (Bhattacharya, 2025), which highlights the role of forests as a supplementary yet essential source of cash income.

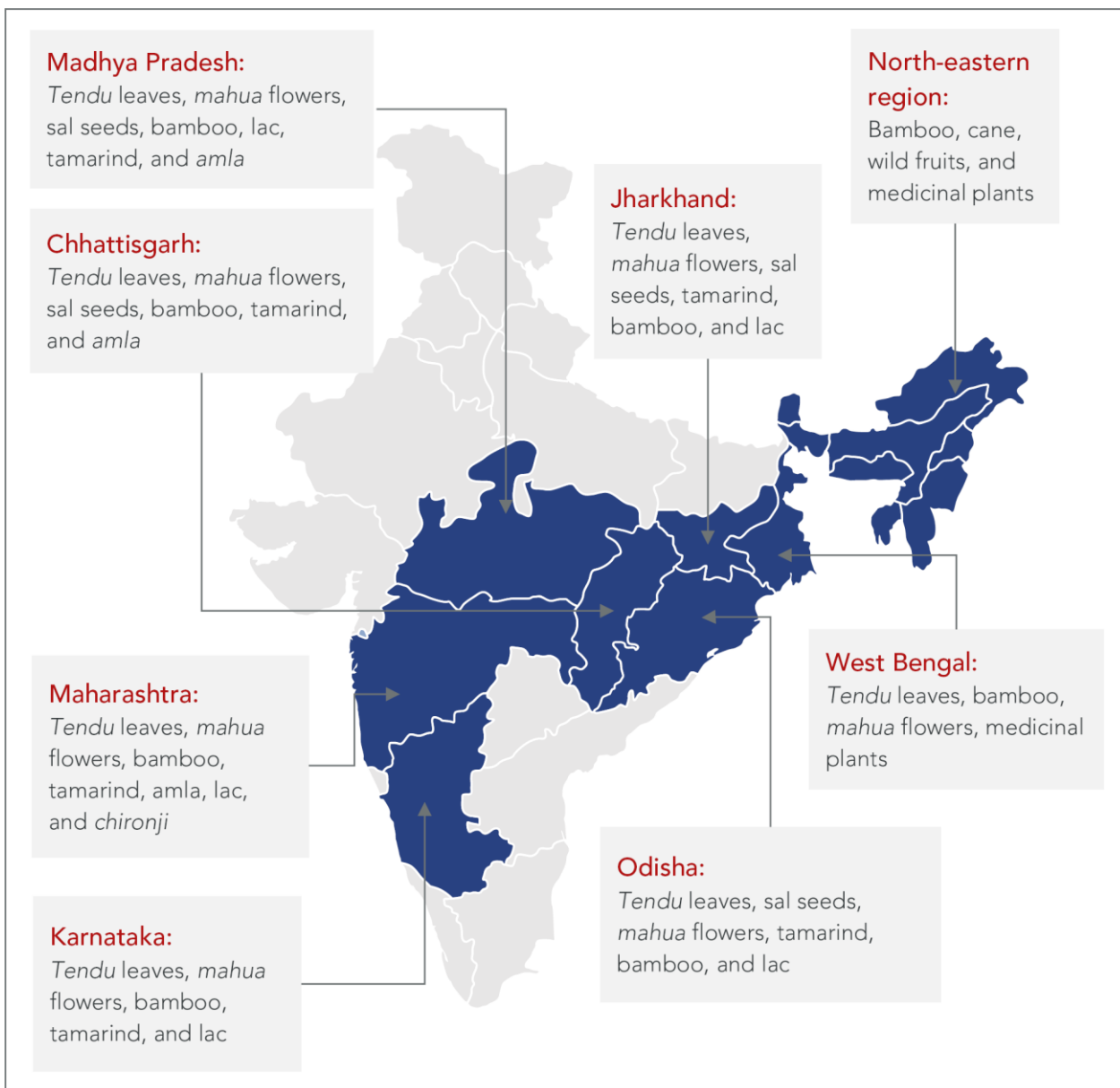


Figure 25: Major NTFP-producing states

Despite their importance, forest-based livelihoods are increasingly under stress. Climate change is already altering forest ecosystems, which directly affects the availability, seasonality, and productivity of NTFPs. Empirical evidence indicates that NTFP yields can decline by up to 40% (Thakur, 2016) during years of drought or excessive rainfall and result in immediate income losses for forest-dependent households. In addition, disrupted work cycles, driven by erratic rainfall, delayed flowering, and extreme weather events, often lead to the loss of two to four weeks of income annually during critical harvesting periods.

At the same time, the economic potential of the forestry sector remains underused. Fragmented value chains, limited local processing capacity, weak market linkages, and high dependence on intermediaries constrain value realization, particularly for small collectors and women, who are central in NTFP collection and primary processing. These constraints reduce livelihood stability and weaken incentives for sustainable forest management.

In this context, the forestry sector sits at a critical juncture. If the sector’s full potential is to be unlocked, livelihood resilience will need to be strengthened, value realization from forest resources improved, and sustainable, inclusive market integration enabled, while safeguarding ecological integrity. This roadmap builds on this premise. It examines the structural constraints that limit performance today and identifies pathways through which forestry can evolve into a more resilient, inclusive, and scalable economic ecosystem.

	Resource-base and forest ecology	Collection, and harvesting	Primary processing and storage	Aggregation, transport and market linkages	Processing and value addition	Labor and knowledge system	Finance and livelihood security
Core functions	<ul style="list-style-type: none"> Regeneration of NTFP species Biodiversity and ecosystem balance Pollination and seed cycles Soil moisture and nutrient support 	<ul style="list-style-type: none"> Manual collection of NTFPs Primary sorting at source Seasonal harvest timing 	<ul style="list-style-type: none"> Drying, cleaning, grading Traditional storage Moisture and quality control 	<ul style="list-style-type: none"> Aggregation by traders and FPOs Transport to markets Sale and price realization 	<ul style="list-style-type: none"> Processing of oils, resins, and foods Grading and standardization Packaging and value addition 	<ul style="list-style-type: none"> Labor for collection and processing Traditional ecological knowledge Community institutions 	<ul style="list-style-type: none"> Income from non-timber forest products (NTFPs) Access to credit or savings Risk management
Key risks	<ul style="list-style-type: none"> Erratic rainfall, temperature rise Drought, altered monsoon Soil degradation, low moisture Forest fires, habitat loss, invasives Declining pollination 	<ul style="list-style-type: none"> Higher labor effort Heat stress, unsafe conditions Seasonal mismatch Shortened harvest windows 	<ul style="list-style-type: none"> Humidity spoilage, fungal growth Heat degrades oils and resins Insect infestation Reduced shelf life Contamination through smoke or chemicals 	<ul style="list-style-type: none"> Climate-disrupted transport Market timing mismatch Quality loss in transit Price volatility 	<ul style="list-style-type: none"> Poor raw material quality Limited tools and mechanization Limited skilled labors Supply variability 	<ul style="list-style-type: none"> Rising labor burden Unsafe conditions Skill erosion, youth exit Weak institutional support 	<ul style="list-style-type: none"> Income volatility No insurance coverage Market shocks Debt dependence
Climate impact	<ul style="list-style-type: none"> Erratic rainfall and rising temperatures disrupt regeneration cycles, reducing forest productivity. Drought and extreme events lower soil moisture and ecosystem resilience. 	<ul style="list-style-type: none"> Rainfall variability alters flowering and fruiting cycles, leading to unpredictable availability and lower collection volume. Heat stress and extreme weather reduce working hours and shorten harvest windows. 	<ul style="list-style-type: none"> High humidity and unseasonal rainfall hinder drying and increase fungal spoilage. Rising temperatures accelerate degradation of oils and resins. Warmer conditions increase pest infestation risks. 	<ul style="list-style-type: none"> Floods and storms disrupt transport routes and delay market access. Weather variability causes mismatches in aggregation and market timing. Heat and humidity during transit lead to quality deterioration. 	<ul style="list-style-type: none"> Climate variability affects the quality and consistency of raw materials. Heat and humidity reduce shelf life and processing efficiency. Water stress disrupt processing operations. 	<ul style="list-style-type: none"> Heatwaves and extreme weather reduce labor productivity and safe working hours. Climate variability undermines traditional ecological knowledge. Repeated climate shocks weaken community institutions. 	<ul style="list-style-type: none"> Climate variability leads to income volatility and uncertainty. Frequent shocks increase dependence on credit. Uncertainty reduces savings capacity and long-term resilience.

Table 14: Climate-linked risks and impacts across the forestry value chain

Forest-dependent households differentiated by proximity, livelihood strategy, and income dependence

Forest-dependent households and community institutions form the core operational layer of India's non-timber forest product (NTFP) economy. This segment is characterized by its proximity to forest landscapes and the intensity and regularity of its engagement with forest resources across activities, such as collection, primary processing, storage, and informal trade. In highly forest-dependent regions, NTFPs alone contribute approximately 40–60% of annual household income (TRIFED, 2021), which shows their critical importance as a primary source of subsistence and cash earnings.

Category	Description	Average annual income (household)	Share of NTFP income (%)	Main income sources	Major states
Core forest dwellers (Living inside the forest)	Reside within forest interiors or settlements officially classified as forest villages.	INR 50,000 to 60,000 (approx. USD 537 to 645)	50-60% (primary source of income)	NTFP collection Agriculture Wage labor in the forest	Chhattisgarh Odisha Jharkhand Madhya Pradesh
Fringe dwellers with marginal land	Live along forest peripheries (within 5 km of the forest boundary) and have marginal landholdings	INR 60,000 to 70,000 (approx. USD 645 to 752)	30-40%	Agriculture and allied activities NTFP collection Wage labor	Odisha Maharashtra Madhya Pradesh
Fringe dwellers with livestock dependence	Live along forest peripheries (within 5 km of the forest boundary) but primarily depend on the livestock for livelihoods.	INR 60,000 to 80,000 (approx. USD 645 to 860)	20-30%	Livestock Dairy NTFP collection	Himachal Pradesh Uttarakhand Rajasthan

Table 15: Categorization of forest dwellers

Source: Based on expert consultations

Across forested regions, forest-based livelihoods are typically organized at the household level, with income earned and managed collectively rather than individually. While income composition varies by geography and asset base, forest resources are consistently a vital component of diversified livelihood portfolios.

Evidence from forest-dominated states indicates that annual household incomes among forest-dependent communities generally range between INR 50,000 to 80,000 (approx. USD 537 to 860).

Meanwhile, NTFPs contribute between 20% and 60% of total household income (TRIFED, 2021; Boyapati & Muthukumarappan, 2025), with variation across regions depending on proximity to forests and access to alternative livelihood options. This variation reflects differences in forest productivity, market access, and institutional support rather than differences in effort or engagement.

For households that live closer to forest interiors or have limited access to cultivable land, NTFPs often represent the primary source of cash income. For those located along forest peripheries, forest-based activities typically complement agriculture, livestock rearing, and wage labor. These provide seasonal income support and buffer households against agricultural risk. In both contexts, forests function as a critical source of liquidity, particularly during lean agricultural periods and in years of climatic stress.

Across the segment, NTFP income is characterized by seasonality, climate sensitivity, and price volatility. Households earn income through multiple small transactions rather than stable wage flows, which increases their exposure to short-term shocks. Women contribute a substantial share of labor across NTFP collection, sorting, grading, and primary processing activities. Yet, their participation remains largely informal and concentrated in lower-value segments of the value chain. This limits their power to realize income and bargain.

