CHAPTER

4

ECONOMIC ENTOMOLOGY OF KERRIA LACCA: FROM TRADITIONAL LAC CULTURE TO GREEN INDUSTRIAL APPLICATIONS

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Abstract

The lac insect (Kerria lacca Kerr) is a commercially important scale insect that secretes a natural resin widely used in pharmaceutical, food, cosmetic, electrical, and heritage industries. India remains the leading global producer and processor, with cultivation concentrated in tribal regions of Jharkhand, Chhattisgarh, Odisha, and Madhya Pradesh, where it supports about 450,000–500,000 farming families and numerous processing and handicraft livelihoods. Lac-based agroforestry systems also provide key ecosystem services, including carbon sequestration, biodiversity conservation, soil improvement, and restoration of degraded lands. However, the sector faces serious constraints from pests and diseases, climate variability, host plant decline, market volatility, and low adoption of improved technologies. Addressing these challenges requires coordinated genetic improvement, climate-smart cultivation protocols, and targeted policy support to stabilize producer incomes and sustain resource bases. Strengthening local processing, branding, and value-addition can further enhance lac's role in green industrial development and inclusive rural livelihoods in South Asia.

Keywords: *Kerria lacca, Lac cultivation, Natural resin, Rural livelihoods, Sustainable development*

Introduction

Lac culture is widely regarded as one of the earliest organized systems of beneficial insect domestication, with literary and archaeological evidence indicating that lac resin has played a sustained cultural and economic role in the Indian subcontinent for over three millennia (Tiwari *et al.,* 2021). Historically, communities employed lac for sealing palm-leaf manuscripts, embellishing ritual and ceremonial artefacts, colouring and waterproofing textiles, and crafting ornamental objects, embedding the resin within a rich artisanal heritage across South Asia (Ghosh *et al.,* 2021).

Industrialisation has subsequently redefined lac as a strategic natural polymer. Its combination of moisture and heat resistance, dielectric properties, strong film-forming behaviour, pH-dependent solubility, and food-contact safety has underpinned its adoption in pharmaceutical coatings, electronics, food glazing, cosmetics, specialty adhesives, and art conservation (Chansatidkosol *et al.,* 2025; Yuan *et al.,* 2021). India's diverse agroclimatic conditions and abundant native host trees have consolidated its position as the global centre for lac cultivation, processing, and associated knowledge systems (Singh & Verma, 2020).

From a development standpoint, lac cultivation is now promoted as a low-input, low-risk livelihood option suited to marginal and degraded lands, providing cash income that complements food crop production and underpins poverty reduction and livelihood diversification, particularly among tribal households (Sharma *et al.,* 2023). Concurrently, lac-based agroforestry enhances tree cover, biodiversity, soil quality, and carbon sequestration, with projections indicating that expanded agroforestry in India could sequester roughly 10.5 petagram CO_2 equivalent annually by mid-century (Hazarika *et al.,* 2024). Collectively, these historical, economic, and ecological dimensions underscore the need for integrated analysis of lac insect biology, production technologies, value chains, ecosystem services, and enabling policy frameworks.

Biology and Developmental Ontogeny of *Kerria Lacca*

Taxonomic Classification and Natural History

Kerria lacca Kerr belongs to the scale insect family Lacciferidae (Order Hemiptera, Superfamily Coccoidea) and represents the only commercially viable lac-producing species among approximately 35 identified lac-secreting insect species recognized globally (Rao *et al.,* 2022). The species exhibits hemimetabolous development characterized by gradual morphological differentiation, sessile adult females, and pronounced sexual dimorphism with respect to body size, longevity, locomotor capacity, and reproductive function. Lacciferidae populations demonstrate bivoltine or trivoltine life cycles contingent upon regional temperature regimes, photoperiod duration, and host plant phenological development, permitting two or three harvestable crop cycles per calendar year across favorable geographic zones (Patel & Singh, 2022).

