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Bridging the lab-to-farmgate gap: Extension strategies for transferring modern meat-processing and preservation technologies to rural small-scale producers in India — A review

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ABSTRACT

India is one of the world's largest meat producers, yet the bulk of its output originates from millions of small and marginal livestock keepers, backyard poultry rearers and unorganised butchers who remain largely disconnected from the modern meat-processing and preservation technologies developed in research institutions. This disconnect—the “lab-to-farmgate gap”—is a principal reason why post-harvest losses stay high, product safety remains inconsistent, and the value generated by meat animals is captured downstream rather than by producers. This review synthesises the published literature, government statistics and programme evaluations to examine why proven technologies such as hygienic slaughter, chilling and cold-chain management, hurdle-based preservation, modified-atmosphere and vacuum packaging, value-added product manufacture and digital traceability fail to reach rural small-scale producers, and what extension strategies can close the gap. Evidence indicates that the barriers are only partly technical; they are predominantly institutional, economic and communicational—fragmented holdings, weak cold-chain infrastructure, limited credit, low literacy, an acute shortage of livestock-products extension specialists, and a research agenda historically detached from smallholder realities. The review argues that classical linear “transfer-of-technology” models are inadequate and that closing the gap requires a pluralistic, demand-driven extension architecture combining decentralised micro-processing units, cluster and producer-organisation approaches, information and communication technology (ICT)-enabled advisory services, skill certification, women's self-help-group enterprises, and public-private partnerships anchored to Krishi Vigyan Kendras and veterinary institutions. Critical analysis reveals a persistent research gap: rigorous impact evaluations of meat-technology extension interventions are scarce, and most ICT tools address crop rather than livestock-products domains. The paper proposes an integrated extension framework and a future research agenda emphasising participatory technology development, last-mile digital advisory, and measurable indicators of adoption, safety and income. Strengthening livestock-products extension is positioned as both a food-safety imperative and a rural-livelihood opportunity.

Keywords: Meat processing, Technology transfer, Livestock extension, Rural livelihoods, Cold chain, Small-scale producers, Food safety

Introduction

Meat is among the fastest-growing segments of Indian agriculture. According to the Basic Animal Husbandry Statistics 2024 [2], national meat production reached about 10.25 million tonnes in 2023–24, growing nearly 5% over the previous year, with West Bengal, Uttar Pradesh and Maharashtra leading output (Basic Animal Husbandry Statistics, 2024) [2]. India is simultaneously the world's largest producer of buffalo (carabeef) meat and among its largest exporters, while poultry meat has expanded rapidly on the strength of vertically integrated operations (APEDA, 2023; FAO, 2023) [4, 3]. Behind these aggregate figures, however, lies a structurally dualistic sector. A small, capital-intensive, export-oriented segment operates modern integrated abattoirs and processing plants, whereas the overwhelming majority of animals are reared by small and marginal holders and slaughtered in unorganised, often unlicensed, municipal or backyard facilities with minimal hygiene control and almost no cold chain (BIS, 2016) [5]. The 20th Livestock Census confirms that livestock ownership in India is dominated by households holding very few animals, for whom livestock is a supplementary rather than a primary enterprise (DAHD, 2019) [6].

This structure produces a paradox. Meat science in India has generated a substantial body of applicable technology—humane and hygienic slaughter protocols, rapid chilling and cold-chain logistics, hurdle technology for shelf-stable products, vacuum and modified-atmosphere packaging (MAP), functional and value-added products such as sausages, nuggets, patties and pickles, natural preservatives and biopreservation, and, more recently, digital traceability and artificial-intelligence-based quality grading (Leistner, 2000; McMillin,

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2008; Mehta *et al.*, 2015; Verma *et al.*, 2010) [7, 8, 9, 10]. Yet very little of this reaches the rural producer or the small butcher. The technologies remain, in effect, confined to research stations, a few progressive entrepreneurs and the organised export sector. The distance between the point at which a technology is validated in the laboratory or pilot plant and the point at which a rural producer actually uses it is what this review terms the lab-to-farmgate gap.