Community-level institutions, including forest protection committees, collectors' groups, self-help groups, and community forest rights institutions, are vital, as they mediate access to forest resources and shape livelihood outcomes. Where institutional capacity is stronger, households can better aggregate produce, improve quality, and access markets. However, uneven institutional capacity, limited access to finance, and weak market integration continue to constrain value realization across much of the segment.

Overall, forest-dependent households share a common set of structural characteristics. They have a high exposure to ecological and market risk, a strong reliance on seasonal forest income, and limited access to formal employment and financial systems. These shared features, rather than fine-grained segmentation, define the target segment for this roadmap and shape the nature of constraints and opportunities examined in the subsequent sections.

Climate change is a compounding challenge for forest-based livelihoods

Climate change is emerging as a systemic and compounding challenge for forest-based livelihoods. It affects the availability of forest resources and also their quality, predictability, and economic value. Changes in temperature, rainfall patterns, and the frequency of extreme weather events are disrupting ecological processes that forest-dependent households rely on, with direct implications for income stability and livelihood security.

A significant challenge is the decline in forest resource productivity and regeneration (CGSCCC, 2021). Erratic rainfall, prolonged dry spells, and rising temperatures disrupt flowering, pollination, and natural regeneration cycles of key NTFP species. These ecological disruptions reduce yields and increase uncertainty about harvest volumes to directly undermine household incomes that depend on seasonal forest collection. Declining regeneration also raises longer-term concerns about the sustainability of forest-based livelihoods, particularly in regions already experiencing forest degradation.

Climate change is also contributing to the deterioration of NTFP quality (Das, Chaturvedi, Roy, Karmakar, & Gosh, 2022), which has direct market consequences. Increased heat, humidity, and

exposure to pests and contaminants during collection and storage periods are reducing shelf life and increasing spoilage. Lower-quality produce fetches reduced prices in local and regional markets, weakens price realization for collectors, and amplifies income losses even in years when volumes remain stable.

A related challenge is the loss of habitat and biodiversity (Reddy, Sreelekshmi, Jha, & Dadhwal, 2013), driven by rising temperatures and shrinking or fragmented forest patches. Reduced species diversity affects the availability of high-value NTFPs and alters forest composition, which can permanently shift livelihood options for forest-dependent communities. These ecological changes weaken the resilience of forest systems and reduce their capacity to buffer households against climatic and economic shocks.

Climate stress is also intensifying labor-related challenges (Singh, et al., 2024) within forest-based livelihoods. Rising temperatures and forest degradation are increasing the physical strain during collection activities, reducing workdays, and contribute to declining labor productivity. In several forest-dependent regions, this has accelerated workforce withdrawal from forest-based activities, particularly among younger populations, further constrained household labor availability, and increased dependence on precarious wage labor.

In addition, climate variability is exacerbating harvest, post-harvest, and storage losses (CGSCCC, 2021). Shortened or disrupted harvest windows, combined with high humidity and inadequate drying or storage infrastructure, lead to increased post-harvest losses and value degradation. Delays in transport during extreme weather events further compound these losses to reduce both immediate income and incentives for sustainable harvesting practices.

Finally, changing climatic conditions are driving an increase in pest and disease outbreaks (Paschapur, Arns, Gupta, & Parihar, 2022), weakening forest health, and reducing yields across multiple NTFP species. Similar stresses are observed in forest-linked pollination systems, where disruptions to flowering cycles and bee foraging patterns (Amit, Singh, Tandon, & Shivanna, 2024) have been affecting honey production and quality. These impacts are particularly significant for smallholders and forest-dependent households for whom honey and pollination-related products form an important source of supplementary income.

Taken together, these challenges highlight that climate change affects forest-based livelihoods not through a single pathway, but through interconnected ecological, economic, and labor-related stresses. For forest-dependent households, climate change translates into lower yields, poorer quality produce, higher effort requirements, and increased income volatility, which reinforce existing vulnerabilities and underscore the need for interventions that address both ecological resilience and livelihood outcomes.

Rising labor and resource stress in forest-based livelihoods

Declining forest regeneration is increasing labor effort and reducing returns

Across many forest landscapes, changes in rainfall patterns, longer dry spells, and rising temperatures are beginning to alter the natural rhythms that forest-based livelihoods depend on. The regeneration of forests has slowed, and the flowering and fruiting cycles of key non-timber forest product (NTFP) species have become less reliable.

For forest-dependent households, this shift is felt most directly in the effort required to earn a living. Collectors now spend more time in forests to gather quantities of produce that were previously available with less effort. In practical terms, this means longer days, greater physical strain, and diminishing returns from the same work. Over time, this growing mismatch between effort and income has weakened labor productivity and placed sustained pressure on household livelihoods.

Resource depletion is extending collection distances and shrinking effective workdays

As forest resources become more unevenly distributed, collectors are increasingly required to travel farther into forest areas to access viable collection sites. These longer distances, often over difficult terrain, reduce the time and energy available for actual collection. Because NTFP harvesting is seasonal and time-bound, even modest increases in travel time can significantly reduce the number of productive workdays in a season.

For households that depend on forest income to meet basic needs, fewer effective workdays translate quickly into income shortfalls, particularly during lean periods when alternative employment opportunities are limited or unavailable.

Climate disruptions are fragmenting harvest cycles and increasing lost labor time

Weather patterns that were once relatively predictable are now becoming increasingly erratic. Unseasonal rainfall, storms, and prolonged humidity are disrupting established harvesting, drying, and storage practices for forest produce, such as *mahua*, *sal* seeds, and *tendu* leaves.

Harvest windows are no longer clearly defined, and collection often takes place under suboptimal conditions. As a result, a greater share of collected produce is damaged or degraded before it can be sold. For collectors, this means that both the produce and labor invested in collecting and processing it are partially or entirely lost, which adds to income uncertainty and frustration.

Income volatility and debt are driving distress migration

The combined effects of lower yields, unstable prices, and unpredictable harvests have made forest-based incomes increasingly uncertain. Many forest-dependent households operate with limited savings and restricted access to formal financial services. When incomes fall short, households often rely on borrowing from informal sources, frequently at high cost.

As debt accumulates, temporary migration in search of wage labor becomes a necessary coping strategy. While migration may provide short-term cash relief, it also reduces the availability of household labor for forest-based activities and disrupts local livelihood systems. Over time, this weakens the continuity of forest-based livelihoods and increases dependence on precarious external employment.

Distress-driven over-extraction is accelerating resource degradation

During periods of increased stress, such as droughts, crop failures, or extended lean seasons, forest-dependent households may intensify their forest extraction to compensate for lost income. While this response is often unavoidable in the short term, repeated reliance on distress-driven extraction places additional pressure on already stressed forest ecosystems.

Reduced regeneration and declining resource availability will make future livelihoods even more labor-intensive and less productive. Over time, this creates a self-reinforcing cycle in which ecological degradation and livelihood vulnerability deepen together to make recovery increasingly difficult for both forest systems and the communities that depend on them.

Why is direct intervention inside forests not feasible?

Approximately 84% of India's forest area (FAO, 2024) is classified as Reserved Forests and Protected Forests under the Indian Forest Act, 1927, where access and use rights are regulated to varying degrees. While Reserved Forests are subject to stricter controls with limited community access, Protected Forests allow certain customary uses, but remain under state oversight and regulation.

Direct economic intervention in forest landscapes poses significant limitations and risks, particularly at scale. Forest areas in India operate within complex governance and regulatory frameworks designed to safeguard ecological integrity, conserve biodiversity, and protect the customary and legal rights of forest-dwelling communities. In this context, activities, such as infrastructure development, mechanization, and commercial enterprise operations, are subject to stringent legal, environmental, and administrative safeguards. These conditions substantially constrain the feasibility of implementing direct livelihood or market-oriented interventions inside forest boundaries in a compliant, scalable, and sustainable way (Murthy & Kumar, 2019).

Besides regulatory constraints, intensive intervention within forest interiors raises important ecological considerations. Forest ecosystems perform a range of critical functions that extend beyond livelihood support. They regulate the climate, protect watersheds, conserve the soil, and maintain biodiversity. Interventions that introduce economic activity within forest landscapes, particularly those involving physical infrastructure or increased extraction, may alter ecological balances and accelerate resource degradation if not managed carefully. Over time, such impacts can undermine ecosystem health and increase long-term vulnerability for forest-dependent communities.

Operational realities further limit the viability of in-forest interventions. Forest interiors are often remote, difficult to access, and characterized by limited connectivity and service delivery infrastructure. Under these conditions, costs and challenges are higher to deliver finance, establish and maintain assets, ensure reliable market linkages, and monitor outcomes. These practical constraints reduce implementation effectiveness and make it difficult to replicate or scale successful models across regions.

Taken together, these regulatory, ecological, and operational factors indicate that direct intervention in forest landscapes is not an effective primary pathway to strengthen forest-based livelihoods at scale. More viable approaches lie in the design of interventions outside forest boundaries that remain closely linked to forest ecosystems to enhance livelihoods and integrate markets in ways that respect ecological safeguards, comply with regulatory frameworks, and can be sustained over the long term.

The possible livelihood intervention

The most effective pathways to strengthen forest-based livelihoods lie outside forest boundaries, yet remain closely linked to forest ecosystems and the communities that depend on them. Viable

interventions do not concentrate economic activity within forest interiors. Instead, they focus on forest-fringe and peri-forest areas, where aggregation, primary processing, storage, and market access can be developed more feasibly and at scale.

These approaches enable greater value capture closer to communities, reduce dependence on distress sales, and improve income stability without increasing pressure on forest resources. At the same time, strengthening local institutions and improving access to suitable financial services support collective action, reduce transaction costs, and help households manage seasonal and climate-related income fluctuations.

By operating within regulatory frameworks and ecological safeguards, these approaches provide a practical and scalable means of integrating forest-linked livelihoods into broader market and financial systems while maintaining long-term forest conservation objectives.

The pathways forward: Market-linked livelihood interventions beyond forest boundaries

Improving forest-based livelihoods at scale requires approaches that protect forest ecosystems and also help households earn more stable incomes from their work. The most workable options are those that link livelihoods to markets in ways that remain connected to forests but do not depend on heavy economic activity within forest areas. By building on the existing skills, local resources, and market demand, forest-adjacent livelihood options can increase income opportunities and reduce pressure on forests. Based on this approach, we have identified the following intervention areas as priority opportunities.

Honey-bee farming and forest-linked pollination services

Market overview

India is among the world's leading producers of honey. Annual production exceeds 100,000 metric tonnes in 2025 (Department of Commerce, 2025), and exports are valued at more than USD 200 million in 2025 (Department of Commerce, 2025). Domestic demand for natural sweeteners and wellness products continues to grow, alongside rising recognition of the economic value of pollination services for agriculture. Forest-adjacent landscapes, with their diverse and seasonal floral resources, are particularly well suited for small-scale and migratory beekeeping.

Indicative setup cost for smallholder farmers

A smallholder or forest-fringe household typically has to initially invest approximately INR 1,10,000 to 1,30,000 (approx. USD 1,182 to 1,397) to establish a basic beekeeping unit of 10 bee colonies (NABARD, 2025). This investment covers bee boxes, colonies, protective equipment, basic tools, and initial training. Meanwhile, recurring expenditure amounts to INR 30,000 to 40,000 (approx. USD 322 to 430) on wax sheets, raw input materials, and labor. Group-based models, shared equipment, and institutional support can further reduce costs.