Life Cycle and Developmental Stages

The ontogenetic cycle of *K. lacca* encompasses approximately six to seven months from egg oviposition through adult sexual maturation and spans three morphologically distinct phases: ovum, nymph, and adult imago (Desai *et al.,* 2023). Following copulation, gravid females oviposit between 300 and 1,000 eggs within the resinous protective enclosure designated the lac cell, which functions simultaneously as a maternal shelter and reproductive chamber (Kumar *et al.,* 2020). Embryonic development proceeds rapidly, with eggs hatching within hours to days, releasing mobile first-instar nymphs colloquially termed "crawlers" in reference to their characteristic ambulatory behavior (Patel & Singh, 2022).

Neonate crawlers actively navigate host plant surfaces, employing piercing-sucking mouthparts to penetrate vascular phloem tissue and commence phytophagous nutrient extraction. Following suitable microhabitat location, typically requiring 2 to 14 days of active dispersal, crawlers become permanently sessile and initiate resin synthesis, progressively encasing their bodies within an expanding resinous matrix that progressively hardens and provides protective shelter (Mehta *et al.,* 2022). Throughout the nymphal growth period, insects undergo three successive ecdysial events (molts), with profound morphological restructuring occurring immediately post-first molt, including regression of locomotive appendages, sensory organs, and functional mouthparts (Kumar *et al.,* 2020). Notably, these anatomical structures experience partial regeneration during the subsequent intermolt period, permitting sustained phloem feeding and continuous resin production (Rao *et al.,* 2022; Patel & Singh, 2022).

Nymphal development from egg hatch to adult sexual differentiation typically requires approximately 8–10 weeks, depending upon ambient temperature, humidity conditions, and host plant nutritional quality (Sharma *et al.,* 2022). Sexual differentiation initiates within the protective resinous enclosure, with male nymphs undergoing complete metamorphosis to produce small, winged imaginal adults possessing brief lifespans (2–3 days), non-functional digestive systems, and high reproductive motivation (Desai *et al.,* 2023). Upon imaginal eclosion, male insects emerge from the lac cell and actively seek immobile females concealed beneath their respective resinous coverings, accomplishing insemination through abdominal insertion, after which males rapidly deteriorate and die (Patel & Singh, 2022). Conversely, female nymphs develop into permanently sedentary, fecund adult imagines that remain perpetually enclosed within the lac cell, continuously extracting phloem sap and depositing resinous secretion until ovarian maturation triggers oviposition and subsequent senescence (Sharma *et al.,* 2022). Female longevity extends from 60–150 days contingent upon environmental temperature regimes, host plant sap quality, and absence of predation or parasitoid attack (Rao *et al.,* 2022). During this extended sessile period, females increase substantially in body volume through continuous nutrient assimilation and resin deposition, ultimately depositing their complete reproductive complement before death (Kumar *et al.,* 2020).

Host Plant Selection and Nutritional Relationships

Successful *K. lacca* establishment and population persistence depend critically upon host plant species identity and physiological vigor (Sharma *et al.,* 2022). Primary commercial host species include *Butea monosperma* (palas), *Ziziphus mauritiana* (ber), and *Schleichera oleosa* (kusum), each supporting geographically distinct lac strains with characteristic resin properties, productivity profiles, and market value differentiation (Verma *et al.,* 2021). *Schleichera oleosa* cultivation produces premium-grade Kusmi lac internationally recognized for exceptional clarity, light chromatic characteristics, and superior viscosity profiles commanding substantially elevated market prices relative to alternative strains (Singh & Verma, 2020). Conversely, *Butea monosperma* and *Ziziphus mauritiana* support Rangeeni strains producing darker-hued resin with elevated yield volumes but comparatively reduced resin quality metrics and market valuations (Sharma *et al.,* 2023).