The consequences are tangible. Post-harvest and quality losses along the meat chain are substantial because carcasses move without chilling in ambient tropical conditions; microbial contamination and adulteration undermine consumer confidence and public health; and, critically, the value added by processing and preservation is captured by intermediaries and downstream firms rather than by the producer, who typically sells live animals at the farm gate and exits the value chain at its lowest-margin point (Landes *et al.*, 2016) [11]. Closing this gap is therefore not merely a technical exercise; it is central to food safety, to reducing waste, and to the social-development objective of raising and stabilising the incomes of resource-poor livestock keepers. Agricultural extension is the mechanism through which such gaps are meant to be bridged, but livestock-products extension is among the weakest links in the Indian extension system. The public extension apparatus has historically been oriented toward crop production and, within animal husbandry, toward breeding, feeding and health rather than post-production processing, preservation and marketing (Glendenning *et al.*, 2010; Meena *et al.*, 2013) [12, 13]. There is no widely institutionalised cadre of “meat-technology extension specialists,” and the discipline of Livestock Products Technology, though well developed in research and education, is thinly represented at the field level.

The purpose of this review is therefore threefold: first, to characterise the modern meat-processing and preservation technologies that are relevant and transferable to rural small-scale producers; second, to diagnose the technical, institutional, economic and communicational barriers that keep these technologies from reaching the farm gate; and third, to synthesise and critically evaluate the extension strategies—organisational, digital, financial and participatory—that can close the gap, and to propose an integrated framework and research agenda. The review is deliberately positioned at the intersection of meat science and agricultural extension and social development, reflecting the conviction that technological and social innovations must advance together if smallholder meat producers are to benefit.

Materials and Methods

This paper is a narrative (critical) review rather than a report of primary experimentation; the “materials” are the published and documentary literature, and the “method” is structured synthesis. Literature was assembled from peer-reviewed journals, institutional and government publications, and programme evaluations. Databases and repositories consulted included Google Scholar, ScienceDirect, PubMed and the archives of Indian animal- and extension-science journals, together with official sources such as the Department of Animal Husbandry and Dairying (DAHD), the Food Safety and Standards Authority of India (FSSAI), the Agricultural and Processed Food Products Export Development Authority (APEDA) and the Food and Agriculture Organization (FAO).

Search terms were combined across two conceptual domains. The first captured technology—“meat processing,” “meat preservation,” “cold chain,” “hurdle technology,” “packaging,” “value-added meat products,” “meat traceability,” and “hygienic slaughter.” The second captured the social and extension dimension—“technology transfer,” “agricultural extension,” “livestock extension,” “ICT,” “adoption,” “smallholder,” “rural producers,” “self-help group,” and “farmer producer organisation.” Priority was given to literature relevant to India and comparable low- and middle-income countries, published mainly over the last two decades, while retaining seminal earlier work.

Sources were included when they addressed either a transferable meat technology, a barrier to its adoption, or an extension mechanism, and were excluded when they dealt purely with laboratory optimisation without any transfer, livelihood or adoption dimension. The evidence was then organised thematically—technologies, barriers, and strategies—rather than enumerated study by study, and synthesised to identify convergences, contradictions and gaps. Because the literature is heterogeneous and largely observational, findings are treated as indicative rather than as the product of formal *meta-analysis*, a limitation acknowledged explicitly in the discussion.

Results

The transferable technology base: what is available to be transferred

A realistic extension strategy must begin from a clear view of which technologies are both mature and appropriate for small-scale settings. Not everything validated in a research plant is transferable to a village context; the relevant subset is that which is low-cost, robust, and matched to the scale and skills of rural users.

Hygienic slaughter and dressing. The single most consequential intervention is not exotic; it is the adoption of basic hygienic slaughter and dressing practice—clean water, ante- and post-mortem inspection, proper bleeding, avoidance of floor contact, and separation of clean and dirty operations—codified in national standards for abattoirs (BIS, 2016; FSSAI, 2017) [5, 14]. In most rural slaughter, these fundamentals are absent, making them the first and highest-return target for transfer.

Chilling and the cold chain. Rapid post-slaughter chilling and an unbroken cold chain are the foundation of meat safety and shelf life, yet they are precisely where rural systems fail. Ambient distribution of warm carcasses is the norm. Small-scale cold-chain solutions—insulated transport, small chilling units, and decentralised cold rooms serving producer clusters—are technically available but rarely reach the farm gate for want of investment and reliable power (Landes *et al.*, 2016) [11].