Benefits and livelihood outcomes

Honey-bee farming offers a relatively low-entry, high-return livelihood option that can be practiced alongside existing forest-based activities. A well-managed small unit of 10 boxes can generate INR 45,000 to 60,000 (approx. USD 484 to 645) per year (Chaurasia, 2025) in net income within the first few production cycles, with additional upside as colony numbers expand. Beyond direct income,

beekeeping improves pollination services for nearby crops and forest species, and also enhances overall ecosystem productivity. The activity is well-suited for women and elderly household members, requires limited land, and provides more regular cash flows compared to seasonal NTFP collection.

Problem context

Forest-dependent households engaged in honey collection or traditional beekeeping face declining yields (Mohanty, 2021) and rising labor effort due to disrupted flowering cycles, heat stress, and increased colony losses (Manoj, 2023). Informal practices, poor scientific colony management, and weak aggregation (Singh, 2021) limit productivity and quality. This results in volatile incomes and poor price realization.

Addressable gaps

- Limited access to climate-resilient beekeeping practices (Arethwala, 2024), equipment, and extension support
- Weak aggregation, quality control, and traceability mechanisms for honey
- Poor integration with formal buyers, certification systems (Economic Advisory Council to the Prime Minister, 2019), and the export market
- Working capital constraints and absence of risk mitigation instruments for colony losses

Mushroom farming

Market overview

India's mushroom market has grown rapidly over the past decade and was valued at USD 276 million in 2024 (IMARC, 2025). The growth is driven by rising urban consumption, expanding institutional demand, and increasing nutritional awareness. The sector is estimated to be growing at 6.5% annually (IMARC, 2025), with strong demand for button, oyster, and milky mushrooms. Mushroom cultivation offers a short-cycle, high-value livelihood opportunity well suited to rural and forest-fringe areas, as it can be practiced using locally available agricultural and forest-based biomass residues.

Indicative setup cost for smallholder farmers

A basic small-scale mushroom production unit for oyster or milky mushrooms can be established at approximately INR 5,000 to 6,000 (approx. USD 54 to 65) (ICAR, 2020). It covers the spawn and basic inputs, and can be cultivated in a basic-level shed with coverings. Entry-level units can be scaled incrementally based on performance, which makes mushroom cultivation accessible even for households with limited capital.

Benefits and livelihood outcomes

Mushroom farming offers rapid income generation, with production cycles of 30–45 days, which enables multiple harvests per year. Even small units can generate INR 40,000 to 80,000 (approx. USD 430 to 860) (ICAR, 2020) annually in supplemental income under favorable market conditions. The activity requires limited land, can be managed close to the household, and is particularly suitable for women and youth. Importantly, mushroom cultivation diversifies income sources, reduces dependence on climate-sensitive forest extraction, and provides a buffer during lean agricultural or forest collection periods.

Problem context

Declining and uncertain incomes from NTFP collection, combined with reduced workdays due to climate variability, have increased livelihood stress for forest-dependent households. While mushroom farming offers an alternative income stream, adoption remains limited due to a lack of technical knowledge, starter infrastructure, and assured market access.

Addressable gaps

- Limited availability of quality spawn, training, and low-cost production units
- Absence of aggregation, cold storage, and buyer linkages for small producers
- High perceived risk and limited access to startup finance
- Weak institutional platforms for collective production and marketing

Carbon credits through community-based forest stewardship and agroforestry

Market overview

Indian voluntary carbon markets are expanding rapidly. Annual market values exceed USD 4 billion in 2023 (CEEW, 2025), driven by corporate net-zero commitments. Nature-based solutions, including forest conservation, restoration, and agroforestry, account for a significant share of traded credits. Community-managed forests and forest-fringe agroforestry systems in India offer a strong potential to generate high-integrity carbon credits with livelihood co-benefits.

Problem context

Forest-dependent communities face significant barriers to participation in carbon markets. Measurement, reporting, and verification (MRV) requirements are complex and costly, transaction sizes are small, and benefit-sharing mechanisms are often unclear. As a result, carbon value chains largely exclude communities despite their role in forest stewardship.

Benefits and livelihood outcomes

Carbon credits offer a predictable, medium- to long-term income stream that is not directly tied to seasonal forest extraction, which helps stabilize household and community finances. In many community-managed forest systems, carbon revenues can generate approximately INR 2,000 to 3,000 (approx. USD 54 to 65) per hectare per year (Expert consultation with Naveen Kumar), to provide a modest but reliable supplementary income.

Revenue from carbon credits can support community institutions, reduce reliance on distress-driven forest extraction, and strengthen incentives for sustainable forest management and regeneration. At the system level, carbon finance improves the economic viability of conservation, enhances community governance capacity, and can crowd-in complementary climate and development finance. When integrated with broader livelihood and institutional support, carbon credits can play a catalytic role in aligning forest conservation with livelihood resilience.

Addressable gaps

- Limited technical capacity and awareness for carbon project development
- High upfront costs for MRV, registration, and verification
- Weak institutional arrangements for governance and benefit sharing
- Lack of intermediaries to aggregate small, community-level projects

List of experts consulted across different stages of research

#	Name	Organization
1	Arghya Chowdhury	Procurement Manager (Zonal Head), Terviva
2	Aruna Rangachar Phol	Chairperson, IFHD
3	Dr. Manohar Chauhan	Senior Program Manager, Foundation for Ecological Security (FES)
4	Naveen Kumar	Consultant, Kosher Climate
5	Punarbhava Banik	State Development Coordinator, SEWA Bharat





4.4 Waste and circularity

From an informal safety net to a system under stress: Why India's material recovery model must transition

India's waste and circularity sector forms the invisible foundation of the country's material economy. It quietly enables consumption, urbanization, and industrial growth by recovering value from discarded materials at scale, largely outside formal public systems. For decades, a decentralized network of informal waste pickers, aggregators, traders, and small recyclers has enabled this recovery. They collectively extract economic value from what would otherwise be landfilled or burned. This model has allowed India to achieve relatively decent recovery rates for select materials despite limited municipal infrastructure, weak enforcement, and low per-capita spending on waste management.

However, the conditions that enabled this system to function are no longer stable. Rising consumption, increasing material complexity, climate stress, and shifting policy expectations have been collectively pushing India's waste economy beyond the limits of a model built on informality, low margins, and manual sorting. What was once a resilient shock absorber is now showing signs of structural fatigue.

How waste and value currently flow

India's waste management system does not operate in a linear chain managed by urban local bodies. Waste flows through a hybrid system where informal labor performs the bulk of value recovery, while formal institutions primarily manage transport and disposal.

Material flows typically begin at the point of consumption, with households, commercial establishments, and small industries discarding waste into mixed streams. Source segregation remains inconsistent across cities, with collection rates as low as 50% (NITI Aayog, 2021) in small cities. As a result, most waste enters the system in a contaminated state, which reduces its recoverability downstream.

Informal and semi-formal actors dominate the collection. Waste pickers collect directly from households, streets, bins, and dumpsites to selectively extract materials with resale value. They then sell this recovered material to small aggregators or traders, who further sort and bulk it before passing it on to recyclers or processors. Municipal systems, where present, focus largely on transporting mixed waste to landfills, dumps, or processing facilities with limited sorting capacity.

An estimated 1.5–4 million informal workers are directly engaged in waste recovery across Indian cities and peri-urban areas. They comprise one of the world's largest informal recycling systems. They systematically recover, categorize, and channel recyclable materials back into supply chains after collecting them from households, streets, municipal bins, dumping grounds, and processing centers.

Their labor underpins recovery rates for high-value materials, such as PET bottles, certain rigid plastics, paper, and metals. Yet this system functions not because it is efficient in a conventional sense, but because it relies on minimal labor costs, high flexibility, and the absence of social and environmental safeguards.

This reliance on informality is not accidental. It is embedded in the design of the system itself. Public investment in waste infrastructure has historically remained limited within municipal

budgets. Even where extended producer responsibility (EPR) frameworks have been introduced, they often operate implicitly and depend on existing informal collection and recovery networks rather than systematically integrating, upgrading, or formalizing them. As a result, the system appears functional on the surface, but this performance is sustained by fragile arrangements that mask structural vulnerabilities.

A waste system under structural strain

The stress currently visible in India's waste economy is not simply the result of poor implementation or governance gaps. It reflects a deeper mismatch between the material reality of today's waste and the system designed to manage it.

India generates more than 62 million tonnes (Central Pollution Control Board 2022) of municipal solid waste annually, a figure projected to reach 125 million MT (NITI Aayog 2021) by 2031. While volume growth alone would strain existing infrastructure, a significant challenge also lies in changing composition. As consumption patterns evolve alongside urbanization, industrialization, and globalized production systems, waste streams are becoming more heterogeneous, chemically treated, and materially layered.

Multi-layer packaging, composite plastics, blended textiles, treated paper, and electronic waste now constitute a growing share of discards. These materials cannot be easily identified, separated, or processed through the low-capital, labor-intensive methods that underpin India's existing recovery model.

Historically, informal recovery worked because materials were visually identifiable and manual sorting could extract value with minimal infrastructure. The downstream recycling markets could absorb recovered material without stringent quality requirements. Today's waste increasingly violates all three conditions. Contamination rates are higher, material identification is more complex due to mixed waste, and processing often requires controlled environments, specialized machinery, and regulatory compliance that informal systems cannot provide.

At the same time, the economic logic that sustains informal recovery is steadily weakening. The system assumes that discarded materials have sufficient resale value to offset the time, labor, and risk involved in collection and sorting. Yet, this assumption no longer holds across much of today's waste stream. In practice, materials fall along a spectrum of values. High-value materials, such as PET bottles, certain rigid plastics, paper, and metals, continue to be recovered efficiently due to stable market demand, while medium-value materials are recovered inconsistently and remain sensitive to contamination and price volatility.

A growing share of waste consists of low-value materials, such as thin films, sachets, multilayer packaging, and composite plastics that yield marginal or negative returns once sorting effort and transport costs are considered.

Informal workers, therefore, rationally prioritize a shrinking set of high-value items, which leaves much of the remaining waste uncollected or discarded.