Host plant phloem sap composition, encompassing dissolved carbohydrates, proteinaceous compounds, inorganic mineral nutrients, and secondary plant metabolites, fundamentally determines insect developmental velocity, reproductive fecundity, resin chemical composition, and ultimately product commercial value (Sharma *et al.*, 2022; Rao *et al.*, 2022). Vigorous host plants manifesting abundant canopy development and rapid shoot elongation provide nutritionally superior phloem substrates enabling elevated crawler settlement density, accelerated nymphal development rates, maximized resin deposition volume, and superior resin quality characteristics (Tiwari *et al.*, 2021; Singh & Verma, 2020). Research conducted by Meshram *et al*. (2024) on host plant performance across Chhattisgarh found that *Schleichera oleosa* yielded a maximum stick lac of 237.91 sticks per plant with a total productivity of 54.94 kg per plant. Conversely, host plants experiencing water deficit stress, nutrient limitation, or pest-induced canopy damage demonstrate reduced phloem nutrient concentration and substantially diminished lac insect survival rates, population establishment success, and final resin productivity (Sharma *et al.*, 2022).

Lac Production Technology and Cultivation Systems

Broodlac Selection and Quality Assessment

Successful lac production initiates with the procurement of high-quality broodlac—sticklac containing living, reproductively mature female insects intended for transfer onto candidate host plants. Superior broodlac demonstrates elevated fecundity rates, rapid developmental progression, vigorous resin secretion capacity, and environmental stress tolerance characteristics (Kumar *et al.*, 2023). Experienced cultivators employ visual inspection protocols to assess broodlac quality, evaluating criteria including resin coloration uniformity, physical cell integrity, optimal moisture content, and visible absence of pest damage or fungal colonization (Sharma *et al.*, 2022).

Host Plant Management and Pruning Protocols

Contemporary lac production technology emphasizes systematic host tree management optimizing continuous availability of young, nutrient-dense twigs supporting crawler colonization and sustenance. Post-harvest pruning operations stimulate apical dominance and lateral shoot development, promoting synchronous new-shoot emergence coinciding with seasonal brood maturation and crawler dispersal periods (Verma *et al.*, 2021). Excessive pruning intensity or inappropriate timing precipitates tree physiological stress and compromises long-term productivity potential, whereas insufficient pruning restricts suitable settlement substrates and diminishes per-hectare resin yield. Strategic pruning thus represents a critical intervention balancing competing objectives of tree health maintenance and production optimization (Singh & Verma, 2020).

Brood Inoculation and Crop Management

Strategic timing of broodlac inoculation operations ensures synchronization between female reproduction and crawler emergence with host plant shoot flush development, thereby maximizing settlement success and ultimate resin production (Singh, 2017). Cultivators conventionally apply broodlac during the season immediately preceding anticipated shoot emergence, permitting adequate time for female oviposition and crawler mobilization (Kumar *et al.*, 2023; Rao *et al.*, 2022). Research by Patel *et al*. (2023) examining broodlac inoculation rates demonstrated that optimal inoculation at 30 g per plant yielded maximum stick lac production of 619.20 sticks, with highest scraped lac yield of 407.94 g per plant, suggesting that higher inoculation rates result in overcrowding-related crawler mortality. Environmental conditions during the inoculation-to-settlement interval critically influence population establishment outcomes; optimal results occur when ambient temperatures remain within 20–30°C ranges, relative humidity exceeds 70%, and soil moisture adequacy supports plant physiological function (Sharma *et al.,* 2022; Mehta *et al.,* 2022).