Preservation by hurdle technology. Hurdle technology—combining mild treatments such as reduced water activity, lowered pH, mild heat, and natural antimicrobials to produce shelf-stable products without heavy dependence on refrigeration—is particularly well suited to Indian conditions because it partially circumvents the cold-chain constraint (Leistner, 2000; Mehta *et al.*, 2015) [7, 9]. Intermediate-moisture and dried products, fermented sausages and traditional preserved items are natural vehicles for this approach.

Packaging. Vacuum packaging and modified-atmosphere packaging substantially extend shelf life and improve hygiene and presentation, and retort-processed and aseptically packaged shelf-stable meat products are technically established (McMillin, 2008) [8]. At the small-scale level, even simple improvements in primary packaging and labelling raise safety and marketability, though equipment cost remains a barrier.

Value addition. Conversion of raw meat into sausages, nuggets, patties, kebabs, meatballs, pickles and snacks captures margin and diversifies markets. These products use manageable equipment and are the most direct route by which a rural producer or a self-help group can move up the value chain (Verma *et al.*, 2010) [10]. Value addition is therefore central to any income-oriented extension strategy.

Traceability and digital quality tools. Traceability systems—from ear-tag and batch identification to barcode, QR-code and, increasingly, blockchain-based chains of custody—are emerging as instruments of both food safety and consumer trust, and AI/ML and computer-vision methods for carcass and quality grading are advancing rapidly (Chmiel *et al.*, 2011; Karlsen *et al.*, 2013) [15, 16]. For smallholders these are largely aspirational today, but simplified, mobile-phone-mediated versions are plausible near-term extension content.

The nature of the gap: barriers to transfer

The evidence consistently shows that the lab-to-farmgate gap is only partly a matter of technology awareness; it is sustained by a dense set of interacting barriers.

Structural and infrastructural barriers. Fragmented holdings and tiny per-household animal numbers make individual investment in processing or cold-chain equipment uneconomic, while unreliable electricity, poor rural roads and the near-absence of decentralised chilling infrastructure make even willing adopters unable to maintain a cold chain (DAHD, 2019; Landes *et al.*, 2016) [6, 11]. The dominance of unorganised, frequently unlicensed slaughter facilities means there is often no hygienic node at which improved technology could even be inserted (BIS, 2016) [5].

Economic and financial barriers. Capital cost, thin and volatile margins, weak access to institutional credit, and the risk aversion of resource-poor households all deter adoption. Producers who sell live animals avoid the working capital, spoilage risk and market uncertainty that processing entails; without assured markets and credit, the rational choice is often to remain a live-animal seller (Landes *et al.*, 2016) [11].

Institutional and policy barriers. Livestock-products extension is under-institutionalised. Public extension is thinly staffed for post-production meat technology, coordination between animal-husbandry departments, food-safety regulators, municipalities and research institutions is weak, and regulatory compliance (licensing, standards) is perceived by small operators as costly and opaque (Glendenning *et al.*, 2010; Meena *et al.*, 2013) [12, 13]. The result is that even good technology lacks an institutional carrier to the field.

Communication and human-capital barriers. Low literacy, language diversity, limited numeracy for cost-benefit reasoning, and the historically top-down “transfer-of-technology” communication model reduce the uptake of complex technical messages. There is a shortage of trained meat-technology extension personnel and of extension content designed for low-literacy, mixed-language audiences (Aker, 2011; Meena *et al.*, 2013) [1, 13]. Social factors—gender norms, caste and community dimensions of the meat trade, and the low social status attached to butchery—further complicate participation.

Research-extension disconnect. A recurring theme is that much meat-science research has optimised products and processes under laboratory conditions without a parallel investment in understanding smallholder constraints, so that technologies arrive “finished” and ill-fitted to village realities (Meena *et al.*, 2013) [13]. The feedback loop from producer to researcher is weak.

Extension strategies that can bridge the gap

Against this diagnosis, the literature and programme experience point to a set of mutually reinforcing strategies. No single instrument suffices; the evidence favours a pluralistic, demand-driven and organisationally embedded approach.

Decentralised micro-processing and the cluster model. Because individual investment is uneconomic, aggregation is the pivot. Establishing shared, decentralised micro-processing and chilling units at the level of a village cluster, a producer organisation or a Krishi Vigyan Kendra (KVK) converts an unaffordable individual asset into an affordable collective one, and creates a hygienic node into which slaughter, chilling, preservation and value-addition technologies can be introduced together (Trebbin, 2014) [17].