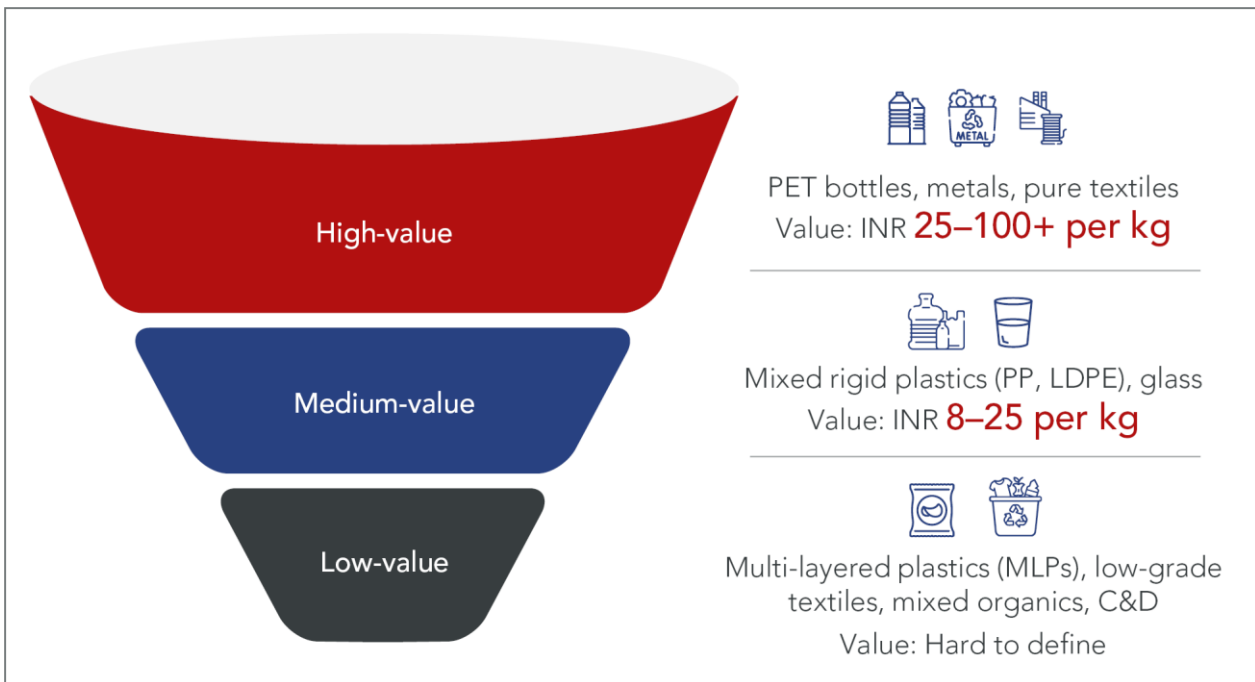


Figure 26: Waste streams have high, medium, and low value waste

This selective recovery has system-wide consequences. Recovery rates remain high only for a narrow subset of materials, estimated at roughly 25–30% of dry waste (Centre for Science and Environment 2019). Meanwhile, the remainder leaks out of recovery pathways into landfills, open dumps, or is burned informally. Importantly, this leakage does not result from individual failure or lack of effort. It is the predictable outcome of a system operating beyond its design parameters, where material complexity has outpaced both economic incentives and technical capacity.

For informal waste workers, this dynamic translates into declining and volatile incomes. As high-value materials become scarcer, competition intensifies, while the time and effort required to collect low-value waste rarely yield adequate compensation. For cities, the result is rising landfill pressure, higher transport costs, and escalating environmental and public health risks. For the broader economy, it represents a growing loss of recoverable materials and the energy they contain.



Even with 85% source segregation, valuable materials disappear before they reach the MRF because waste pickers are paid INR 5,000–7,000 per month by contractors. So they have no choice but to steal high-value items to survive.

- Sri Chandra Menon, Associate Director, The/Nudge Institute

What was once a resilient informal safety net is now becoming a source of systemic fragility. This fragility does not originate in any single waste stream, nor can it be attributed solely to technological or policy gaps. It emerges from the way India’s waste management value chain is structured. Across materials and geographies, the same set of system functions, that is, collection, aggregation, logistics, processing, and market absorption, repeatedly determine whether waste will be recovered or lost.

	Generation and segregation	Collection and transport	Processing and treatment	Recycling and recovery	Circular markets	Governance and finance
Core functions	<ul style="list-style-type: none"> Waste generation at household and community level Source segregation of waste streams Primary handling and containment 	<ul style="list-style-type: none"> Waste collection from households and businesses Transport systems and vehicle management Route planning and logistics 	<ul style="list-style-type: none"> Waste processing and sorting Composting or biogas production Disposal systems management 	<ul style="list-style-type: none"> Material recovery through sorting, recycling, and reuse Largely driven by the informal sector Secondary material re-entry into supply chains 	<ul style="list-style-type: none"> Demand and trade for recycled materials Secondary resource markets across industries 	<ul style="list-style-type: none"> Policy, regulation, and institutional coordination Financing mechanisms across the value chain Enabling frameworks for MSMEs and informal actors
Key risks	<ul style="list-style-type: none"> Low segregation at source contaminates recyclable streams Open burning of waste in rural areas Informal handling systems with no standards High contamination of recyclable materials 	<ul style="list-style-type: none"> Inadequate collection coverage; dependence on informal systems Inefficiencies in routing and logistics Infrastructure gaps in peri-urban and rural areas 	<ul style="list-style-type: none"> Limited processing capacity and low efficiency of treatment systems Reliance on landfills or traditional methods in rural areas Methane emissions from unmanaged organic waste 	<ul style="list-style-type: none"> Dependence on informal workers with poor working conditions Weak formal recycling systems; low recovery for complex materials Low value recovery for mixed or contaminated streams 	<ul style="list-style-type: none"> Weak market linkages and price volatility for recyclables Limited demand for recycled materials; barriers for MSMEs Virgin material price competition undermines circular markets 	<ul style="list-style-type: none"> Fragmented governance and limited enforcement Inadequate financing and weak private sector participation Weak technical capacity, especially in rural areas
Climate impact	<ul style="list-style-type: none"> Higher temperatures increase decomposition, raising methane emissions and odor Heavy rainfall disrupts segregation, mixing waste streams and increasing leakage Flooding overwhelms containment, spreading 	<ul style="list-style-type: none"> Flooding blocks collection routes, leading to uncollected waste accumulation Heat stress reduces labor productivity, delaying collection Increased risk of public health impacts from 	<ul style="list-style-type: none"> Excess moisture reduces efficiency of composting and biogas systems Floods damage processing infrastructure, increasing untreated waste and methane emissions from landfills Heat accelerates 	<ul style="list-style-type: none"> Excess moisture reduces efficiency of composting and biogas systems Flooding damages recycling infrastructure, increasing untreated waste and methane emissions Climate stress reduces 	<ul style="list-style-type: none"> Supply volatility reduces availability of quality recyclables, weakening market demand Climate shocks increase costs for MSMEs, limiting participation Slower uptake of circular economy 	<ul style="list-style-type: none"> Extreme events divert public resources, slowing system improvements Climate risks increase uncertainty, constraining financing and resilience investment Inefficient waste management

	Generation and segregation	Collection and transport	Processing and treatment	Recycling and recovery	Circular markets	Governance and finance
	waste into communities	uncollected waste	odor and pathogen risks at treatment sites	quality and volume of recoverable materials	practices; continued reliance on virgin materials <ul style="list-style-type: none"> Income instability for small-scale actors deepens exclusion 	systems persist; limited capacity to absorb shocks

Table 16: Climate-linked risks and impacts across the urban waste value chain

Constraints that shape waste recovery outcomes

Across waste streams, five cross-cutting constraints consistently undermine recovery outcomes. These are systemic, mutually reinforcing, and worsening over time.

The human cost of recovery

There are between **1.5 to 4 million informal waste pickers** across India, forming a significant part of the informal recycling and resource recovery economy.

Key characteristics

- 1 Includes a high proportion of marginalized communities with many women and children involved. Often from economically disadvantaged and socially excluded groups.

- 2 Working hours: 8–12 hours per day, often 6–7 days a week.

- 3 Collect, sort, and sell recyclable waste from streets, households, bins, landfills, and material recovery facilities. Operate mostly in unorganized, informal settings.

- 4 Social stigma, lack of formal recognition, poor access to waste due to privatization, unsafe and unhygienic working conditions, absence of health and social security.

<p>Role in waste management</p> <p>Recover about 15-20% of municipal solid waste in cities, which contributes significantly to recycling and cost savings in municipal waste collection</p>	<p>Earnings</p> <p>Monthly income is generally less than INR 10,000 with daily earnings ranging from INR <u>100-400</u>. Earnings vary with location, waste volume access, and market conditions.</p>
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Figure 27: Key characteristics of a waste picker in India

Even though waste pickers comprise the backbone of India’s material recovery system, their work remains fragile and undervalued. Their incomes are unstable and often declining, as the effort required to collect, sort, and transport waste rarely provides reliable earnings. Daily exposure to hazardous materials without proper protective equipment, from biomedical and electronic waste to chemically treated plastics, puts them at constant risk of injury and illness. Despite their critical role, waste pickers are frequently excluded from formal programs, emerging waste streams, and policy decisions, which leaves them marginalized and overlooked.

Many waste pickers operate in unsafe, poorly resourced conditions and have limited access to infrastructure, tools, and social protection. Daily work exposes them to health hazards, and dependence on informal networks and intermediaries reduces their bargaining power and increases their vulnerability to exploitation. Across cities and towns, waste pickers navigate these challenges every day to sustain a system essential to public health and environmental management while facing persistent insecurity and social marginalization.

Coordinated action across multiple stakeholders is needed to address these challenges. Government and local authorities can support waste pickers by providing protective equipment, healthcare, training, social security, and formal recognition as essential workers. Industry actors and formal recyclers can collaborate with waste picker cooperatives to ensure safer working conditions, stable incomes, and access to better tools and facilities. Civil society organizations can organize and empower workers, provide skills development, and advocate for their rights to serve as a bridge between waste pickers, the government, and industry.

Solutions must be holistic and cover safety, livelihoods, social protections, and inclusion at every stage of the value chain, from collection and sorting to transport and processing. By centering waste pickers in policies, programs, and partnerships, India can strengthen both its recovery system and the livelihoods of the people who sustain it.

Technological constraints

At every stage of the waste value chain, technological limitations hinder recovery outcomes. Critical infrastructure for sorting and processing remains underdeveloped in many urban and peri-urban areas. While collection and transport capacity have expanded in many cities, the technologies required for effective sorting, processing, and material-specific treatment remain underdeveloped or poorly aligned with the characteristics of today’s waste. These gaps are not isolated to any single waste stream. They reflect a broader mismatch between infrastructure design, material complexity, and the economics of recovery.

The table below outlines key technology-related constraints across the waste value chain:

Stage	System-level technology constraints
Collection	<ul style="list-style-type: none"> ▪ Waste is generated in a highly dispersed manner and typically enters the system mixed and contaminated due to weak source segregation. ▪ Low-density and low-value materials are particularly disadvantaged under existing collection systems.

Stage	System-level technology constraints
Sorting	<ul style="list-style-type: none"> ▪ Sorting infrastructure remains limited in both scale and capability. Manual sorting dominates, while contamination and inconsistent volume of inputs constrain semi-mechanized and mechanized systems. ▪ The absence of effective sorting technologies makes it difficult to separate complex or heterogeneous materials, which leads to selective recovery focused on a narrow set of high-value waste.
Processing	<ul style="list-style-type: none"> ▪ Processing capacity is uneven and often misaligned with material characteristics. Many waste materials require specialized handling, processing, or controlled environments that are capital-intensive and inaccessible to smaller operators. ▪ Centralized facilities struggle with inconsistent feedstock quality and underutilization, while decentralized options lack scale and technical support.
Market integration and end use	<ul style="list-style-type: none"> ▪ Even where processing capacity is available, inconsistent material quality and lack of standardization limit acceptance by downstream users. ▪ Technologies alone cannot compensate for weak coordination across collection, sorting, processing, and offtake markets. ▪ These gaps limit both the scale and quality of circularity, and keep much of the system dependent on informal labor and ad-hoc processes.

Table 17: Key technology-related constraints across the waste value chain

Centralized processing facilities, including material recovery facilities (MRFs), are intended to bridge the gap between mixed waste collection and downstream recycling or treatment. However, their effectiveness depends on upstream sorting quality and consistent material flows. In practice, high contamination levels reduce throughput, dispersed waste generation increases transport costs, and assumptions of uniform feedstock quality are rarely met. As a result, many facilities operate below capacity or function primarily as transfer points rather than effective recovery centers.