Integrated Pest and Disease Management

Kerria lacca populations experience substantial biotic pressure from diverse predatory and parasitic arthropod fauna and entomopathogenic microorganisms. Major predators include Lepidopterous species *Eublemma amabilis* Moore and *Pseudohypatopa pulverea* Mayr (Lepidoptera: Noctuidae), which in larval form pierce lac encrustations and feed upon enclosed insects, with *E. amabilis* inflicting approximately 30–35% of total predation damage across unmanaged populations (Meshram *et al.,* 2023; Sharma *et al.,* 2023). Parasitoid wasps, notably *Tachardiaephagus tachardiae*, oviposit within live lac insects; developing larval parasitoids consume host tissue internally, precipitating mortality rates of 30–50% during peak parasitism periods (Meshram *et al.,* 2023; Kumar *et al.,* 2024). Secondary predators including rodent species and entomopathogenic fungal pathogens further compromise production in unmanaged cultivation systems (Sharma *et al.,* 2022; Desai *et al.,* 2024). Unmitigated pest and disease pressure precipitates yield losses ranging from 30–50% of potential production, necessitating proactive management intervention. Contemporary integrated pest management approaches combine cultural practices (infested branch removal, pruning debris sanitation), deployment of natural biological control agents, and judicious application of environmentally acceptable bioinsecticides (Sharma *et al.,* 2024).

Socioeconomic and Livelihood Dimensions

Geographic Distribution and Farmer Demographics

Lac cultivation concentrates within specific agroclimatic zones characterized by appropriate temperature regimes, suitable monsoon precipitation patterns, and abundant naturally-occurring or cultivated host plant populations (Singh, 2017; Tiwari *et al.,* 2021). India's principal lac production regions encompass eastern and central states, notably Jharkhand, Chhattisgarh, Odisha, Madhya Pradesh, West Bengal, and Maharashtra, where approximately 450,000–500,000 farm families engage in lac production as primary or supplementary livelihood activity (Singh & Verma, 2020). Research conducted by Roy and Sharma (2024) documented that tribal populations in lac-producing districts derive approximately 60–75% of annual non-farm income from lac cultivation, indicating critical livelihood dependence. The farming population predominantly comprises tribal communities and small-scale proprietors controlling limited landholdings, for whom lac cultivation represents an accessible income diversification strategy independent of land tenure status (Singh, 2017; Verma & Patel, 2020).

Income Generation and Household Economic Contribution

Empirical research demonstrates that lac cultivation contributes between 25–40% of annual household monetary income among engaged farmers, with potential income generation ranging from Indian Rupees 40,000–500,000 per hectare contingent upon market commodity prices, seasonal environmental conditions, and cultivation intensity and management quality (Tiwari *et al.,* 2021). Singh and Verma (2020) found that farmers engaged in scientific lac cultivation earned three times more income than those relying on conventional agriculture, with annual returns reaching INR 120,000–150,000 per hectare under optimal management conditions. Critically, lac harvest timing coincides with agricultural lean seasons when subsistence crop income remains unavailable, providing crucial cash flow during periods of seasonal income scarcity and functioning as an income-smoothing mechanism, reducing household vulnerability to seasonal income fluctuation and economic shocks (Singh, 2017).

Income derived from lac cultivation typically finances essential household requirements including food security maintenance, children's education accessibility, healthcare cost management, and productive agricultural investments, directly contributing to poverty reduction and substantive household welfare improvements (Verma & Patel, 2020). The financial returns from lac cultivation exceed alternative land-use options available to resource-poor and land-limited farmers, rendering the activity economically attractive despite significant production risk factors associated with pest pressure and market volatility (Tiwari *et al.,* 2021).

Employment Generation and Value Chain Integration

The lac value chain generates employment across multiple sequential and concurrent stages including on-farm cultivation activities (host tree pruning, broodlac inoculation, pest and disease monitoring, harvest operations), post-harvest handling operations (sticklac scraping, cleaning, drying), primary processing (transformation to seedlac and shellac products), and tertiary manufacturing (handicraft production, retail distribution) (Singh, 2017; Kumar *et al.,* 2023). Labor-intensive operations throughout the complete calendar year create year-round employment opportunities for rural households and generate approximately 1.0–1.5 person-years of labor demand per hectare of cultivation (Singh & Verma, 2020). Mehta and Kumar (2023) documented that lac-based enterprises create approximately 3.2 million person-days of employment annually across primary processing and handicraft production sectors in principal lac-producing states.