Producer organisations and self-help groups. Farmer producer organisations (FPOs) and self-help groups (SHGs) aggregate volume, share risk, improve bargaining power and provide the social platform through which technology and credit can flow. Women's SHGs are a particularly promising vehicle for value-added meat and poultry micro-enterprises, linking technology transfer directly to women's empowerment and household income—an explicit social-development outcome (Verma *et al.*, 2026) [18].

ICT-enabled advisory services. Mobile telephony, voice and video advisories, farmer call centres, WhatsApp and app-based platforms have transformed the reach of agricultural extension, and their poten-

tial for livestock and meat-technology advisory is substantial but under-exploited (Aker, 2011; Fu *et al.*, 2016; Saravanan *et al.*, 2016) [1, 19, 20]. Kisan Call Centres and mobile advisory systems demonstrate feasibility, yet content remains overwhelmingly crop-oriented; a dedicated livestock-products advisory stream—covering hygienic slaughter, preservation and simple value addition in local languages, using video and pictorial formats suited to low literacy—is a clear opportunity (Aker, 2011; Saravanan *et al.*, 2016) [1, 20]. Digital tools also enable simplified traceability that a smallholder can operate from a phone (Karlsen *et al.*, 2013) [16].

Skill development, training and certification. Hands-on vocational training, demonstrations, exposure visits and recognised skill certification (for example through KVKs, veterinary colleges and skill-mission channels) build the human capital that technology adoption requires and confer marketable credentials on rural processors and butchers (Trebbin, 2014; Verma *et al.*, 2026) [17, 18]. Demonstration—seeing a technology work under local conditions—remains one of the most persuasive extension methods for risk-averse adopters.

Public-private and institutional partnerships. Linking research institutions (such as ICAR institutes and state veterinary universities), KVKs, animal-husbandry departments, food-safety regulators, private processors and financial institutions creates the value-chain scaffolding—assured markets, credit, standards support and technical backstopping—without which isolated training does not translate into sustained enterprise (Glendenning *et al.*, 2010; Trebbin, 2014) [12, 17].

Participatory and demand-driven technology development. Cutting across all of the above is a shift from linear technology transfer to participatory, iterative development in which producers help define problems and adapt solutions. This realigns the research agenda toward smallholder-appropriate, frugal technologies and strengthens the producer-to-researcher feedback that the sector currently lacks (Meena *et al.*, 2013; Röling, 1992) [13, 21].

Discussion

The central message emerging from this synthesis is that the lab-to-farmgate gap in meat technology is misdiagnosed when it is treated primarily as a problem of technology availability or producer awareness. The technologies exist; many are mature and some are strikingly well suited to Indian conditions. What is missing is the institutional, economic and communicational architecture to carry them the last mile. This reframing has direct implications for how extension should be designed.

First, the evidence argues strongly against the residual “transfer-of-technology” paradigm, in which a finished technology is pushed outward from the research station through a linear pipeline. The repeated finding that technologies arrive ill-fitted to smallholder realities (Meena *et al.*, 2013; Röling, 1992) [13, 21], combined with the weak producer-to-researcher feedback loop, indicates that the pipeline model is not merely inefficient but self-defeating: it optimises for laboratory performance rather than field adoptability. A participatory, demand-driven model that begins from producer constraints is better supported by the evidence, even though rigorous comparative trials of the two approaches in the meat-technology domain are lacking—itsself a notable gap.

Second, the strategies that recur in the literature are complementary rather than substitutable, and this is where much programming has failed. Training without market linkage produces certificates but not enterprises; cold-chain hardware without producer organisation to share and maintain it falls idle; ICT advisory without local-language, low-literacy content designed for livestock products defaults to crop messaging and bypasses the meat producer. The convergent lesson is that aggregation (through clusters, FPOs and SHGs) is the keystone that makes the other interventions viable, because it simultaneously solves the scale problem for infrastructure, the risk problem for finance, and the social-platform problem for communication (Trebbin, 2014; Verma *et al.*, 2026) [17, 18]. An extension strategy that does not begin with some form of aggregation is unlikely to be sustainable.

Third, there is a genuine tension, visible in the literature, between food-safety regulation and smallholder inclusion. Tightening standards and licensing is essential for public health and for market access, yet if compliance costs and procedures are set without regard to small operators, regulation can push the very producers extension seeks to help further into the unorganised, unregulated segment (BIS, 2016; Glendenning *et al.*, 2010) [5, 12]. The resolution is not to relax safety but to make compliance attainable through shared infrastructure, simplified procedures and extension support—an area where policy and extension must be co-designed.