Budget and space constraints are major barriers—small units need 1,500 square meters for a 50,000 population, and municipalities operate on tight budgets.

- Prathiba Dewett, Chief Sustainability Officer, Lucro Plastecycle

These technological constraints reinforce one another across the value chain. Improvements at a single stage, such as collection or transport, do not translate into higher recovery unless accompanied by corresponding advances in sorting and processing. Without coordinated investment and alignment, technological interventions remain fragmented. This limits both the scale and quality of material recovery and reinforces reliance on informal labor and ad hoc practices.

Circularity and recycling remain challenging

Circularity is often reduced to recycling, but in its full sense, it refers to an economic system in which materials retain value across multiple lifecycles through reuse, repair, remanufacturing, and

high-quality recycling. This requires products to be designed for durability, disassembly, and material recovery. Accordingly, recovery systems must be able to preserve material quality at scale. In India, most waste streams fail on both counts.

Recycling has become the default proxy for circularity largely because it is the last option available once products have already failed to circulate. By the time materials enter the waste system, decisions about product design, material choice, and quality have already locked in the recovery outcomes. As a result, much of what enters India's waste stream is inherently difficult or uneconomic to circulate, regardless of downstream effort.

The economics of recycling compound this challenge. Recovered materials must compete with virgin inputs whose prices depend on global commodity markets rather than local recovery costs. When the prices of virgin material fall, recycled alternatives quickly lose competitiveness. This volatility disproportionately affects low- and medium-value materials, which makes recovery financially unstable and limits investment in recycling capacity. Recycling activity, therefore, expands and contracts with market cycles, rather than with environmental need or material availability.

Material quality is a critical, often-overlooked constraint. Circular systems do not depend only on recovery but also on the quality of what is being recovered. In several Indian waste streams, the original products are not designed to retain value across cycles.

Textiles provide a clear example. Low-cost, fast-fashion garments generate large volumes of post-consumer textile waste. These garments are made of blended fibers, low-grade yarns, and chemical finishes. They are not designed for durability, repair, or fiber-to-fiber recycling. Once discarded, they are difficult to separate by material type, degrade quickly in use, and yield fibers of insufficient quality for reintegration into textile manufacturing.



Figure 28: Textile waste in a dump yard

As a result, almost 41% textile waste is down-cycled (Fashion for Good 2022), exported to informal reuse markets with limited absorption capacity, or discarded entirely. The circularity failure begins at the point of production, not at disposal.

Similar dynamics are visible across packaging, consumer goods, and electronics. Multi-layer plastics, composite materials, and chemically treated products shift the burden of recovery onto waste systems that were never designed to handle such complexity. Even where recycling technologies are available, feedstock quality and contamination severely limit output quality and economic viability.

E-waste represents one of the most acute circularity challenges. India generates more than 1.4 million tonnes of e-waste annually (Press Information Bureau 2025). The volumes of e-waste have been rising rapidly due to shorter product lifecycles, increased electronics penetration, and limited repair or refurbishment ecosystems. Electronic products contain valuable metals, such as copper, aluminum, and precious elements, but also hazardous substances, which include lead, mercury, and brominated flame retardants.

Recovery requires specialized infrastructure, safe dismantling, and environmental controls that are largely absent at scale. Approximately 57% of e-waste (Financial Express, 2025) remains unprocessed in the country. In practice, informal workers use rudimentary methods to handle most e-waste. While this enables partial material recovery, it exposes workers to severe health risks and results in significant material loss.

High-value components are selectively extracted, while complex or hazardous fractions are discarded or processed unsafely. Despite the presence of formal e-waste recycling capacity, it remains underutilized due to weak collection systems, limited consumer awareness, and competition from informal buyers. Circularity, in this context, is fragmented and extractive.

The way responsibility is distributed across the value chain further constrains circularity. Product design decisions are made upstream, while waste workers, municipalities, and recyclers bear the recovery costs downstream. Circular economy policies and targets often assume that recycling systems can compensate for poor design. As a result, they fail to recognize design quality as a foundational condition for circularity.

Until circularity is understood as a function of product quality and system design, rather than end-of-pipe recovery alone, recycling will continue to deliver partial gains and leave the deeper material economy largely unchanged.

Opportunities and innovation pathways in waste and circularity

As traditional recovery pathways strain under waste material complexity, new forms of innovation are emerging across the sector. These opportunities are not confined to specific waste streams. Instead, they sit at critical junctions in the value chain where existing models no longer function effectively.

Rather than offering isolated fixes, these opportunity areas reflect where system constraints are most acute and where targeted innovation can unlock disproportionate impact.

Opportunity	Existing solutions	Why they have not worked	Financing and implementation pathways
<p>Recovery and processing of low-value, hard-to-recycle waste</p>	<ul style="list-style-type: none"> ▪ Mechanical and chemical recycling technologies exist for low-value and hard-to-recycle waste streams. ▪ Co-processing in cement kilns converts mixed waste into refuse-derived fuel (RDF), which large cement manufacturers have widely adopted. ▪ Road construction uses shredded waste blended into bitumen to absorb large volumes of low-value material through government mandates. ▪ Downcycling compresses mixed waste (mainly multi-layer plastics) into boards, panels, tiles, benches, and other construction products. ▪ Small-scale pilot and semi-commercial units have been deployed, largely by private entrepreneurs, to test technical and commercial viability. However, these solutions have not yet been implemented at scale. 	<ul style="list-style-type: none"> ▪ Processing technologies are capital-intensive and remain costly to operate at scale. ▪ Technology performance is highly sensitive to feedstock quality and consistency. ▪ Most deployments remain at pilot or semi-commercial scale, with limited evidence of viability at scale. ▪ Many pathways destroy plastics as fuel or permanently lock them into products, which does not result in true material circularity. ▪ Environmental and health risks, including emissions and leaching, remain under-addressed due to weak monitoring and enforcement. ▪ The market demand for downcycled products is limited and often depends on CSR or public procurement. 	<ul style="list-style-type: none"> ▪ Investment should target pilot-to-commercial demonstration plants and decentralized processing units. ▪ Private waste processors, technology providers, cooperatives, and social enterprises are best positioned , to lead implementation and scale recovery operations, depending on the waste stream and context.

Opportunity	Existing solutions	Why they have not worked	Financing and implementation pathways
Sorting infrastructure	<ul style="list-style-type: none"> ▪ Semi-automated sorting lines and modular sensor-enabled systems are available in some MRFs and waste management facilities. ▪ Near-infrared (NIR) spectroscopy-based sorting systems are used to identify and separate recyclable materials by the type of polymer in semi-automated and automated material recovery facilities (MRFs). ▪ Ballistic separators are deployed to mechanically separate waste streams by shape, density, and weight (e.g., 2D vs 3D materials), improving upstream sorting efficiency. ▪ AI-powered automated sorting systems, combining machine vision and robotic arms, are being piloted to enhance sorting accuracy and reduce manual dependence. 	<ul style="list-style-type: none"> ▪ Optical and sensor-based sorting systems cannot reliably detect black or carbon-black plastics and are affected by contamination, such as dirt, moisture, and labels. ▪ These systems struggle to identify multi-layer or blended plastics and typically provide only coarse sorting rather than polymer-level separation. ▪ Sorting efficiency drops significantly when waste streams are heavily contaminated or mixed. ▪ High upfront capital costs limit deployment, particularly outside large industrial facilities or pilots. ▪ Weak integration with informal collection networks leads to inconsistent feedstock and underutilization. 	<ul style="list-style-type: none"> ▪ Investment should focus on modular sorting infrastructure, aggregation hubs, and operations capacity building. ▪ Municipal-private partnerships, local entrepreneurs, and aggregators are well-placed to implement these investments.

Opportunity	Existing solutions	Why they have not worked	Financing and implementation pathways
Waste picker formalization (formal–informal system integration)	<ul style="list-style-type: none"> ▪ In some cities, cooperative-run sorting centers, hybrid PPP collection models, and aggregator-led platforms integrate informal workers into formal systems. ▪ Digital tracking, payment, and attendance platforms have been piloted to formalize work arrangements. 	<ul style="list-style-type: none"> ▪ Waste pickers have limited access to formal contracts and structured employment. ▪ The governance and operational capacity of cooperatives and aggregators is often weak. ▪ Misaligned incentives and regulatory ambiguity slow formalization at scale. 	<ul style="list-style-type: none"> ▪ Investment should target capacity building for cooperatives and aggregators, digital integration platforms, and formal contracting or social protection pilots. ▪ Municipal authorities, PROs, NGOs, and social enterprises are best positioned to lead implementation.
Material traceability and data systems	<ul style="list-style-type: none"> ▪ AI-based material recognition, sensor-enabled MRFs, and lightweight blockchain or digital ledger systems are available. ▪ Private sector companies and municipalities have been piloting digital tracking platforms. 	<ul style="list-style-type: none"> ▪ Data gaps in the informal sector reduce the reliability and completeness of material tracking. ▪ Digital systems depend on packaging compliance and enabling infrastructure, which are uneven across geographies. ▪ Prohibitive costs and the need for continuous system updates create adoption challenges for smaller operators. 	<ul style="list-style-type: none"> ▪ Investments should focus on pilot-scale deployment of interoperable data systems and verification infrastructure. ▪ Technology providers, municipalities, producer responsibility organizations (PROs), and NGOs are best placed to drive adoption.

Opportunity	Existing solutions	Why they have not worked	Financing and implementation pathways
Upstream design and circular inputs	<ul style="list-style-type: none"> ▪ Brands and manufacturers are exploring design changes, such as easy-to-disassemble products, single-material packaging, and bio-based alternatives. ▪ Pilot programs support the early adoption of these design innovations. 	<ul style="list-style-type: none"> ▪ High upfront R&D costs and long design cycles slow adoption. ▪ Weak market demand for circular design limits scaling. ▪ Supply inconsistency of recycled inputs makes it difficult for manufacturers to rely on them. ▪ Lack of standards and certification for recycled materials reduces buyer confidence. 	<ul style="list-style-type: none"> ▪ Investment should target early-stage product and material innovation, supplier transition support, and market development for circular inputs. ▪ Brands, manufacturers, and material innovators are best positioned to lead this transition.

Table 18: List of opportunities and existing solutions for waste and circularity sectors

trash transformation challenge

develop processing technologies for hard-to-process
waste streams

the big bet

The opportunity	India <u>generates 62 million metric tonnes</u> of waste annually, projected to reach <u>125 million metric tonnes</u> by 2031, yet less than 30% is scientifically processed. Complex, low-value, or hard-to-process waste streams, such as mixed plastics, textiles, e-waste, and organics, face significant barriers due to fragmented infrastructure, inconsistent segregation, and low automation. This represents a substantial untapped opportunity for scalable, modular, and technology-enabled processing solutions.
Choke points	<ul style="list-style-type: none"> ▪ Technologies struggle to process complex waste types, such as multilayer plastics, mixed textiles, and C&D debris, due to high composition variability, contamination, and incompatible material properties. This results in low recovery yields and poor-quality outputs. ▪ Existing recycling technologies often cannot produce outputs comparable to virgin materials, which limits market uptake. ▪ High capital costs, limited financing, and lack of incentives further constrain innovation and accessibility, especially for small or informal processors. ▪ Consequently, waste pickers avoid low-value streams, as weak market demand yields negligible returns.
Solution space	Develop cost-effective processing technologies, such as chemical recycling, hybrid mechanical-thermal reactors, bio-processing units, and modular waste clinics, to overcome material complexity and improve conversion and resource recovery rates for waste streams currently processed at $\leq 50\%$.
Target output(s)	Demonstrate $\geq 70\%$ conversion efficiency of input waste.