Cottage industries and small-scale processing units concentrated within principal lac-producing districts convert raw sticklac into refined seedlac and shellac through mechanical scraping, thermal processing, and chemical refinement, generating substantial employment and income opportunities (Singh, 2017; Verma *et al.,* 2021). These processing enterprises predominantly operate within rural settings, sustaining artisanal production clusters and enabling value addition opportunities and market linkage development favorable to primary producers (Patel & Singh, 2022).

Gender Dimensions and Women's Economic Empowerment

Women constitute a substantial proportion of the lac value chain labor force, particularly within scraping and cleaning operations, lac dye extraction, and artisanal handicraft production (Singh & Verma, 2020). Self-Help Groups (SHGs) composed of rural women have leveraged lac-based production—particularly lac bangle manufacture, jewelry production, and decorative artifact fabrication—as a vehicle for economic independence, enhanced household decision-making authority, community social capital development, and identity formation (Verma & Patel, 2020). Research by Sharma *et al*. (2024) examining women SHGs in Jharkhand found that women artisans engaged in lac-based handicraft production earned average annual incomes of INR 60,000–90,000, with 78% reporting enhanced household decision-making authority. These microenterprises achieve market linkages through participation in regional and national exhibitions, engagement with digital commerce platforms, and integration into tourism infrastructure, enabling income generation and gender-transformative developmental outcomes (Desai *et al.,* 2024).

Industrial and Commercial Applications

Pharmaceutical utilization and drug delivery

Shellac's film-forming ability, chemical stability, and pH-dependent solubility make it a valuable excipient for specialised oral drug delivery. It is widely used in enteric-coated dosage forms to protect acid-labile drugs from gastric degradation while enabling controlled release in the intestine, thereby improving bioavailability, reducing gastric irritation, and lowering dosing frequency (Wang *et al.,* 2024). Recent work on 3D-printed, shellac-based systems has shown that plasticised matrices can deliver site-specific intestinal release with high drug liberation within a few hours at intestinal pH, illustrating their potential in personalised medicine (Chansatidkosol *et al.,* 2025; Doshi *et al.,* 2023). Beyond coatings, shellac acts as a binder in wet granulation and as a moisture barrier for hygroscopic actives, while shellac-based microencapsulation protects probiotics, enzymes, and plant extracts from oxidation, heat, and humidity, extending shelf life and preserving bioactivity during storage and gastrointestinal transit (Kumar *et al.,* 2024).

Food and confectionery applications

In the food sector, shellac is authorised as a surface glazing agent (E904) and applied to confectionery, dried fruits, and nuts to improve gloss, maintain texture, and reduce moisture and oxygen transfer. Thin, high-gloss coatings provide effective protection with negligible mass increase, helping to preserve sensory quality and extend shelf life (Shu *et al.,* 2025).

Wood finishing and heritage restoration

Shellac remains a preferred natural finish for high-value wood and musical instruments due to its warm appearance, high gloss, and ease of repair. Traditional French polishing builds up multiple thin shellac layers to achieve depth and luster superior to many synthetic finishes, which is why conservators favour it for restoration of antiques and heritage objects; it is reversible, compatible with aged wood, and has a favourable safety profile (Singh *et al.,* 2024; Patel & Singh, 2022).

Electrical and Engineering Applications

Historically, shellac-based varnishes were important dielectric materials for insulating coils, windings, and fine electrical components. Although petrochemical polymers dominate mass applications today, shellac is still used in niche high-reliability and restoration contexts—such as precision transformers, legacy equipment, and certain aerospace or specialty devices—where its dielectric strength, moisture resistance, and thermal behaviour remain advantageous (Rao *et al.,* 2022).

Cosmetic and Personal Care Formulation

Lac wax and shellac derivatives are incorporated into colour cosmetics and hair and skin products as film-formers, fixatives, and gloss enhancers. They contribute shine, adhesion, flexibility, and wear resistance in lipsticks, mascaras, eyeliners, nail enamels, and styling products, while their natural origin and favourable tolerability align with consumer demand for bio-based, "clean" ingredients (Sharma *et al.,* 2023; Verma & Patel, 2020).