Fourth, the ICT opportunity is real but should not be overstated. Digital advisory dramatically lowers the cost of reaching dispersed producers and can carry video demonstrations of hygienic slaughter or sausage-making into remote villages (Aker, 2011; Fu *et al.*, 2016; Saravanan *et al.*, 2016) [1, 19, 20]. But the same literature cautions that digital tools reproduce existing biases—toward crops, toward the literate, toward the connected—unless content and interfaces are deliberately built for livestock-products users with low literacy and intermittent connectivity. Technology-mediated extension is a complement to, not a replacement for, human demonstration and the trust built through local institutions.

The principal limitation of the present evidence base must be stated plainly. The literature on meat-technology extension is dominated by descriptive accounts, programme reports and cross-sectional studies; rigorous impact evaluations—measuring adoption, safety outcomes and income effects with adequate design—are scarce. Much of what can be said about “what works” is therefore inferential, drawn from analogy with better-studied crop and dairy extension and from the internal logic of the barriers. This review shares that limitation: its synthesis is qualitative and its conclusions are directional. That very scarcity, however, defines the most important research priority.

Proposed integrated extension framework

Drawing the threads together, the synthesis supports an integrated, four-layered framework for bridging the gap. At the base is aggregation—organising producers into clusters, FPOs and SHGs to create scale and a social platform. On this rests shared infrastructure—decentralised, hygienic micro-processing and chilling nodes, often hosted by KVKs or producer organisations, into which appropriate slaughter, preservation, packaging and value-addition technologies are introduced as a bundle. Wrapped around these is a dual advisory channel—combining human, demonstration-based extension (KVKs, veterinary institutions, trained meat-technology facilitators) with ICT-enabled, local-language, low-literacy digital advisory and simplified traceability. Binding all three is an enabling ecosystem—credit, assured market linkages, attainable food-safety compliance, skill certification, and public-private partnership—underpinned by participatory technology development that keeps the research agenda anchored to producer needs. The framework is deliberately modular so that it can be entered at whatever layer local conditions allow, but its logic is that durable impact requires all four to be present over time.

Future perspectives

Several directions follow. Methodologically, the field needs rigorous, preferably longitudinal and quasi-experimental, evaluations of meat-technology extension interventions, with agreed indicators spanning adoption, microbial safety, post-harvest loss reduction and household income, so that “what works” rests on evidence rather than assertion. Substantively, there is scope to develop and validate frugal, smallholder-appropriate versions of preservation, packaging and cold-chain technologies explicitly co-designed with producers. In the digital domain, a dedicated livestock-products advisory stream—pictorial and video-first, multilingual, and integrated with simplified mobile traceability—should be built and tested, and the emerging AI/ML and computer-vision tools for quality grading should be examined for eventual decentralised, phone-based deployment (Chmiel *et al.*, 2011; Karlsen *et al.*, 2013) [15, 16]. Institutionally, the case is strong for creating and formally recognising a cadre of meat-technology extension

specialists and for embedding livestock-products modules within mainstream extension curricula and KVK mandates. Socially, the intersection of meat value addition with women's empowerment through SHGs deserves focused study, both because it is a promising livelihood pathway and because it addresses the sector's gender and equity dimensions directly. Finally, extension and food-safety policy should be co-designed so that formalisation becomes a ladder that small producers can climb rather than a wall that excludes them.

Conclusion

The lab-to-farmgate gap in Indian meat technology is real, consequential and, on the evidence, bridgeable—but not by technology alone. India possesses a rich and largely applicable base of meat-processing and preservation technologies; the binding constraints lie in the institutional, economic and communicational systems that should carry those technologies to millions of small-scale producers, and in an extension apparatus that has historically neglected livestock products. The linear transfer-of-technology model is inadequate to this task. What the literature supports instead is a pluralistic, demand-driven and organisationally embedded extension approach built on producer aggregation, shared decentralised infrastructure, a dual human-and-digital advisory channel, and an enabling ecosystem of credit, markets, attainable compliance and skills—kept honest by participatory technology development and, urgently, by rigorous impact evaluation. Pursued together, these strategies can convert meat processing from a downstream activity that bypasses the producer into a rural-livelihood engine that raises incomes, reduces waste, improves food safety and advances the broader goals of agricultural extension and social development.

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