The big bet

The proposed solution can innovate affordable, cost-efficient processing technologies for hard-to-process, low-value waste streams currently processed at $\leq 50\%$. Solutions should integrate into circularity or recycling frameworks. These should convert under-processed materials into usable feedstocks, secondary raw materials, or products suitable for downstream recycling or reuse. This process will achieve higher efficiency than existing waste-to-energy or conventional recycling systems.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Anish Malpani	Founder, Without (by Ashaya)
2	Chandra Menon	Associate Director, The/Nudge Institute
3	Kavitha Joan	Partnerships Lead, Saahas
4	Natasha Zarine	EcoSattva
5	Varun Reddy	Manager (Programs), Impact Investor Council
6	Vinay Sharma	rePurpose Global
7	Vishal Kumar	Chief Executive Officer, Waste Warriors
8	Zibi Jamal	Consultant, Saamuhika Shakti

b. Listening Circle

#	Name	Organization
1	Chandra Menon	Associate Director, The/Nudge Institute
2	Nikhil Khandelwal	Zero-Waste Waterbody Management Expert, EcoSattva
3	Pratibha Dewett	Chief Sustainability and Marketing Officer, Lucro Plastecycle Pvt Ltd
4	Sachin Bhatt	Waste Sorting Solutions Expert, Ishitva Robotics Systems
5	Dr. Sunil Pandey	Director, Circular Economy and Waste Management, TERI

4.4.1 Rural waste management

The scale of crop residues generated in India

India's predominantly agrarian rural economy generates large volumes of crop residue each year, which poses significant environmental challenges and substantial untapped economic opportunities. According to the Ministry of New and Renewable Energy (MNRE), annual crop residue generation in India is estimated at approximately 500 million tonnes (PMC NCBI, 2019). This volume has increased sharply over time, from 80 million tonnes in 1950–51 to more than 516 million tonnes by 2017–18. This volume is driven by rising cropping intensity, expansion of cultivated area, and productivity-enhancing technological advances (India Data Insights, 2024).

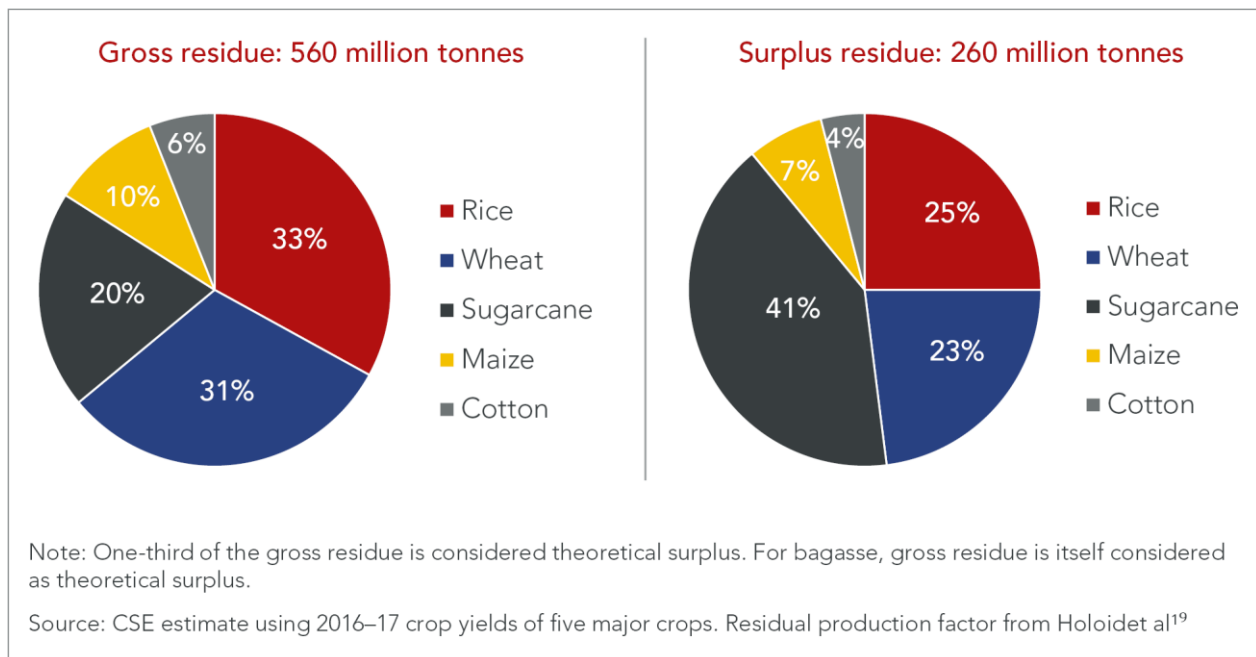


Figure 29: Crop-wise agro-residue generation in India

Source: [CSE India, 2020](#)

Of the total crop residue generated, an estimated 260 million tonnes is classified as surplus, that is, the biomass that remains unutilized after accounting for existing on-farm and off-farm uses. This surplus comprises two distinct streams. Approximately 140 million tonnes consist of field-level residues, primarily rice, wheat, cotton, and maize straw, which are directly accessible to farmers. The remaining 120 million tonnes comprises agro-industrial residues, dominated by nearly 100 million tonnes of sugarcane bagasse. The balance also includes rice husk, wheat pods, soybean husk, and similar by-products.

The problem of low utilization and stubble burning

Despite the significant potential of surplus crop residues for productive uses, such as energy generation, soil health improvement, and other industrial applications, utilization remains limited. Of the 140 million tonnes of surplus residue available at the farm level, an estimated 90–100 million tonnes (nearly 65%) is burned in situ each year (India Data Insights, 2024).

The table below highlights how crop residues in India are predominantly burned or left unused, with only a marginal share utilized for industrial applications:

End use	Main crop residues used (accessible to farmers)	Est. % utilization
Animal feed or fodder	Wheat straw, rice straw, maize stover, sugarcane tops, groundnut haulm, sorghum, and bajra stover	~25–30%
Compost, vermicompost, or bio-slurry	Any crop residue (chopped) + dung + kitchen waste	~15–20%
Mulching or soil cover	Paddy and wheat straw, sugarcane trash, banana leaves, cotton stalk residues, and maize stover	~3–5%
Briquettes or pellets (solid fuel)	Rice straw, wheat straw, groundnut shells, cotton stalks, sawdust, and maize cobs	~5–7%
2G ethanol (biofuel)	Rice and wheat straw, maize cobs, cotton stalks, and sugarcane trash	<1%
Bio-CNG or biogas	Dung, food waste, crop residues (maize stover, sugarcane trash)	~1–2%
Biochar or charcoal	Cotton stalks, maize cobs, woody residues, coconut shells, and rice husk	~1%
Paper, particle board, or packaging	Bagasse (mills), paddy and wheat straw, jute sticks, cotton stalks	~3–5%
Bio-based construction or packaging materials	Rice husk, paddy straw, cotton stalks	<1%
Burned or left unused	Rice and wheat straw (mainly North India), cotton stalks (partial)	~60–65%

Table: Utilization of crop residues

Source: Author's analysis

Stubble burning in India releases an estimated 150 million tonnes of carbon dioxide, over 9 million tonnes of carbon monoxide, and 1 million tonnes of particulate matter annually ([Kumar et al., 2021](#)). The resulting smog, concentrated during October and November, routinely pushes the Air Quality Index (AQI) to hazardous levels ([Abdurrahman et al., 2020](#)). According to a study, stubble burning in India causes between 44,000 and 98,000 premature deaths annually due to exposure to PM 2.5. Of these, 67–90% are linked to burning in Punjab, Haryana, and Uttar Pradesh alone ([Sha et al., 2022](#)). Beyond air quality, the practice destroys soil health. Burning one tonne of crop residue leads to the loss of most organic carbon and around 5.5 kg of nitrogen, 2.3 kg of phosphorus, and 25 kg of potassium from the soil. ([Bhuvaneshwari et al., 2019](#)).

Why farmers continue to burn crop residue

Despite stubble burning being illegal under the Air (Prevention and Control of Pollution) Act of 1981, farmers continue the practice due to economic and logistical reasons. The primary drivers include:

- **Time constraints:** The window between rice harvest and wheat sowing is extremely narrow, typically only 10-15 days. Farmers must clear their fields quickly to prepare for the next planting cycle, and burning provides the fastest, cheapest solution.
- **Cost barriers:** The cost of residue collection and transportation, which includes raking, baling, and hauling, is approximately INR 2,000 (USD 24.1) per tonne. This significantly erodes potential margins when residues sell for only around INR 3,000 (USD 36.1) per tonne.
- **Machinery access gaps:** Low ownership of required machinery, such as balers and tractors, along with limited availability of custom hiring services, makes the collection of biomass unfeasible.
- **Absence of market linkages:** Smallholder farmers lack defined buyer networks, pricing transparency, and clear quality standards for crop residues. Collection and transportation logistics represent the main barrier for farmers who want to supply biomass to industrial buyers.

Growing industrial demand for biomass

As farmers struggle to dispose of their residues, a parallel reality is taking shape. Industrial demand for agricultural biomass is growing faster than the infrastructure to supply it. Across multiple sectors, policy mandates create markets that could absorb millions of tonnes of the very waste that farmers currently burn. Yet the supply chains to deliver this biomass remain underdeveloped. Billions of rupees of potential farmer income remain unrealized. Three sectors, in particular, offer considerable potential:

2G ethanol

India's ethanol blending program has achieved significant progress. Blending rates have risen from 1.53% in 2014 to nearly 20% by early 2025. However, nearly all production relies on first-generation (1G) technology, where ethanol is derived from food crops, such as sugarcane, maize, and rice. In 2024–25, Food Corporation of India made a record allocation of 5.2 million metric tonnes of rice for ethanol, equivalent to nearly 9% of global rice shipments and up from under 3,000 tonnes the previous year. This sharp increase underscores the growing tension between energy and food security ([Reuters, 2025](#)).

Second-generation (2G) ethanol offers a structurally superior path as it converts agricultural waste, such as rice straw, wheat straw, and bagasse, into fuel without competing with the food supply. India burns an estimated 92 million tonnes of crop residue annually ([Kadian et al., 2024](#)). If India can channel even a fraction into 2G ethanol, the country could yield more than 50 billion liters by 2030–31 ([ScienceDirect, 2021](#)) and cut greenhouse gas emissions by 85–108% compared to gasoline ([Leaf-Lesaffre, 2025](#)).

The policy infrastructure is also taking shape. The Pradhan Mantri JI-VAN Yojana has committed INR 19.7 billion (USD 240 million) in viability-gap funding for 12 commercial-scale biorefineries

(MoPNG, GoI). Indian Oil Corporation's Panipat plant, which produces 100 kiloliters of rice-straw ethanol daily, already demonstrates commercial feasibility ([AdvanceBiofuel, 2025](#)).