Printing Inks and Specialty Adhesives

Shellac-based resins are used in printing inks for pharmaceuticals and food packaging, where they provide strong adhesion and film integrity while meeting food-contact safety requirements. In adhesives, shellac contributes toughness and bond strength in bookbinding, fine wood joinery, laminates, and certain composites, occupying specialised niches where a natural, thermoplastic resin with good mechanical and aesthetic properties is desirable (Pandey & Verma, 2023; Singh *et al.,* 2024).

Traditional and Medicinal Applications

Ayurvedic and Traditional Medicine Utilization

Purified lac powder, designated *laksha churna* in Ayurvedic medicinal nomenclature—has maintained traditional therapeutic roles within South Asian medical systems for several centuries (Kumar *et al.,* 2020; Sharma *et al.,* 2022). Traditional practitioners historically employed purified lac preparations for wound healing and dermal infection management, attributed to documented antimicrobial and antiseptic properties facilitating accelerated tissue repair and epithelialization (Rao *et al.,* 2022). Bone pathology management, including fracture treatment and osteoporosis amelioration, represents another significant traditional application domain, with lac formulations combined with complementary herbal ingredients providing calcium-enriched matrices supporting optimal skeletal tissue regeneration and mineralization (Singh & Verma, 2020; Mehta *et al.,* 2022). Traditional practitioners also employed lac preparations for gastrointestinal disorder management, specifically for diarrhea and dysentery treatment, representing crucial therapeutic options for populations with limited access to allopathic pharmaceutical interventions (Kumar *et al.,* 2023).

Biochemical Constituents and Pharmacological Properties

Lac resin comprises multiple bioactive organic compounds, including aleuritic acid, shellolic acid, anthraquinone pigments, and protective waxes, which exhibit documented antimicrobial, antifungal, antioxidant, anti-inflammatory, and wound-healing biological activities (Pandey & Verma, 2023; Sharma *et al.,* 2024). These constituent bioactive properties provide biochemical and pharmacological rationale for traditional medicinal applications while simultaneously suggesting promising contemporary research trajectories exploring lac-derived compounds in novel therapeutic contexts, including antimicrobial resistance management, chronic inflammation treatment, and dermatological applications (Kumar *et al.,* 2024; Singh *et al.,* 2024).

Environmental and Ecological Benefits

Agroforestry Integration and Landscape Management

Lac cultivation demonstrates inherent ecological and economic compatibility with agroforestry frameworks integrating tree species and shrub components into agricultural and pastoral management systems, thereby enhancing landscape-level biodiversity, productive capacity, ecological resilience, and adaptive capacity to environmental perturbations (Tiwari *et al.,* 2021). Host trees including *Butea monosperma*, *Schleichera oleosa*, and *Ziziphus mauritiana* provide substantive ecosystem services encompassing soil stabilization and erosion prevention, reduction of surface runoff through enhanced infiltration, nutrient cycling via litterfall decomposition and mineralization, and microhabitat provisioning for diverse fauna including arthropods, avifauna, and small mammals (Hazarika *et al.,* 2024).

Incentivizing lac cultivation through income generation opportunities motivates farmer investments in tree planting and long-term maintenance on field bunds, homesteads, degraded sites, and marginally productive landscapes, cumulatively increasing on-farm tree cover and associated ecological functionality This integrated land-use system permits income generation without requiring agricultural land displacement or conversion of productive subsistence crop cultivation areas, enabling economically productive landscape management on otherwise marginal or underutilized sites (Kumar *et al.,* 2023).

Biodiversity Conservation and Habitat Provision

Lac-based agroforestry ecosystems function as microhabitat complexes supporting diverse associated biota encompassing beneficial arthropods, predatory insects, parasitoid wasps, avifauna, small mammalian species, and soil decomposer organisms. Maintenance of heterogeneous host plant species assemblages preserves in-situ populations of native flora and associated fauna, contributing substantively to alpha diversity (within-site species richness) and beta diversity (between-site species compositional turnover) conservation within cultivation landscapes (Nath *et al.,* 2021).

Carbon Sequestration and Climate Mitigation

Host trees employed in lac cultivation accumulate substantial aboveground biomass over multi-decade lifespans, functioning as effective atmospheric carbon sinks through continuous CO_2 capture and long-term organic carbon storage in woody tissues (Hazarika *et al.,* 2024). Contemporary research estimates that agroforestry management practices in India possess carbon sequestration potential of 10.5 petagram CO_2 equivalent per annum by 2050 under expanded adoption scenarios, while average sequestration potential across Indian agroforestry systems averages 25 megagram carbon per hectare over growth periods (Nath *et al.,* 2021; Bremer *et al.,* 2025). The cultivation system's minimal agrochemical requirements, absence of irrigation infrastructure dependence, and reliance upon native tree species result in negligible greenhouse gas emissions compared to conventional intensive agricultural systems, thereby contributing substantively to climate change mitigation objectives and global carbon neutrality targets (Bremer *et al.,* 2025).

Landscape Restoration and Soil Health Enhancement

Lac cultivation demonstrates significant potential for ecological rehabilitation of degraded landscapes encompassing mined lands, erosion-prone hillslopes, abandoned agricultural sites, and semiarid drought-vulnerable zones (Hazarika *et al.,* 2024). Economic incentives derived from lac production motivate community investments in host tree establishment, propagation, and long-term maintenance on previously unproductive or abandoned sites, facilitating vegetation recovery, soil structure amelioration through organic matter accumulation, microhabitat restoration, and wildlife habitat provision (Kumar *et al.,* 2024).

Constraints and Production Challenges

Pest and disease complex

Populations of *Kerria lacca* are heavily constrained by a complex of predators, parasitoids, and pathogens that can collectively destroy a major share of the standing crop. White lac moth (*Eublemma amabilis*) and black lac moth (*Pseudohypatopa pulverea*) larvae bore through the resin encrustation and feed on immature stages, causing high crawler and nymph mortality, with *E. amabilis* alone often responsible for roughly one-third of total predation losses in unmanaged plantations (Meshram *et al.,* 2023; Sharma *et al.,* 2024). Primary parasitoids such as *Tachardiaephagus tachardiae* oviposit within living lac insects; their developing larvae consume host tissues internally, frequently killing 30–50% of the population during peak activity, while rodents, entomopathogenic fungi, and secondary parasitoids further erode yields in poorly managed orchards (Desai *et al.,* 2024; Rao *et al.,* 2023).

Climatic stress and environmental vulnerability

Lac cultivation is highly sensitive to weather variability because insect development must remain synchronized with host phenology. Irregular monsoon onset, prolonged dry spells, heat waves, and intense rainfall events disrupt flushing of host shoots, reducing suitable sites for crawler settlement and weakening plant vigor (Sharma *et al.,* 2023). High temperatures and low humidity desiccate crawlers, whereas heavy rains physically dislodge newly settled nymphs, leading to poor crop establishment and unstable yields that threaten income security for lac-dependent households (Mehta *et al.,* 2022).

Host plant scarcity and genetic erosion

Expansion and sustainability of lac cultivation are increasingly constrained by the decline of key host species such as *Butea monosperma*, *Schleichera oleosa*, and *Ziziphus mauritiana*. Deforestation, agricultural conversion, mining, and urban growth reduce host tree density, forcing cultivators to travel farther for broodlac, raising transport and labour costs, and intensifying competition for remaining trees (Tiwari *et al.,* 2021; Singh, 2017). Low investment in systematic planting, regeneration, and long-term management of host trees accelerates local genetic erosion and creates a vicious cycle of declining resource base, rising costs, and shrinking returns (Singh & Verma, 2020; Verma & Patel, 2020; Kumar *et al.,* 2023).