Biomass cofiring in thermal power plants

India operates roughly 216 GW of coal-based thermal power capacity, which consumes nearly 980 million tonnes of coal annually ([SAMARTH, Ministry of Power](#)). The Ministry of Power's revised biomass policy, adopted in June 2023, mandates that all these plants cofire a minimum of 5% biomass pellets from FY 2024–25, which should rise to 7% from FY 2025–26 ([Press Information Bureau, 2023](#)). At full implementation, this would require approximately 50 million tonnes of biomass pellets annually, equivalent to roughly 96,000 tonnes per day. These pellets could displace 50–100 million tonnes of coal and cut CO₂ emissions by an estimated 38 million tonnes a year ([Down To Earth, 2022](#)). Biomass consumption in thermal plants more than quadrupled, rising from 375,000 tonnes in FY 2023–24 to 1.62 million tonnes in FY 2024–25 ([Argus Media, 2025](#)), as 71 plants moved to active co-fire operations ([Energetica India, 2025](#)). Yet even at this pace, the sector meets only a fraction of the mandate. India's pellet manufacturing capacity stands at 7,000 tonnes per day against the 96,000-tonne daily requirement, a gap of more than 90% ([Down To Earth, 2022](#)).

Compressed biogas (CBG)

India is the world's third largest energy consumer, and its energy demand is expected to rise sharply over the next 15 to 20 years. Around 50% of the country's natural gas requirement is met through imports. In this context, compressed biogas can reduce dependence on imported natural gas and crude oil, and lower fertilizer subsidy costs. India's CBG potential is estimated at 40 to 60 million tonnes per annum.

Government policy and industry participation could help realize 15 to 20% of this, or about 8 to 12 MMTPA, over the next 7 to 8 years. However, installed capacity remains below 1% of potential, and many existing plants operate at low utilization levels. A key constraint for this is the lack of a stable, continuous biomass supply. At scale, more than 100 million tonnes of organic biomass can produce 15 MMTPA of CBG annually, based on typical feedstock to output conversion ratios of 8 to 15% ([EAC International Consulting, 2023](#)).

How to build the missing value chain

Taken together, the industrial demand outlined (2G ethanol, biomass cofiring, and compressed biogas) collectively requires tens of millions of tonnes of agricultural biomass each year. Yet the infrastructure to collect, process, and move this biomass from dispersed smallholder farms to industrial buyers barely exists. Biomass economics remain challenging. Residue collection, baling, and transport to the nearest straw bank cost approximately INR 1,330 (USD 16.0) per tonne. Transport to an end-user 50 km away increases costs to INR INR 2,500–3,000 (USD 30.1–36.1) per tonne for bales and INR 4,000–5,000 (USD 48.2–60.2) per tonne for densified pellets or briquettes ([Kurinji and Kumar, 2021](#)).

“

Raw residue cannot travel beyond 15 to 20 km. Beyond that, transport costs exceed its value. This is a critical distance economics principle for residue-based value chains.

- Ashwin Save - Co-founder, BiofuelCircle

Fragments	Components	Bale (INR)	Briquette (INR)	Pellet (INR)
Residue collection + first-mile transportation	Residue cost	1,351	1,757	1,757
Interim storage (optional)	Storage cost	880	1,144	1,144
Biomass processing (optional)	Biomass processing cost (briquette/pellet)	NA	1,034	1,437
Final transportation	Transport charges	347	250	250
	Loading and unloading cost	364	135	135
Total cost (INR/tonne)		2,942	4,320	4,723
Total cost (INR/5,000 Mcal)		5,979	6,013	6,626

Table 19: Delivered cost of biomass per tonne to the end user located at a distance of 50 km

Source: [CEEW, 2021](#)

Most smallholder farmers lack the capital for balers, rakers, and high-horsepower tractors. They also do not have access to assured buyers who want to purchase their residue at a viable price ([CEEW, 2024](#)). This results in a stark paradox: Farmers burn what the industry needs because no connective tissue is available between the field and the factory.

A new category of technology-driven biomass aggregation platforms is emerging to bridge this gap. These platforms take on the functions that individual farmers cannot perform at scale. These can procure collection machinery, coordinate baling and transport, conduct quality assurance, warehousing, and market access. These platforms will bundle these tasks into an end-to-end service.

For instance, Pune-based BiofuelCircle has pioneered a “Biomass Bank” model. In this model, village-level hubs equipped with balers, slashers, and rakers operate with support from a multilingual mobile application through which farmers can register their residue and pre-book evacuation services. Each biomass bank serves more than 2,000 farmers. It also creates income

opportunities for local tractor owners who provide aggregation and transport services and earn between INR 300,000–1,000,000 (USD 3,614–12,048) annually ([Renewable Watch, 2024](#)). The company operates across five states with more than 20,000 registered farmers and annual transactions that exceed INR 2 billion (USD 24.1 million) ([BiofuelCircle, 2024](#)). It plans to scale to 50 biomass banks nationwide, each equipped with GPS- and telematics-enabled machinery ([Bioenergy Insight, 2025](#)).

Coimbatore-based Buyofuel takes a complementary approach. It operates as a B2B digital marketplace that matches biomass suppliers with large industrial consumers. These include UltraTech Cement, ITC, JSW Steel, and the TVS Group. Its on-ground sourcing teams locate and onboard small, scattered producers who would otherwise have no route to market ([YourStory, 2022](#)).

These models are transformative not just due to the logistics they provide, but the economic incentive they create at the farm level. These aggregation platforms arrive in the field with machinery, clear the residue, and pay the farmer for it. These convert what was previously a disposal burden into a revenue stream. Farmers who once paid INR 1,000 (USD 12.0) per acre to have their stubble removed, or simply set it alight, can now earn supplementary income from the same biomass ([CEEW, 2025](#)). This simultaneously addresses the stubble burning problem and channels supply to thermal power plants, CBG facilities, 2G ethanol refineries, and pellet manufacturers that operate well below capacity due to feedstock shortages.

However, these platforms operate in only a handful of states. The biomass supply chain must expand this model of technology-enabled aggregation, coupled with decentralized physical infrastructure nationwide for baling, storage, and transport to meet even a fraction of the projected industrial demand.

the parali challenge

unlocking additional farm income through crop
residue management

the big bet

<p>The opportunity</p>	<p>India generates around 560 million tonnes of crop residue annually, with a surplus of approximately 140 million tonnes largely left on fields. Due to tight sowing windows, around 90 million tonnes of this surplus is burned each year, which causes severe pollution and soil health degradation.</p> <p>Simultaneously, the demand for biomass is at an all-time high and expected to increase significantly. As of 2025, India requires around 10 billion liters of ethanol annually to sustain its achieved 20% blending (E20) status. Further, thermal power plants are now mandated to co-fire 7% biomass from FY 2025-26. However, the use of crop residue sourced directly from farmers for these sectors remains nascent, which creates a massive supply-demand gap that could monetize waste for smallholders and generate additional income of up to INR 9,000 annually (USD 108 annually).</p>
<p>Choke points</p>	<ul style="list-style-type: none"> ▪ High aggregation and transport costs of around INR 1800 (USD 19) per tonne erode margins, while these residues sell for around INR 3,000 (USD 32) per tonne. This cost structure makes it difficult for smallholder farmers with fragmented 1–2 hectare plots to participate on their own. ▪ Smallholder farmers lack access to balers, tractors, and market linkages with buyers to participate in the biomass value chain. Expensive machinery that costs more than INR 15 lakhs (USD 1606) remains out of reach for smallholders. ▪ Rural ecosystem actors, such as those with tractors and balers, are fragmented and need to be brought into the value chain. ▪ Collection of crop residues must be completed within 10-15 days post-harvest window to allow for timely sowing for the next season.
<p>Solution space</p>	<p>Low-cost models for residue collection and aggregation that bundle baling, transportation, storage, and market linkage for crop residues produced by smallholders. Solutions should bridge the last-mile gap between fragmented farms and biomass buyers, such as 2G ethanol, CBG, or biomass pellet plants. These solutions should also create local rural employment for service providers, such as tractor and baler owners.</p>

Target outputs

- Fair value share for local actors should ensure that farmers and local service providers, such as baler, tractor owners, and transporters together receive at least INR 2,250 (USD 27.1) per tonne of residue supplied. This represents about two-thirds of the approximately INR 3,000 (USD 36.1) per tonne market price.
- Meaningful net income for farmers should generate at least INR 500 (USD 5.3) per tonne in net farm income from residue sales. A typical cereal smallholder with 1 hectare can produce approximately 6 tonnes of residue per season.
- Timely field clearance should achieve complete residue removal from the field within 10–15 days post-harvest.
- Reliable market linkage should demonstrate consistent supply relationships with bio-energy buyers, which meet required quality standards for moisture and calorific value.

The big bet

Innovate decentralized, low-cost collection and aggregation models that ensure the rural ecosystem captures at least INR 2,250 (USD 24) per tonne of the market value up to INR 3,000 (USD 32) per tonne for crop residues. This approach will eliminate on-farm burning and generate reliable income for smallholder farmers and rural ecosystem actors.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Onkar Pandey	Director, Social Alpha
2	Sashi Kumar	CEO, Akshayakalpa Organic
3	Suhas Baxi	Co-founder and CEO, BiofuelCircle

b. Listening circle

#	Name	Organization
1	Amitabh Malaviya	Director, Araville Green Energy Ventures
2	Ashwin Savé	Co-founder and COO, BiofuelCircle
3	Kurinji Kemanth	Programme Lead, CEEW
4	Dr. Parveen Dhamija	Adviser, Ministry of New and Renewable Energy
5	Sunil Dhingra	Director and CEO, Bio Trend Energy

4.4.2 Wastewater treatment and reutilization

The underused potential of wastewater

Wastewater is one of the largest underused resource streams in India's circular economy. Urban areas in India generate about 72,368 MLD of sewage, but installed treatment capacity is only 31,841 MLD, and actual treatment is much lower at about 20,236 MLD. This means a large share of wastewater continues to be discharged without adequate treatment. This discharge deepens river pollution, degrades lakes and groundwater, and increases public health risks. At the same time, it represents a major missed opportunity, as treated wastewater can substitute for freshwater in industry, landscaping, construction, agriculture, groundwater recharge, and several municipal uses ([PIB](#), [CEEW](#)).

National policy direction has been moving toward reuse for some time. The National Water Mission explicitly calls for incentives to recycle wastewater and to ensure that a considerable share of urban water needs is met through recycling and reuse. The National Mission for Clean Ganga (NMCG) has also developed a National Framework for Safe Reuse of Treated Water to help states build reuse policies, market mechanisms, and city-level action plans. ([PIB](#), [NMCG](#), [NWM](#)) There is also growing evidence from Indian cities that reuse can move from pilot to market.

Surat Municipal Corporation's 2019 action plan reported that the city was already reusing more than 30% of its treated wastewater. Surat had plans to increase that share further, with reuse across industrial, gardening, agriculture, road-washing, sewer-jetting, and even greywater-for-flushing applications. The city-level template issued under the NMCG framework similarly positions reuse as a means to substitute for freshwater, improve sewage treatment plant (STP) performance, and create value from treated water rather than treating it as waste. ([SMC](#), [NMCG](#))

Bengaluru illustrates both the urgency and the market gap. The Bengaluru Water Supply and Sewerage Board (BWSSB) currently operates a large network of STPs. Recent reporting indicates the city generates roughly 1,480 MLD of sewage while treating about 1,212.7 MLD. BWSSB's own documents and notices also point to a growing treated-water ecosystem for non-potable uses and continued investment in STP capacity and upgrades.