Market price volatility and value-chain inefficiency

Lac producers operate in a volatile market shaped by fluctuating global demand, competition from synthetic resins, and cyclical changes in industrial consumption. Pronounced interseasonal price swings complicate production planning and make household cash flows highly unpredictable, especially for smallholders with minimal savings or access to formal credit (Singh, 2017; Mehta & Kumar, 2023). Weak bargaining power, limited access to organized markets, and dependence on itinerant traders mean many farmers must sell raw sticklac at distress prices, capturing only a fraction of the value embedded in processed seedlac and shellac (Sharma *et al.,* 2024; Tiwari *et al.,* 2021).

Technology and knowledge adoption gaps

Significant yield and quality losses persist because large numbers of cultivators still rely on empirical practices and lack exposure to improved technologies. Deficits in training on systematic pruning, broodlac quality assessment, pest surveillance, and scientific inoculation lead to low insect establishment and high mortality. Extension services are sparse in remote tribal belts, and the upfront costs of modern tools and small processing units exceed the investment capacity of most producers, slowing adoption of profitable innovations such as improved broodlac strains, integrated pest management, and mechanized scraping and cleaning (Kumar *et al.,* 2023; Sharma *et al.,* 2023).

Future Directions and Research Priorities

Genetic improvement and strain development

Future gains in productivity and stability will depend heavily on breeding and selection of superior lac insect strains. Research priorities include lines with higher resin secretion, shorter life cycles, and enhanced tolerance to predators, parasitoids, and climatic stress, backed by tools such as whole-genome sequencing, molecular markers, SNP genotyping, and transcriptomics to identify and track key adaptive traits (Singh & Verma, 2020; Sharma *et al.,* 2024).

Climate-responsive production systems

Developing climate-smart lac cultivation packages tailored to specific agroclimatic zones is essential to buffer the impacts of increasing variability. Promising strategies integrate diversified host-tree portfolios, water-conserving soil and canopy management, improved pruning calendars, and real-time climate and pest advisory services to help farmers align inoculation and harvest with favourable windows (Nath *et al.,* 2021).

Value addition and market development

Upgrading the lac value chain requires decentralised processing clusters, producer-owned enterprises, and branding mechanisms that reward sustainable and high-quality production. Establishing village or block-level seedlac and shellac units can shift value capture closer to producers, while geographic indications, eco-labels, and links to green procurement policies can open premium markets for natural bio-resins (Singh & Verma, 2020; Kumar *et al.,* 2023; Verma *et al.,* 2021).

Policy and institutional strengthening

Supportive policy frameworks are needed to reduce risk and crowd-in private and community investment. Priority interventions include minimum support prices, tailored crop insurance products, subsidies or incentives for host tree planting on degraded lands, and targeted credit for small processing and storage infrastructure (Singh & Verma, 2020; Mehta *et al.,* 2022). Stronger coordination among research institutes, forestry and agriculture departments, cooperatives, NGOs, and farmer organizations will be critical to scale training, technology dissemination, and collective marketing, positioning lac as a resilient pillar of climate-smart rural development (Kumar *et al.,* 2023).

Conclusion

Lac insect culture exemplifies how a single beneficial insect can simultaneously generate economic, social, and ecological gains within economic entomology. As a productive scale insect, *Kerria lacca* underpins multi-stage value chains from resin production and industrial processing to handicrafts, while offering a low-input, high-value livelihood option for tribal and marginal farmers in lac-growing regions. At landscape scale, lac-based agroforestry systems enhance tree cover, soil health, biodiversity, and carbon sequestration, aligning insect-based production with broader sustainability and climate-mitigation objectives. These benefits are, however, constrained by biotic stresses, climatic instability, host plant decline, price volatility, and limited uptake of improved technologies, all of which affect both insect populations and producer welfare. Strengthening the sector therefore requires integrating entomological research on biology, genetics, and pest complexes with climate-responsive cultivation, local value addition and marketing, and enabling policies that reduce risk and reward sustainable practices, positioning lac as a robust model for insect-based bioresource management that supports rural livelihoods and ecosystem resilience.

Disclosure Statement

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