Yet, even in a relatively advanced city, the system still faces the classic barriers. These include uneven treatment performance, network and distribution gaps, weak trust in treated water quality, and a limited match between supply and end-use demand. This demand makes Bengaluru a strong example of why innovation is now needed at the treatment plant, and in monitoring, quality assurance, distribution, pricing, and demand aggregation. ([BWSSB \(a\)](#), [BWSSB \(b\)](#), [TOI](#))

The strategic case for wastewater use is strong. The Council on Energy, Environment and Water (CEEW) notes that the reuse of treated wastewater has not yet become mainstream in India, even as water stress intensifies and urban demand rises. Its analysis argues that the next generation of wastewater solutions in India will need to go beyond treatment capacity alone. These solutions must address conveyance, allocation, smart metering, pricing, sustainable O&M, and use-based quality standards. The focus should move from "can we treat wastewater?" to "can we build viable systems that match treated water of a given quality to paying demand at scale?" ([CEEW \(a\)](#), [CEEW \(b\)](#), [Bassi, Gupta, and Chaturvedi](#))

Globally, the logic for wastewater reuse is even clearer. The UNEP argues that wastewater is still treated primarily as an environmental liability when it should be managed as a resource stream. It notes that wastewater is a growing environmental threat, but could also provide substantial alternative water, energy, and nutrient value if properly managed. The UNEP's recent work on circular water systems frames reuse as essential in a world of growing scarcity, pollution, and climate stress. ([UNEP \(a\)](#), [UNEP \(b\)](#), [UNEP \(c\)](#))

the re-freshwater challenge

decentralized water treatment for residential and
commercial buildings

the big bet

<p>The opportunity</p>	<p>Centralized wastewater treatment alone cannot meet the domestic wastewater treatment needs of India’s urban households. Urban governing bodies across cities, such as Bengaluru and Pune, now increasingly mandate the design and setup of decentralized, on-site sewage treatment plants for existing and new residential or commercial buildings.</p> <p>The mandate to set up these units lies with the builders. However, they prioritize economic over ecological and quality concerns, and install sewage treatment plants (STPs) with low CapEx that result in significant issues with O&M and increased OpEx.</p>
<p>Choke points</p>	<ul style="list-style-type: none"> ▪ Treatment gap and infrastructure constraints exist as installed capacity of approximately 31,800 MLD is significantly lower than sewage generation, with even lower effective utilization due to poor O&M. ▪ High capex and O&M intensity make centralized STPs capital-heavy, energy-intensive, and often financially unsustainable for urban local bodies (ULBs). ▪ Lack of decentralized, modular solutions results in limited adoption of building-level, cluster-level, or industrial-zone wastewater systems. ▪ Weak quality monitoring and compliance leads to inconsistent effluent quality, lack of real-time monitoring, and weak enforcement by SPCBs reduce trust in treated water. ▪ Absence of demand aggregation and offtake markets means treated wastewater supply is not systematically matched to industrial or municipal demand. ▪ Low trust and behavioral barriers mean end-users, such as industry, institutions, and households, lack confidence in the quality and safety of reused water. ▪ Fragmented governance and unclear ownership create execution gaps due to overlap between ULBs, SPCBs, private operators, and utilities, such as BWSSB.
<p>Solution space</p>	<ul style="list-style-type: none"> ▪ Decentralized and modular treatment systems <ul style="list-style-type: none"> ○ Plug-and-play STPs for apartments, commercial buildings, and industrial clusters ○ Low-energy, low-maintenance biological and hybrid treatment technologies ▪ Greywater recycling systems <ul style="list-style-type: none"> ○ Household or community-level systems for reuse in flushing and landscaping ○ Retrofit solutions for existing buildings

	<ul style="list-style-type: none"> ▪ Advanced tertiary treatment and fit-for-purpose systems <ul style="list-style-type: none"> ○ Membrane filtration, Ultraviolet (UV) disinfection and polishing systems tailored to end-use requirements ○ Cost-optimized treatment aligned to the use case without over-treatment ▪ Real-time monitoring and compliance technology <ul style="list-style-type: none"> ○ IoT-enabled sensors for effluent quality tracking ○ AI-driven predictive maintenance and compliance reporting ○ Digital integration with SPCBs and regulators ▪ Wastewater marketplaces and demand aggregation <ul style="list-style-type: none"> ○ Platforms to connect treated water supply with industrial or municipal demand ○ Long-term offtake contracting models ▪ Sludge-to-value pathways <ul style="list-style-type: none"> ○ Conversion of sewage sludge into biogas, compost, or industrial inputs ▪ Industrial cluster reuse systems <ul style="list-style-type: none"> ○ Closed-loop water systems for MSME clusters ○ Zero liquid discharge (ZLD)-lite or hybrid solutions for cost-sensitive industries
Target outputs	<ul style="list-style-type: none"> ▪ Enable high-quality wastewater treatment and reuse across urban and peri-urban systems ▪ Achieve 30–50% substitution of freshwater demand in targeted industry and municipal use cases ▪ Reduce untreated wastewater discharge and associated pollution loads ▪ Lower cost of treatment through decentralized and energy-efficient systems ▪ Build trusted and verifiable reuse systems through real-time monitoring ▪ Unlock new revenue streams and viable business models for wastewater reuse ▪ Improve resilience of cities that face water stress and climate variability

The big bet

Modular, cost-effective wastewater treatment needs to be developed and scaled. Solutions that enable at least 50% substitution of freshwater demand should be reused in defined urban or industrial contexts. These solutions must ensure real-time quality compliance and viable offtake models within 18–24 months.

List of experts consulted across different stages of research

a. Expert consultations

#	Name	Organization
1	Chitra Vishwanath	Managing Director, Biome Environment Solutions
2	Shashank Palur	Manager, WELL Labs
3	Shreya Nath	Managing Partner, WELL Labs



Closing reflection

India has already set its destination: Viksit Bharat by 2047. However, no journey begins with the destination alone. Mapping a path to our destination requires clarity on where we must start and why we want to start there.

This report has been an effort to bring that “current location” into focus.

The evidence is abundantly clear across food systems and circularity. The most climate-exposed livelihoods in India do not face isolated shocks. They operate within systems where small losses compound into income erosion, insecurity, and eventual exclusion. This report examines the agriculture, dairy, poultry, goateries, fisheries, forestry, and urban & rural waste management sectors. These together support hundreds of millions of households, including 86% of farmers who cultivate less than 2 hectares, 30 million goat-rearing households, 28 million fishers, 125 million forest-dependent people, and 1.5–4 million informal waste pickers.

What this study has tried to do is identify not every problem in the system, but the chokepoints that matter most—the places where a meaningful shift can unlock disproportionate value. That is why the report focuses on a set of high-leverage Big Bets: Soil rejuvenation, crop diagnostics, livestock health monitoring, aquaculture pond management, aggregation-led poultry pathways, crop residue valorization, and hard-to-process waste technologies. These are not isolated ideas, but rather **entry points to deeper system change**.

The pathway to scale will not be singular. It will require markets that reward resilience, technologies that work at the last mile, catalytic capital that can absorb early risk, and institutions that can align incentives across sectors. Moreover, moving from problem recognition to implementation will require collective effort from government, civil society, startups, corporates, academics, and funders.

This roadmap is therefore not an endpoint, but rather a **starting point**, a way to see the terrain more clearly, identify where leverage exists, and focus attention where it can matter most.

What comes next is the journey itself: Collective action that is patient, coordinated, and bold enough to turn these pathways into lived resilience for the communities that cannot afford to wait.

At the Δ prize, we are committed to advancing this journey by shaping pathways to induce solutions and enable interventions led by technology and market where they can matter most. We will work to align ecosystems, strengthen the capacity of founders and changemakers, and strategically deploy catalytic philanthropic capital toward high-leverage points of intervention to build more climate-resilient livelihoods. This roadmap is one contribution to that effort. It is an attempt to identify where the path is clearest, where the need is greatest, and where collective action can create lasting change.

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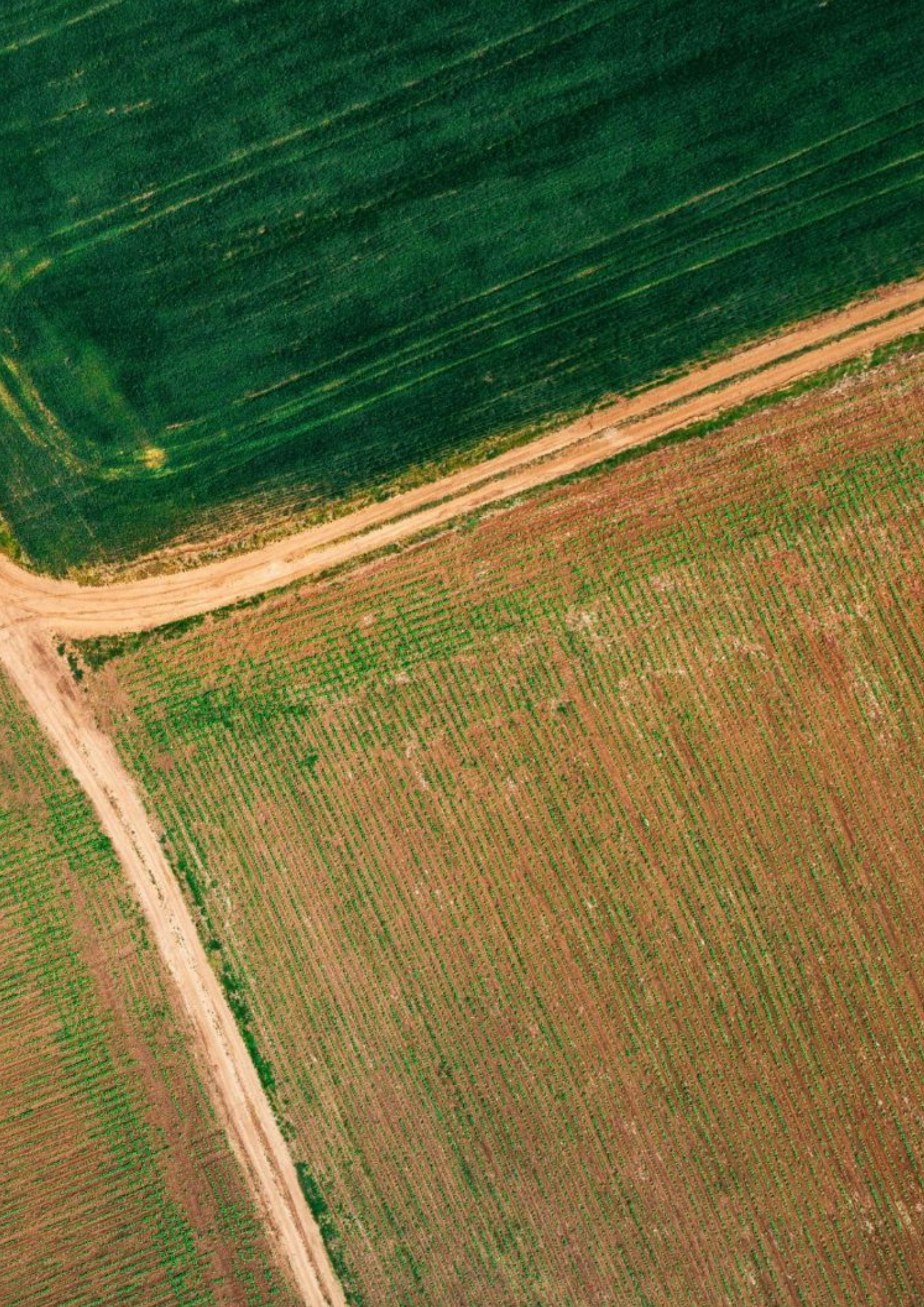
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The **right problems** don't
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they unlock solutions, align
ecosystems and direct capital
when it matters most.



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